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TRIANGLE UNIVERSITIES NUCLEAR LABORATORY

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# Introduction

The Triangle Universities Nuclear Laboratory (TUNL) is a center for low-energy nuclear physics that is staffed by faculty from three consortium universities: Duke University, North Carolina State University, and the University of North Carolina at Chapel Hill. TUNL faculty supervise about 50 graduate students conducting Ph.D. thesis projects on a wide variety of topics that include nuclear astrophysics, fundamental symmetries, weak interactions, few-nucleon and sub-nucleon systems, many-body nuclear systems, neutrino physics, and applications of nuclear physics. This document is a compilation of status reports of research projects conducted by TUNL research groups during the period of **September 1, 2009 to August 31, 2010**. It covers the second half of year-1 (March 1, 2009 - February 28, 2010) and first half of year-2 (March 1, 2010 - February 28, 2011) of the three-year grant (March 1, 2009 - February 29, 2012) to the three collaborating universities from the Low-Energy Program in the Office of Nuclear Physics at the U.S. Department of Energy.

During this reporting period research groups at TUNL published 47 papers in refereed journals of which 5 were letter articles. Consortium members delivered 66 invited talks at APS meetings, conferences workshops and department colloquia and seminars. In addition, the consortium groups published 18 papers in conference proceedings and gave 40 contributed talks at APS meetings and conferences. About 35% of the journal papers and 30% of the invited talks were based on work done at the on-site accelerator and research facilities. Highlights of research accomplishments made during the reporting period are given below.

- **New data from HI $\gamma$ S reveal dominant electric nature of pygmy dipole resonance:**

A common feature in medium- and heavy-mass nuclei is the prevalence of neutron excess and the resulting formation of a neutron skin. A consequence of the neutron skin is a collective vibrational mode of motion at low excitation energies. This excitation mode is dipole in nature and is referred to as the pygmy dipole resonance (PDR) because its small strength relative to the dominate giant dipole resonance (GDR) which occurs at higher excitation energies. The PDR is often modeled as the vibration of the neutron skin against the core of the nucleus which is composed of equal numbers of neutrons and protons. The PDR is of practical importance in nuclear astrophysics because of its impact on the reaction landscape at energies relevant to nuclear synthesis in the stellar medium. For example, the existence of this low-energy excitation mode influences  $(n, \gamma)$  reaction rates relevant to the rapid neutron capture process in stars.

Using nuclear resonance fluorescence at HI $\gamma$ S we have verified for the first time in  $N = 82$  isotones that the observed pygmy dipole strength from 4 MeV to the particle separation energy is predominantly electric in nature. Interpretation of our data with a quasiparticle phonon model indicates that there are two components to the PDR: the low-lying group of  $1^-$  states are due to the excitation of the neutron-skin and the higher-lying  $1^+$  states that belong to a transitional region on the tail of the GDR. For details see the article by Tonchev *et al.* in Sect. 6.4.2.

- **Two-body photodisintegration of  $^3\text{He}$  between  $E_\gamma=7$  and 16 MeV:**

We have completed the most accurate measurements of the total cross-section of the  $^3\text{He}(\gamma, p)^2\text{H}$  reaction in the energy range from 7 to 16 MeV at HI $\gamma$ S. These data confirm the reported discrepancy between three-nucleon calculations and measurements. However, these new data from HI $\gamma$ S are closer to theory than almost all of the data obtained during the last half century for this classical three-nucleon reaction. For details see the article by W. Tornow *et al.* in Sect. 6.2.3.

- **Space-star anomaly confirmed in new neutron-deuteron breakup measurements:**  
 Our recent cross-section measurements for the  $^2\text{H}(n, np)n$  reaction at 16 MeV incident neutron energy confirm earlier results for the  $^2\text{H}(n, nn)p$  reaction in the Space Star configuration at neutron beam energies below 25 MeV. These new data along with reported results show that theoretical calculations based on all modern nucleon-nucleon potential models under-predict this cross section by about 30%. For details see the article by A. H. Couture *et al.* in 4.3.1.
- **First Compton scattering measurements with HINDA: A new method for observing the Isovector Giant Quadrupole Resonance (IVGQR) in nuclei:**  
 Six of the eight NaI detectors in the HI $\gamma$ S NaI Detector Array (HINIDA) were used to measure the Compton scattering cross section from  $^{209}\text{Bi}$  in the energy range from 15 to 30 MeV. These data provide the first high precision determination of the energy, width, and strength of the IVGQR. The IVGQR is a general feature of the collective modes of motion of nuclei. However, because of the lack of accurate measurements a detailed theoretical understanding has not been developed. The combination of the 100% polarized beams at HI $\gamma$ S and the HINDA array along with the realization that the E1-E2 interference term observed using polarized  $\gamma$  rays changes sign when going from a forward to a backward angle has lead to an order of magnitude improvement in the values of the parameters which describe the IVGQR. The collaboration plans to prepare a proposal to study the IVGQR via Compton scattering as a function of mass number (A) to submit to the 2011 HI $\gamma$ S PAC. For further details refer to the article in this report by S. Henshaw *et al.* in Sect. 6.4.1.
- **First photodisintegration measurements on radioactive targets at HI $\gamma$ S:**  
 The tunable monoenergetic  $\gamma$ -ray beam and high resolution detection systems at HI $\gamma$ S enable precision cross-section measurements of photonuclear reactions on targets having masses of only a few hundred micrograms. This capability creates opportunities to study nuclear structure of radioactive nuclei, which are typically available in sparse amounts, and to make measurements important for national security and energy research. The first photodisintegration cross-section measurements on a radioactive target at HI $\gamma$ S were made this year on  $^{241}\text{Am}$ . We performed the highest accuracy  $(\gamma, n)$  cross-section measurements on  $^{241}\text{Am}$  in the energy range from 9 to 16 MeV. Unlike the common observation for strongly deformed nuclei, the  $(\gamma, n)$  cross section for  $^{241}\text{Am}$  shows only a single Lorentzian peak at around 12 MeV. This feature is due to the opening of a strong second-chance fission decay channel  $(\gamma, nf)$  around 12 MeV that inhibits the  $(\gamma, n)$  channel. For more details see A. P. Tonchev *et al.*, Phys. Rev. C, **82**, 054620 (2010).
- **New evaluation of thermonuclear reaction rates:**  
 Evaluated thermonuclear reaction rates, which are the foundation for any successful stellar model, were first presented by Willy Fowler and collaborators (until 1988) and later updated by the large European NACRE collaboration (in 1999). TUNL has led the way in completing a new rate evaluation effort that is based on an entirely new method (a Monte Carlo procedure). Our method provides for the first time realistic rate uncertainties and rate probability density functions. This technique opens a window of opportunity for new kinds of nucleosynthesis studies that were previously unattainable. This comprehensive work has been published as a series of four papers in a "Topical Issue", see Nucl. Phys. A **841** (2010). Applications of these new evaluations are presented in Chapter 3 of this report.
- **MAJORANA Demonstrator status updates:**

  - The temporary cleanroom at UNC passed safety inspection and was put into service in January 2010.
  - The low background counting facility (MALBEK) was put into operation at the Kimballton Underground Research Facility in Kimballton, VA in January 2010.
  - The MAJORANA Demonstrator (MJD) project passed CD-1 review in May 2010.
  - Operation of a P-type point contact detector with low-mass cable and custom front-end electronics was demonstrated in July 2010. The operational characteristics of this detector illustrate many of the main design features of the concepts in the MJD detector modules.
  - An underground copper electroforming facility was put into operation at DUSEL.

- **Upstream target room at HI $\gamma$ S:**

The new upstream target room (UTR) at HI $\gamma$ S was completed and put into service during the first quarter of calendar year 2010. The UTR is used to run experiments that require only moderate amounts of floor space. Examples of experiments that run in the UTR include nuclear fluorescence resonance measurements and photoneutron reaction measurements with compact neutron detector arrangements. Experiments with large equipment setups are run in the main target room, which is referred to as the Gamma Vault (GV). The photofission, Compton-scattering,  $^{16}\text{O}(\gamma, \alpha)$  with the OTPC, nucleon polarizabilities and the GDH experiments will run in the GV. Having two target rooms greatly enhances the efficiency of running experiments at HI $\gamma$ S by providing the capability of running an experiment in the UTR while another one is being set up in the GV.

- **New ECR Source at LENA:**

We have completed construction and commissioning of the new ECR accelerator for LENA. The maximum proton beam current delivered to target is 1.2 mA for  $E_p = 150 - 200$  keV, which exceeds the design goal of 1 mA. The source is currently being used for a cross-section measurement of the  $^{23}\text{Na}(p, \gamma)^{24}\text{Mg}$  reaction. For details see the articles by J.M. Cesaratto *et al.* in Sections 3.1.3 and 8.3.1.

- **$^2\text{H}(d, n)^3\text{He}$  neutrons produced with a pyroelectric two-crystal assembly:**

For the first time neutrons have been produced during the heating and cooling phase of a pyroelectric crystal assembly. Also for the first time, a substantial neutron yield has been obtained without an electric field enhancing nano-tip that is normally attached to one of the two crystals. For details see the article by W. Tornow *et al.* in Sect. 7.2.1.

Groups at TUNL are conducting research in all three physics frontier areas identified in the most recent Long Range Plan of the DOE/NSF Nuclear Science Advisory Committee. In addition, their activities include applications of nuclear physics, instrumentation R&D and nuclear data evaluation and dissemination. The work in each area is summarized below.

## NUCLEAR PHYSICS RESEARCH

### 1. Hadron Structure

The main activities in this area are:

- nucleon EM and spin polarizabilities
- the GDH sum rule on the deuteron and  $^3\text{He}$

The primary off-site facilities used for this work are Jefferson Laboratory and MAX-lab (Sweden).

### 2. Nuclei: From Structure to Exploring Stars

There are three major efforts at TUNL in this area. Each effort is summarized below.

#### (a) *Few-nucleon systems*

The main aim of this work is to test and refine few-nucleon calculations and theoretical description of the nuclear force and its currents used in such calculations. Specific experiments address:

- the role of three-nucleon forces in the 3N and 4N continuum using hadronic and electromagnetic probes
- the analyzing power puzzle in 3N and 4N scattering
- light-nucleus reaction dynamics

#### (b) *Many-body physics*

The emphasis of this research is on:

- descriptions of nuclear reaction data with random matrix theory
- the study of collective response of nuclei using polarized  $\gamma$ rays at HI $\gamma$ S

- measurements of  $(n, 2n)$  cross sections on actinide nuclei
- the excitation of isomeric states
- the study of preequilibrium nuclear reactions

The main off-site facility used by TUNL research groups for this research is the Los Alamos Neutron Science Center (LANSCE).

(c) *Nuclear astrophysics*

The focus of this research is on measurements which are important for solar-neutrino physics, stellar evolution and nucleosynthesis. Specific experiments address:

- astrophysical S-factors of  $(p, \gamma)$  reactions
- the explosive nucleosynthesis in novae
- the evolution of massive stars
- reaction rates important for the r, s and p processes

The main off-site facilities used by TUNL research groups are Argonne National Laboratory (ANL) and Oak Ridge National Laboratory (ORNL).

### 3. In Search of the New Standard Model

The two main research activities in this frontier are summarized below.

(a) *Fundamental-symmetry studies*

The experiments in this area include:

- measurement of time-reversal invariance (neutron EDM)
- non-unitarity tests of the CKM matrix
- measurement of the neutron lifetime

Off-site facilities used for this research include the Spallation Neutron Source (SNS), the Kernfysisch Versneller Instituut (KVI), LANSCE, and the National Institute of Standards and Technology (NIST).

(b) *Neutrino physics*

The main activities in this research program include:

- neutrinoless  $\beta\beta$  decay search using  $^{76}\text{Ge}$  (Majorana Collaboration)
- geo-anti-neutrino and solar neutrino studies at KamLAND
- measurements of data needed to correct the neutrinoless  $\beta\beta$  decay and dark-matter detector measurements for neutron-induced backgrounds
- the study of double-beta decay to excited  $0^+$  states
- neutrino mass determination by  $^3\text{H}$   $\beta$  decay (KATRIN Collaboration)

Off-site facilities used for this research include ORNL, the Deep Underground Science and Engineering Laboratory (DUSEL), the Kimballton Underground Research Facility (KURF), the Waste Isolation Pilot Plant (WIPP), and the Karlsruhe Institute of Technology (KIT).

## INSTRUMENTATION R&D

Developments in technology and instrumentation are vital to our research and training program. Our current instrumentation development activities include:

- instrumentation for characterizing the  $\gamma$ -ray beam at HI $\gamma$ S
- polarized target development
- detector and scattering chamber development
- polarimeters for charged particles, neutrons and  $\gamma$ -rays

## BROADER IMPACT ACTIVITIES

In addition to the above research in the frontier areas of nuclear physics, we run a nuclear data program and are conducting research important for applications of nuclear physics in national nuclear and homeland security, biology and medicine.

## 1. Nuclear Data Program

- nuclear data evaluation for  $A = 3 - 20$  for which TUNL is the international center
- web dissemination of nuclear structure information for  $A = 3 - 20$

## 2. Applications

The focus of these activities includes:

- gamma-ray induced reactions for homeland security and national nuclear security
- neutron-induced reactions for national nuclear security
- plant physiology using accelerator produced  $^{11}\text{CO}_2$  and  $^{13}\text{NO}_3$
- nuclear energy

## EDUCATION

These activities include:

### 1. *Research Experience for Undergraduates*

TUNL runs a NSF-supported Research Experience for Undergraduates (REU) program in nuclear physics. This year ten students participated in this 10-week summer program; eight of them were supported by the NSF REU grant and the other two by grants to TUNL faculty.

### 2. *TUNL Seminar Program*

The TUNL seminar program continues with characteristic vigor (22 invited speakers). This series is augmented by the TUNL Informal Lunch Talks (TILT) where graduate students and postdocs present their research projects, the TUNL Astrophysics Journal Club and a special lecture series given by local speakers on Advances in Physics as part of the REU program during the summer. A related talk series, the Triangle Nuclear Theory Colloquia, is also beneficial to TUNL faculty and students.

The success of our research program is largely attributable to the talents and enthusiasm of the faculty members (17 tenured/tenure track), post-doctoral associates and research staff and graduate students from the three Triangle universities. Also essential to our research program are long-term collaborations with research groups from: Gettysburg College, North Carolina A&T State University, North Carolina Central University, North Georgia College and State University, Penn State Altoona, Tennessee Technological University, University of Connecticut at Avery Point, All-Russian Research Institute of Technical Physics (Snezhinsk), Istituto Nazionale di Fisica Nucleare (Pisa), Jagiellonian University (Cracow), Joint Institute for Nuclear Research (Dubna), Technische Hochschule Darmstadt, University of Cologne, and University of Mainz. In our applications and interdisciplinary research program we collaborate with scientists from several national laboratories, including Lawrence Livermore National Laboratory, Thomas Jefferson National Accelerator Facility, and Los Alamos National Laboratory and with scientists from private companies, such as, the Accelerator Driven Neutron Applications Corporation, the Physical Optics Corporation, and Tri Alpha Energy, Inc.

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| Gao, H. (Professor)                                                                | Duke |
| Golub, R. (Professor)                                                              | NCSU |
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| Haase, D. G. (Professor)                                                           | NCSU |
| Henning, R. (Assistant Professor)                                                  | UNC  |
| Howell, C. R. (Director, Professor)                                                | Duke |
| Huffman, P. R. (Associate Director, Professor)                                     | NCSU |
| Iliadis, C. (Professor)                                                            | UNC  |
| Karwowski, H. J. (Professor)                                                       | UNC  |
| Kelley, J. H. (Research Associate Professor)                                       | NCSU |
| Ludwig, E. J. (Professor Emeritus)                                                 | UNC  |
| Merzbacher, E. (Professor Emeritus)                                                | UNC  |
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| Roberson, N. R. (Professor Emeritus)                                               | Duke |
| Tilley, D. R. (Professor Emeritus)                                                 | NCSU |
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| Garvey, G. T.     | Los Alamos National Laboratory |
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| Rehm, K. E.           | Argonne National Laboratory                      |
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| Tajima, S. (Visiting Research Scholar)                 | Duke/NCCU   |
| Ye, Q. (Research Scientist)                            | Duke        |

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| Wang, P.                   | RF Engineer (at HI $\gamma$ S)                             |

<sup>1</sup>Departed 06/10<sup>2</sup>Supported by NNSA/DOE<sup>3</sup>As of 5/10<sup>4</sup>As of 7/10<sup>5</sup>Supported by NSF/DOE<sup>6</sup>As of 3/10<sup>7</sup>Part-time<sup>8</sup>Supported by DHS

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| Witała, H.       | 7/10 - 8/10 | Jagiellonian University, Cracow, Poland    |

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| Strope, J. <sup>6</sup> | Staff Assistant |
| West, B.                | Staff Assistant |
| Kengla, B.              | Temporary Staff |

<sup>1</sup>Graduated with Ph.D. degree between 9/09 and 8/10<sup>2</sup>Supported by NNSA/DOE<sup>3</sup>Supported by NSF/DOE<sup>4</sup>Departed 02/10<sup>5</sup>Graduated with M.S. degree between 9/09 and 8/10<sup>6</sup>Partially supported by the Duke University Physics Department

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| Holmes, R.                  | UNC                     | R. Henning                    |
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<sup>1</sup>Supported by the TUNL NSF REU Program





# Fundamental Symmetries in the Nucleus

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Chapter 1

- Time-Reversal Violation: The Neutron Electric Dipole Moment
- Fundamental Coupling Constants

## 1.1 Time-Reversal Violation: The Neutron Electric Dipole Moment

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### 1.1.1 Search for the Neutron Electric Dipole Moment

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M.W. AHMED, M. BUSCH, H. GAO, R. GOLUB, C.R. GOULD, D.G. HAASE, P.R. HUFFMAN, D. KENDELLEN, E. KOROBKINA, C.M. SWANK, Q. YE, A.R. YOUNG, Y. ZHANG, W.Z. ZHENG, TUNL; THE nEDM COLLABORATION

TUNL plays a major role in an experimental program to develop a new technique to search for the neutron electric dipole moment (EDM). This technique offers an improvement in sensitivity of up to two orders of magnitude over existing measurements. A more precise value for this moment has the potential to challenge calculations that propose extensions to the Standard Model. During the past year, researchers at TUNL have constructed and commissioned an apparatus for studying the geometric phase effect; developed a prototype slow controls EPICS system; finalized the design of the  $^4\text{He}$  refrigeration system, dilution refrigeration system, and cryovessel; simulated the spin transport of polarized  $^3\text{He}$  into the apparatus; and are in the process of developing an apparatus to study systematic effects using polarized  $^3\text{He}$  and ultracold neutrons.

The experimental search for a neutron electric dipole moment has the potential to reveal new sources of time reversal (T) and charge conservation and parity (CP) violation and to challenge calculations that propose extensions to the Standard Model. The goal of the current experiment is to improve the measurement sensitivity of the neutron EDM by one to two orders of magnitude. Achievement of this objective will impact our understanding of the physics of both weak and strong interactions. The physics goals of this experiment are thus timely and of unquestioned importance.

The experiment is based on the magnetic-resonance technique of rotating a magnetic dipole in a magnetic field. Polarized neutrons and polarized  $^3\text{He}$  atoms coexist in a bath of superfluid  $^4\text{He}$  at a temperature of  $\sim 450$  mK. When placed in an external magnetic field, both the neutron and  $^3\text{He}$  magnetic dipoles precess in the plane perpendicular to the magnetic field. The measurement of the neutron EDM involves measuring the difference in the precession frequencies of the neutrons and the  $^3\text{He}$  atoms in a strong electric field parallel or anti-parallel to the magnetic field. In this comparison measurement, the neutral  $^3\text{He}$  atom is assumed to have a negligible electric dipole moment.

In principle, this new type of nEDM experiment in conjunction with the Spallation Neu-

tron Source (SNS) can achieve more than two orders of magnitude improvement in the experimental limit for the neutron EDM. This factor results from the possibility of an increased electric field (a factor of  $\sim 5$ ) due to the excellent dielectric properties of superfluid  $^4\text{He}$ , an increase in the total number of ultracold neutrons (UCNs) stored ( $\sim 100$  fold improvement that leads to factor of 10 gain in sensitivity) and an increased storage time ( $\sim 5$  times, which produces a factor of 2 in sensitivity). The current experimental EDM bound, however, is limited by magnetic field systematics. With the proposed experiment, an EDM limit of  $10^{-28}$  e-cm is possible; the use of  $^3\text{He}$  as a volume comagnetometer is crucial to the minimization of the magnetic-field systematics.

TUNL plays an active role in all aspects of this experiment. Crucial to the initial development of this project is the research and development work of key components of the overall experiment. Researchers at TUNL are presently addressing a number of outstanding issues related to maximizing the sensitivity of the measurement. These contributions include measuring the lifetime of polarized  $^3\text{He}$  in a  $\sim 450$  mK deuterated TPB/polystyrene-coated acrylic cell filled with superfluid  $^4\text{He}$ ; testing the efficiency at which the  $^3\text{He}$  injector system can infuse polarized  $^3\text{He}$  into a bath of  $\sim 450$  mK liquid helium, including spin transport; investigating the

use of the heat flush technique to transport the polarized  $^3\text{He}$  from the collection volume to the measurement cell and, afterwards, the depolarized  $^3\text{He}$  from the measurement cell to the purifier; determining a method by which one can remove the unpolarized  $^3\text{He}$  from the liquid  $^4\text{He}$ ; theoretical and experimental validation of the behavior of the geometric phase effect in our experimental geometries; development of a prototype EPICS slow controls system; and development of an apparatus that will enable tests using a single full-size measurement cell (without an E field) of key systematic effects.

As the experiment proceeds toward the CD-2/3A milestone, TUNL researchers are designing the  $^4\text{He}$  refrigeration system, dilution refrigeration system, and cryovessel. Working in collaboration with faculty from the NCSU mechanical engineering department and a NASA consultant, we have also designed the 1,000 l fiberglass-composite vessel that will house the experimental

cells and high-voltage capacitor system. We are also designing the  $^3\text{He}$  injection system. In addition, work has begun on the development and characterization of a transient waveform digitization system for the light collection system. An overview of the apparatus is shown in Fig. 1.1.

In addition to the research outlined above, details of which can be found in subsequent or previous contributions, several TUNL faculty serve in leadership roles in the project. Gao, Golub, and Huffman serve on the project's executive committee; Haase and Huffman serve as subsystem managers for the construction of the cryovessel and for the assembly and commissioning of the subsystems, respectively; Golub serves as one of the principal scientists; and Huffman serves on the federal project team as the project's technical coordinator and deputy project manager. Several others serve as work-package managers for components of the subsystems.

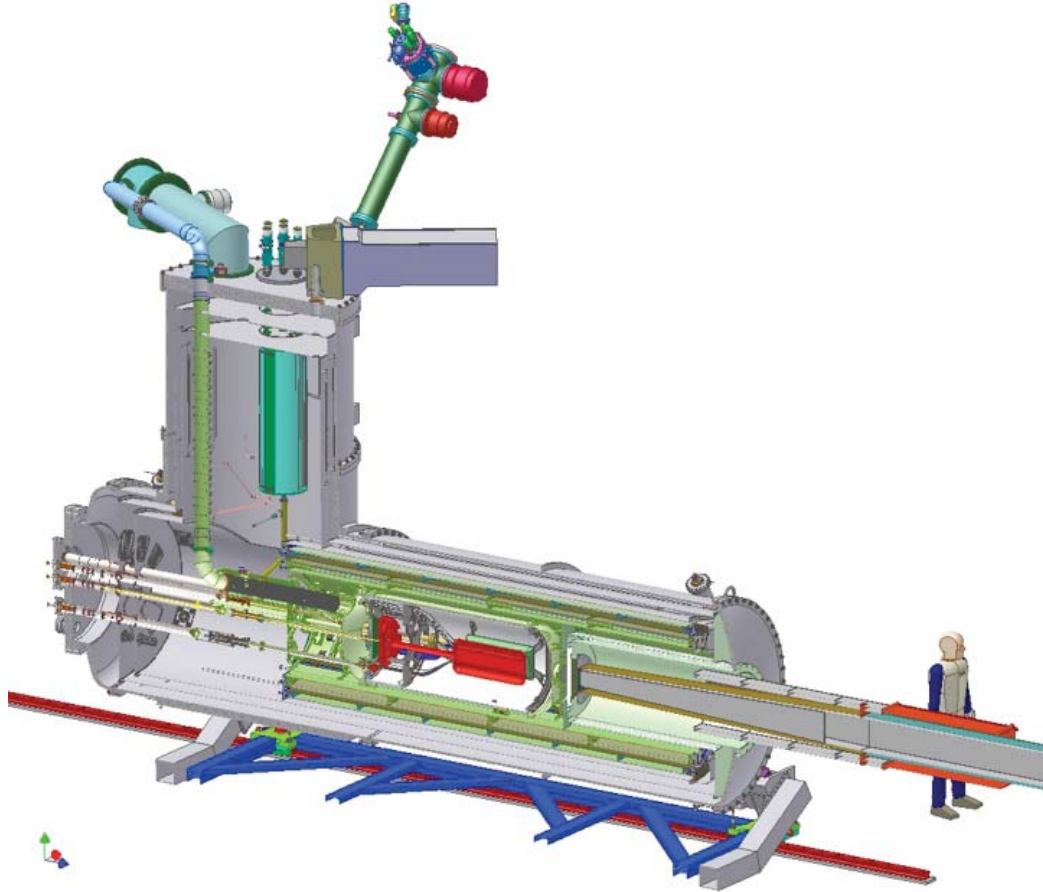


**Figure 1.1:** (Color online) Cross sectional view of the nEDM apparatus. The approximate dimensions are 7.5 m long, 5.5 m tall, and 2.2 m wide. The neutron beam enters the central volume from the right and is down-scattered in liquid helium to produce ultracold neutrons that are confined within the measurement cells. The cells are positioned within a strong electric field and weak magnetic field. The cells are surrounded by a roughly 1,000 l of liquid helium housed in a composite vessel. The  $^3\text{He}$  system and central volume are cooled to below 500 mK with a  $^3\text{He}/^4\text{He}$  dilution refrigerator.

### 1.1.2 Search for the Neutron Electric Dipole Moment: Geometric Phase Effects

R. GOLUB, H. GAO, P.R. HUFFMAN, C.M. SWANK, Q. YE, *TUNL*; THE NEDM COLLABORATION

In order to achieve the targeted precision of the nEDM experiment, it is necessary to deal with the systematic error associated with the interaction of the well known  $\vec{v} \times \vec{E}$  field with magnetic field gradients. This systematic effect was studied theoretically for a number of operating conditions and is being investigated experimentally in a newly constructed apparatus at TUNL.

In the neutron electric dipole moment (nEDM) apparatus, the interaction of the field  $\vec{B}_{eff} \sim \vec{v} \times \vec{E}$  with magnetic field gradients will produce a frequency shift linearly proportional to the electric field. Known as the geometric phase effect and mimicking a true EDM, this effect has recently emerged as a primary systematic error limiting the precision of the next generation of neutron EDM searches.

In the context of neutron EDM experiments, this effect was first investigated experimentally and theoretically by Pendelbury *et al.* [Pen04]

and later by Lamoreaux and Golub [Lam05]. In our recently published work [Bar06], we introduced an analytic form for the correlation function that determines the behavior of the frequency shift, and we showed in detail how it depends on the operating conditions of the experiment. Using this analytic function for the case of gas collisions, we averaged over a Maxwellian velocity distribution to calculate the temperature dependence of the frequency shift for  $^3\text{He}$  diffusing in superfluid  $^4\text{He}$ .

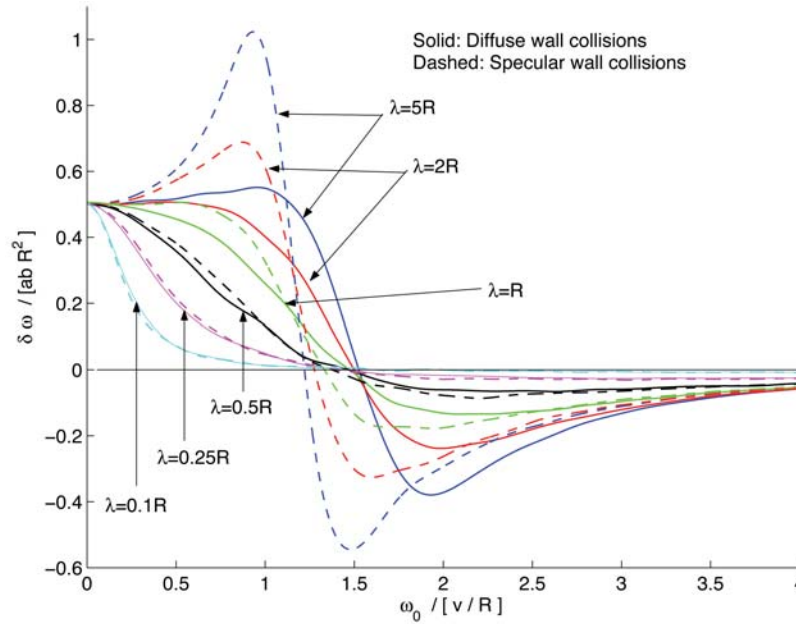


Figure 1.2: (Color online) Fixed-velocity frequency shift induced by the geometric phase effect for UCN's and for  $^3\text{He}$  [Bar06].

The results indicate that it may be possible to fine-tune the effect to a high degree by an appropriate choice of operating temperature. The present understanding of the effect is summarized in Fig. 1.2. This is a plot of the normalized (linear in  $E$ ) frequency shift  $\delta\omega$  vs. the normalized Larmor frequency  $\omega_0$  for various values of the collision mean free path  $\lambda$  and wall specularity. Values are calculated for particles moving with fixed velocity  $v$  in a cylindrical measurement cell of radius  $R$ , and the horizontal scale is fixed by the frequency of motion around the cell,  $v/R$ . In general the shift for ultracold neutrons (UCNs) will be given by a value of  $\omega_0/(v/R) > 4$ , and for  $^3\text{He}$  by  $\omega_0/(v/R) \sim 1$ . From an experimental point of view it is very appealing to try to make use of the zero crossings apparent in the figure to reduce the systematic effects to zero. Our theoretical work indicates it is plausible to do this for  $^3\text{He}$ , by tuning the temperature of the apparatus to take advantage of the  $1/T^7$  dependence of the diffusion constant for  $^3\text{He}$  in superfluid  $^4\text{He}$ .

Specifically for the nEDM experiment, we have used our simulation results in combination with  $^3\text{He}$  transport calculations to set the nominal operating temperature for the nEDM experiment, 450 mK.

To study these geometric phase effects experimentally, we have constructed a cryogenic apparatus consisting of a dilution refrigerator incorporated into a non-magnetic Dewar. The apparatus is shown in Fig. 1.3. The Dewar is surrounded by a series of eight Helmholtz coils to provide a uniform field.

The initial experiments aimed at verifying the predicted depolarization rates of polarized  $^3\text{He}$  in superfluid  $^4\text{He}$  at  $T \leq 500$  mK in a deuterated polystyrene rectangular cell have been completed. We verified the depolarization probability per bounce of  $\sim 1 \times 10^{-7}$  using an improved set of NMR excitation and detection coils and superconducting constant-field and gradient coils. We carried out a series of measurements of the appropriate correlation function at different densities. To compensate for the fact that the relaxation takes place at different frequencies, we ramped the magnetic field so that measurements can be made at a constant frequency. It is necessary to ramp the gradient on and off to enable measurements of the polarization as a function of decay time. We have recently improved the attainable temperature, which did not quite reach the necessary level, and are working on improving the signal-to-noise ratio further, so as to push the

measurable  $^3\text{He}$  density to lower limits.

The geometric-phase-effect measurements rely on theoretical calculations that show that one can determine the effect by measuring the  $T_1$  relaxation rate of the  $^3\text{He}$  polarization in a magnetic field gradient. Thus it is not required to measure directly the  $(\vec{v} \times \vec{B})$ -induced frequency shift. If one applies a uniform magnetic field gradient  $\partial B_z/\partial z$  large enough so that it dominates all other field gradients, the relaxation time  $T_1$  can be determined by traditional NMR techniques, assuming wall relaxation can be neglected. This technique does not require an electric field and thus significantly simplifies the experiment.



**Figure 1.3:** (Color online) TUNL dilution-refrigerator setup for studying  $^3\text{He}$  depolarization in superfluid  $^4\text{He}$  and the temperature dependence of the geometric phase effect.

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- [Bar06] A. L. Barabanov, R. Golub, and S. K. Lamoreaux, *Phys. Rev. A*, **74**, 052115 (2006).
  - [Lam05] S. K. Lamoreaux and R. Golub, *Phys. Rev. A*, **71**, 032104 (2005).
  - [Pen04] J. M. Pendlebury *et al.*, *Phys. Rev. A*, **70**, 032102 (2004).

### 1.1.3 Development of the Cryogenic Design for the nEDM Experiment

D.G. HAASE, P.R. HUFFMAN, D.P. KENDELLEN, *TUNL*; J. BOISSEVAIN, *California Institute of Technology, Pasadena, CA*; L. BARTOSZEK, *Bartoszek Engineering, Aurora, IL*; W. YAO, *Oak Ridge National Laboratory, Oak Ridge, TN*

A multi-institution collaboration is designing an experimental apparatus for a new measurement of the nEDM. The experiment will be mounted on a dedicated beam line at the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory. In the last year there have been several advancements in the design of the cryogenic systems, which must cool a cubic meter of liquid helium to 0.25 K to produce ultracold neutrons. The design, procurement, construction, and implementation of the cryogenic subsystem are led by TUNL faculty.

#### 1.1.3.1 The nEDM Cryogenic System

The nEDM experiment requires cooling a 1 m<sup>3</sup> volume of superfluid liquid helium to an operating temperature between 0.25 K and 0.45 K. This central volume encloses a separate target volume of superfluid in which 0.89 nm neutrons from the SNS are down-scattered into ultracold neutrons and confined in an acrylic measurement cell. The central volume and target, plus associated experimental services, are cooled by a high-flow <sup>3</sup>He-<sup>4</sup>He dilution refrigerator. The vacuum container enclosing the cryogenic systems is called the cryovessel and is cooled using liquid helium through a permanent connection to a helium liquefier system. The cryogenics Work Package 1.03 for the nEDM construction project includes the cryovessel with its enclosed 80 K and 4 K thermal shields, the helium liquefier system, the <sup>3</sup>He-<sup>4</sup>He dilution refrigerator, the central volume, and the associated vacuum hardware, cryogenic sensors, and controls.

Over the last year, the nEDM cryogenic system has passed two significant project reviews, and refinements have been made to the experimental design. The 1.03 subsystem was reviewed at an nEDM collaboration meeting at ORNL in February and the DOE annual project review in March 2010. The modifications have accompanied improved calculations of the cryogenic cool-downs and thermal loads. Several modifications are driven by the stringent requirements for low magnetic fields and minimal electrical noise.

#### 1.1.3.2 Modifications to the helium liquefier system

A dedicated system with a helium liquefier and helium flow to the cryovessel has been adopted. The nEDM project and the SNS are composing a Memorandum of Understanding for the construction and operation of a common helium liquefier that will serve the SNS users, the nEDM experiment, and another proposed SNS user project. In this plan, the nEDM experiment will receive liquid helium and return cold or warm helium gas to a liquefier located in a building adjacent to the Fundamental Neutron Physics Beam (FNPB) external building. This arrangement should improve the reliability of helium supply to the nEDM cryovessel and reduce maintenance requirements. The nEDM experiment will maintain a large liquid-helium (LHe) storage volume and piping system to connect to the cryovessel. The design of the flow system is driven by the need to fill the 1 m<sup>3</sup> central volume with liquid helium at 4 K and to cool the rest of the cryovessel as quickly and efficiently as possible. To reduce vibrations, the 80 K thermal shields will be cooled by a positive pressure flow of liquid nitrogen driven by an external cryogenic pump and phase separator.

#### 1.1.3.3 Modification to the dilution refrigerator

The process for cooling the central volume and target cell from 4 K to 0.25 K has been simplified. The design of the <sup>3</sup>He-<sup>4</sup>He dilution refrigerator is modified so that it can function as a <sup>3</sup>He or <sup>4</sup>He evaporative refrigerator above 1 K. This is achieved by adding a flow circuit to recircu-

late  $^4\text{He}$  and a “stopper” below the still that can short-circuit the low-temperature heat exchangers and increase the effective pumping speed of the recirculation system.

At the beginning of the cooling process, the 1 m<sup>3</sup> target volume will be filled with liquid from the helium liquefier. At this point, the stopper will be raised, and the dilution refrigerator will act as a helium evaporator by circulating and pumping LHe from an 80 l LHe entrainment volume inside the cryovessel. The refrigerator cooling rate will be controlled by a liquid flow valve. As the target volume is cooled from 4 K to about 2.6 K, the density of the LHe increases, so the volume will be continuously filled with liquid from the entrainment volume. At 2.6 K, the target-volume fill will be ended, and the target volume will be thermally insulated from the entrainment volume by a vacuum valve. As the target volume cools further to near 1 K, the LHe flow will be stopped, and  $^3\text{He}$  from an external gas storage tank will be circulated through the dilution refrigerator. In the temperature range of 1.5 K to 0.6 K,  $^3\text{He}$  evaporation is a powerful cooling process. Finally near 0.6 K the dilution refrigerator stopper will be lowered to start flow through the refrigerator’s heat exchangers, and the gas mixture will be adjusted to start the  $^3\text{He}$ - $^4\text{He}$  dilution process.

#### 1.1.3.4 Re-entrant thermal shields

In the latest design of the nEDM system, the neutron beam guide penetrates the cryovessel to a point only a few inches from the liquid-helium target volume. Therefore the vacuum jacket and the 80 K and 4 K thermal shields must include re-entrant sections extending as far as 60 inches from the target to the upstream end of the cryovessel. The re-entrant components must be electrically non-conducting and non-magnetic so that Johnson noise and eddy currents will not overwhelm the SQUID sensors in the target volume. On the other hand the thermal shields should have thermal conductivities sufficient to cool the interior end caps to near 80 K and 4 K; otherwise an increased thermal load is passed on to the sub-4 K refrigerator.

The re-entrant vacuum jacket and the 80 K re-entrant tube of the cryovessel pressure barrier will be constructed of G-10 composite. At the upstream end of the 80 K shield, an aluminum flange will be cooled by recirculating liquid nitrogen. The re-entrant tube will be composed of sintered alumina ( $\text{Al}_2\text{O}_3$ ) rods epoxied onto a

G-10 form. Alumina is a non-magnetic electrical insulator, but it is also a good thermal conductor at 77 K ( $\lambda = 157 \text{ W/m-K}$ ). Because of construction difficulties, the original 4 K re-entrant thermal shield design has been replaced by a 4 K shield directly attached to the magnet system that surrounds the central volume. This G-10 shield will be cooled by the same helium gas flow that cools the magnet package.

The designs of the helium liquefier, the dilution refrigerator, and the cryovessel are approaching completion. The next steps include negotiations with vendors, completion of the SNS/ORNL safety and quality assurance processes, approval from DOE to proceed, and the beginning of the procurement process.

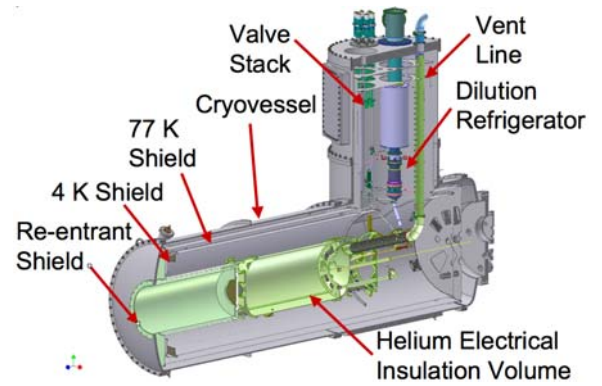


Figure 1.4: (Color online) Schematic of the cryogenic components of the nEDM experiment that compose Work Package 1.03.

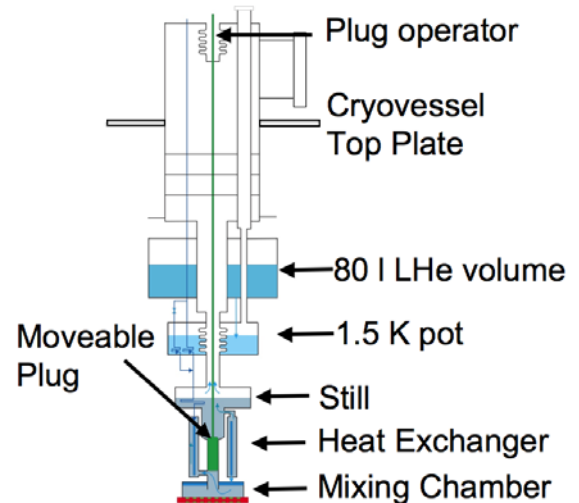


Figure 1.5: (Color online) Schematic of the modified design of the nEDM dilution refrigerator to allow operation as a  $^4\text{He}$  evaporative refrigerator in the range  $1.5 \text{ K} < T < 4.2 \text{ K}$ .

### 1.1.4 $^3\text{He}$ Spin Transport Simulation in the nEDM Experiment

H. GAO, Q. YE, W.Z. ZHENG, *TUNL*;

The transport of  $^3\text{He}$  spin through a magnetic field gradient is simulated in order to demonstrate whether nearly 100%-polarized  $^3\text{He}$  can maintain its polarization after injection from the ABS into the collection volume in the nEDM experiment. A projection is also made of the spin transport from the collection volume to the central measurement cells. This yields negligible polarization loss if only the field-gradient-induced relaxation is considered.

In the nEDM experiment, nearly 100%-polarized  $^3\text{He}$  will be produced using the atomic beam source (ABS). The polarized  $^3\text{He}$  beam will be injected into the collection volume of the nEDM experiment, which is filled with superfluid  $^4\text{He}$ , before being transferred to the central measurement cells. Maintaining a high polarization of  $^3\text{He}$  both through the injection stage and through transport from the collection volume to the measurement cells is crucial to the success of the experiment. In this report, we present studies of the depolarization of  $^3\text{He}$  due to magnetic field gradients between the exit of the ABS and the nEDM measurement cells, as well as projections on spin transport from the collection volume to the central measurement cell.

#### 1.1.4.1 Simulation Methods

The simulation code (from Justin Torgerson, written in C++) is divided into three steps. The first step simulates the polarization of  $^3\text{He}$  at the exit to the ABS. The second step is the  $^3\text{He}$  spin transport and calculates how many  $^3\text{He}$  atoms can successfully pass through the long transport tube without undergoing collisions with the wall. The last step calculates how the spin precesses as the  $^3\text{He}$  travels from the ABS to the collection volume inside the transport tube. The 4th order Runge-Kutta method is used to calculate the Bloch equation of the spin  $\vec{M}$  precessing in a magnetic field  $\vec{B}$ . The vector form of the Bloch equation is written as:

$$\frac{d\vec{M}(t)}{dt} = \gamma \vec{M}(t) \times \vec{B}(\vec{r}) \quad (1.1)$$

where  $\vec{r}$  is the position vector of the spin. By integrating the Bloch equation, one can obtain the magnetization of the  $^3\text{He}$  spin inside the collection volume. Since the magnetic field inside the collection volume is in the  $\hat{x}$  direction, the  $\hat{x}$

component of the spin,  $M_x$ , gives the polarization after normalization.

#### 1.1.4.2 Simulation Results

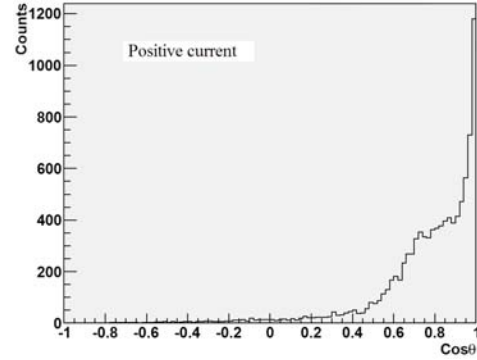


Figure 1.6: Counts vs.  $\cos\theta$ . The average polarization in the positive current configuration is 76%.

The ABS simulation shows that 59.2% of the atoms in the right spin state can pass through the quadrupole magnets and  $< 0.01\%$  of the atoms in the wrong state can pass through, resulting in a polarization of  $> 99.9\%$ . The spin-transport simulation shows that 82.8% of the atoms in the right spin state can pass through the transport tube and arrive at the collection volume. The latest magnetic field design (March 2010 from Septimiu Balascuta) has two current configurations: one with the current in the cylindrical  $\cos\theta$  coil in the positive direction, so that the  $B$  field in the collection volume is in the  $+\hat{x}$  direction, and the other with the current in all the coils reversed, so that the  $B$  field is in the  $-\hat{x}$  direction. Nearly 10,000 events have been simulated for each configuration, giving a statistical uncertainty of  $\sim 1\%$ . Figure 1.6 shows the histogram of  $\cos\theta$  for the positive current configuration (The negative current configuration is

similar). Here,  $\theta$  is the angle between the spin and the holding field inside the collection volume. The mean value of the histogram gives the average polarization of all the events and is shown in the box in the upper right corner of the figure.

For the positive current configuration, the averaged polarization is about 76%, and for the negative current configuration, it is slightly better, 79%. We also simulate the average polarization of the ensemble as a function of distance measured from the center of the collection volume. The same number of events are simulated for both current configurations. These results are shown in Figs. 1.7 and 1.8. The origin of the  $x$  axis is the center of the collection volume, and 180 cm corresponds to the exit of the ABS. Two regions leading to polarization loss are identified. One is due to the strong and irregular fringe field at the ABS exit, the other is close to the collection volume, where the spins start to rotate from the  $^3\text{He}$  injection direction to the  $\hat{x}$  direction in order to match the holding field inside the collection volume.

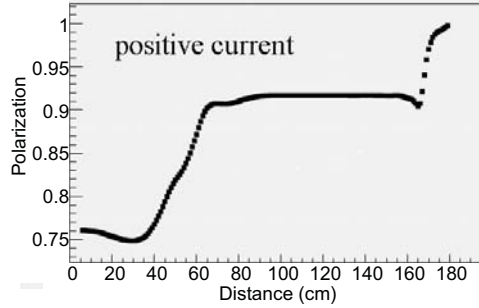


Figure 1.7: Polarization vs. distance in the positive current configuration.

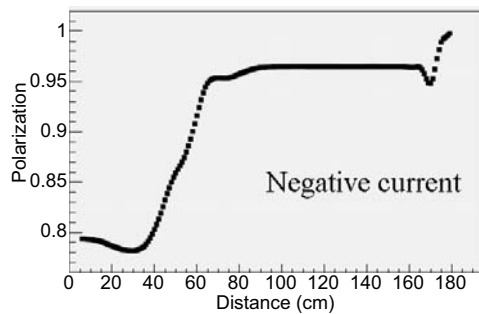


Figure 1.8: Polarization vs. distance in the negative current configuration.

The nEDM experiment requires  $> 95\%$  polarization of  $^3\text{He}$  in the collection volume. Therefore the present results are inadequate, and a more uniform magnetic field is needed to improve the  $^3\text{He}$  polarization in the collection volume. Solutions to this problem can involve either increasing

the overall transport field or stretching the field-transition region so that the spins have more time to reorient themselves to the  $B$ -field direction in the collection volume.

#### 1.1.4.3 Polarization loss between the collection volume and the central measurement cells

Once  $^3\text{He}$  atoms accumulate in the collection volume, they are transferred to the central measurement cells through diffusion. The diffusion coefficient of  $^3\text{He}$  in the  $^4\text{He}$  bath is calculated as  $D = 1.8/T^7 \text{ cm}^2/\text{sec}$  [Lam02], where  $T$  is the temperature of the  $^4\text{He}$  bath. At 350 mK, the diffusion coefficient is roughly  $3000 \text{ cm}^2/\text{sec}$ . Assuming that the distance between the collection volume and the central measurement cells is  $l = 3 \text{ m}$ , the transport time for  $^3\text{He}$  can be estimated by  $t \approx l^2/D = 30 \text{ s}$ . So, the effective diffusion speed is roughly  $V_{eff} = l/t = 0.1 \text{ m/s}$ . This is very slow compared to  $\sim 100 \text{ m/s}$ , the speed of  $^3\text{He}$  as it travels from the ABS to the collection volume. The adiabatic factor for a spin precessing in a changing magnetic field is defined as [Sli63]

$$\alpha = \tan^{-1}\left(\frac{1}{\gamma|\vec{B}|^2}\left|\frac{d\vec{B}}{dt}\right|\right) = \tan^{-1}\left(\frac{1}{\gamma|\vec{B}|^2}\left|\nabla\vec{B}\frac{d\vec{x}}{dt}\right|\right) \quad (1.2)$$

where  $\alpha$  can be thought of as the angle between the spin and the magnetic field. If  $\alpha \ll 1$ , the adiabatic condition is satisfied, and the polarization loss is negligible. The second equality shows the importance of the spin velocity in determining the adiabatic factor. In the current field design, because of the roughly 20% polarization loss during transport from the ABS to the collection volume, the adiabatic factor for the first part is about 0.64 rad. A fair assumption is that the gradient in the transition region between the collection volume and the central measurement cell is no worse than that between the ABS and the collection volume. Since the effective diffusion speed is only 0.1 m/s, compared with  $\sim 100 \text{ m/s}$  in the first part, the adiabatic factor for the second part is projected to be  $7.5 \times 10^{-4}$  rad or 0.04 degree. Therefore, in the region from the collection volume to the measurement cells, the polarization loss from the field gradient is negligible.

[Lam02] S. K. Lamoreaux *et al.*, Europhys. Lett., **5**, 718 (2002).

[Sli63] C. P. Slichter, *Principles of Magnetic Resonance*, Harper and Row, 1963.

## 1.2 Fundamental Coupling Constants

### 1.2.1 The UCNA Experiment

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During the 2009 run period, the UCNA collaboration completed data-taking for a 1.4% measurement of the  $\beta$ -asymmetry in polarized neutron decay. A publication incorporating a total of  $14.7 \times 10^6$  decays from the 2008 and 2009 run periods was prepared, with a value of  $-1.1966 \pm 0.00089(\text{stat}) \pm 0.00123(\text{syst})$  quoted for the  $\beta$ -asymmetry at the 67% confidence level. A value for the axial form factor in the charged weak interaction of the nucleon,  $g_A/g_V$ , of  $-1.27590^{+0.00409}_{-0.00445}$  was extracted from the measured asymmetry.

Measurements of neutron decay provide fundamental information on the parameters characterizing the weak interaction of the nucleon. These parameters, including the axial form factor for the charged weak interaction, impact predictions of the solar neutrino flux, big-bang nucleosynthesis, the spin content of the nucleon, and tests of the Goldberger-Treiman relation. They also place constraints on standard-model extensions such as supersymmetry and left-right symmetric models.

The UCNA (ultracold neutron—the A parameter) experiment is the first attempt to utilize ultracold neutrons (UCNs) for an angular correlation measurement in neutron decay. The use of UCNs for such a measurement provides a different and powerful approach to the systematic errors characteristic of traditional cold- or thermal-neutron-beam experiments. In particular, UCNs provide significant advantages for determining the neutron polarization and for controlling neutron-generated backgrounds. Historically, the neutron density in cold beams has been much higher than the available UCN densities, making beam experiments the favored method for angular correlation measurements, but systematic errors have increasingly driven the uncertainties in such measurements, providing impetus to explore the use of UCN. The first experimental results, a 4.5% measurement of the  $\beta$ -asymmetry, were published in 2009 [Pat09].

UCNA is located in the Los Alamos Neutron Science Center (LANSCE) and utilizes a solid-deuterium ultracold-neutron source developed for this project. The 800 MeV proton beam at LANSCE is directed at a tungsten target sit-

uated within an outer, bucket-shaped shell of graphite and an inner shell of Be, both of which serve to reflect and partially moderate the spallation neutrons produced. The neutrons are further moderated to temperatures under 100 K by a layer of polyethylene held at room temperature and by a cold-moderator at temperatures between 20 and 80 K. A 2 l volume of solid deuterium, held at 5 K inside of a UCN guide, serves as the UCN converter. The UCNs are coupled to the decay volume through a 15 m guide system that incorporates a 7 T polarizer magnet, a spin-flipper system, and finally the bore of a 1 T spectrometer magnet, where decays are observed (see Fig. 1.9).

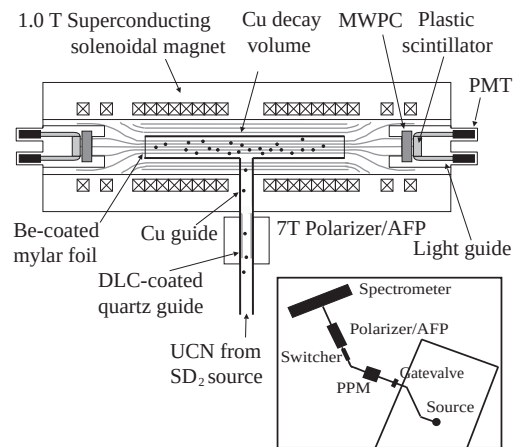


Figure 1.9: A schematic diagram of the UCNA polarizer and  $\beta$ -spectrometer. The inset depicts the layout of the source and guides coupled to the experiment.

The  $\mu \cdot \mathbf{B}$  interaction of the neutron's mag-

netic moment,  $\mu$  with a magnetic field  $\mathbf{B}$  produces an energy change of  $\pm 60$  neV/T, depending on the whether the neutron spin is parallel or antiparallel to the applied field. The extremely low kinetic energy of UCNs (below 180 neV for our experiment) makes possible a method unique to UCNs for producing highly polarized samples. The  $\mu \cdot \mathbf{B}$  interaction produces a 420 neV barrier to the neutrons with spin parallel to the field ( $\mu$  is negative) in our 7 T polarizer magnet, completely blocking the transmission of this spin state through the high field system. There is therefore an essentially 100% polarized sample of UCNs after traversing this region. UCNs then pass through a high-power, radio-frequency adiabatic spin-flipper which permits the preparation of a UCN sample polarized either parallel or antiparallel to the field. The spin-flipper region is then coupled by our guide system to a decay volume within the uniform 1 T field of the  $\beta$ -spectrometer.

During the 2008/2009 run period, we achieved an average decay rate of about 18 Hz for most of the run, an improvement of roughly a factor of 3 over the decay rate in 2007. A run cycle included 60 min of  $\beta$ -decay measurement, followed by an approximately 4 min measurement of the depolarized UCN fraction that accumulated in our decay volume during the  $\beta$ -decay measurement, and about a 12 min measurement of the background. The UCN spin-flipper was set either “on” or “off” in an eight cycle sequence designed to measure decay rates with the neutron spin parallel and antiparallel to the field axis, and to cancel, up to second order, drifts in the backgrounds.

UCNs were confined to a 12.5 cm diameter, 3 m long Cu decay trap, coaxial with a 1 T uniform field at the center of the spectrometer. The ends of the decay trap were sealed with Be-coated, Mylar windows.  $\beta$  particles were recorded in detector assemblies situated at either end of the solenoidal spectrometer, where the field has fallen to 0.6 T. Each detector assembly is composed of a position-sensitive multi-wire proportional counter (MWPC) with aluminum-coated entrance and exit windows, backed by a plastic scintillator to measure the full energy of the  $\beta$  particles. Backgrounds were reduced by requiring a coincidence between the scintillator and MWPC, and by using a cosmic ray veto. Over  $14.7 \times 10^6$  decays were observed in our analysis window between 275 keV and 625 keV, yielding a  $\beta$ -spectrum in good agreement with expectations.

The emphasis of the 2008 run period was to assess the scattering and energy-loss corrections. To this end, we made measurements of

the  $\beta$ -asymmetry with three different sets of decay trap and detector foils. In 2009, we utilized the geometry with the smallest foil thicknesses (and therefore the smallest scattering and energy-loss corrections), and focused on improvements to the decay trap designed to reduce potential spin-dependent systematic effects due to the wall-coatings in our decay trap and polarized neutron transport guides, and on improved neutron polarimetry.

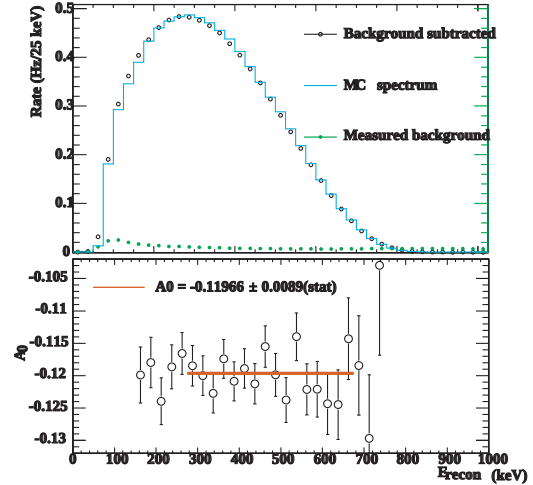


**Figure 1.10:** Upper: background subtracted beta energy spectra (solid red circles), combining both sides of the detectors and two spin states, overlaid with the Monte Carlo spectrum (blue histogram). The open black circles represent the measured background spectrum. Lower: beta-asymmetry vs. the reconstructed beta energy.

The data taken in 2009 completed the necessary data for a convincing measurement of the  $\beta$ -asymmetry in neutron decay at the 1.4% level [Liu09]. Our experimental results are summarized in Fig. 1.10. We also continue to explore the introduction of Si detectors into the UCNA spectrometer in a geometry permitting the detection of  $\beta$  particles and recoil protons in coincidence. Such a scheme should permit the reduction of the systematic error in the polarization and the measurement of additional angular correlations, some of which are particularly interesting in constraining supersymmetric extensions to the standard model. This project, referred to as UCNB, has already benefited from an intensive development effort at Los Alamos producing three different sets of Si detectors with properties appropriate for neutron  $\beta$ -decay measurements.

[Liu09] J. L. Liu *et al.*, ArXiv 1007.3790v1, 2009.

[Pat09] R. W. Pattie *et al.*, Phys. Rev. Lett., **102** (2009).

### 1.2.2 High-precision Measurement of the $^{19}\text{Ne}$ Lifetime

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The  $T=\frac{1}{2}$  mirror transitions, such as the  $\beta^+$  decays of  $^{19}\text{Ne}$ ,  $^{37}\text{K}$  and  $^{21}\text{Na}$ , have been identified as excellent candidates for high-precision studies of the weak interaction in the Standard Model, complementing the well-studied  $0^+ \rightarrow 0^+$ -decay and neutron-decay measurements. In 2009 we completed measurements to extract a high-precision lifetime result for the decay of  $^{19}\text{Ne}$  to  $^{19}\text{F}$  at the Trapped Radioactive Isotopes Microlaboratories for Fundamental Physics (TRI $\mu$ P) facility at the Kernfysich Versneller Instituut, and we hope to achieve a final uncertainty of 0.03%. Upon completion of a detailed analysis of the systematic uncertainties of our experiment and analysis methods, the program can be expanded to high-precision measurements of other mirror transitions.

The lifetime of the decay of  $^{19}\text{Ne}$ , with an additional observable such as the  $\beta$ -asymmetry, can be used to precisely extract the CKM matrix element  $V_{ud}$  and study proposed Standard Model extensions such as left-right symmetric models. We used the TRI $\mu$ P isotope separator to create a very pure beam of  $^{19}\text{Ne}$ . The isotopes were implanted into an aluminum tape, and a custom tape-drive system transported the implantation site into a shielded detector array. The tape was clamped between plastic blocks in which the decay positrons annihilate and release two 511 keV  $\gamma$  rays. The annihilation radiation was detected by two HPGe clover detectors in coincidence. Table 1.1 details the accumulated decays during the spring 2009 data-taking.

Table 1.1: Total Data Acquired

| Isotope          | Prev. Meas. (s)     | Decays          |
|------------------|---------------------|-----------------|
| $^{19}\text{Ne}$ | $17.248 \pm 0.17\%$ | $3 \times 10^7$ |
| $^{37}\text{K}$  | $1.2248 \pm 6.0\%$  | $4 \times 10^5$ |
| $^{21}\text{Na}$ | $22.487 \pm 0.24\%$ | $2 \times 10^6$ |

To meet the goal of a high-precision lifetime measurement, all systematic uncertainties must be very well controlled and understood. We have identified several potential sources of error in our experimental method: ambient backgrounds, contaminant populations in the sample, diffusion of the sample, and rate-dependent effects in the data acquisition. The ambient background levels were evaluated by blocking the implantation of  $^{19}\text{Ne}$  into the tape. By requiring a coincidence between clovers, we were able to achieve a signal to background of better than 1000:1. A silicon detector installed at the isotope separator exit

allowed us to examine the relative isotope levels directly. Most isotopes were present at negligible levels, although in some cases the levels in certain long-lived isotopes could not be evaluated using this method. We performed a separate high-precision measurement of the lifetime with long implanting times, such that the  $^{19}\text{Ne}$  production saturates but longer-lived potential contaminants continue to accumulate, and we do not yet see evidence of contamination at our current level of precision. The third potential source of uncertainty comes from possible diffusion of  $^{19}\text{Ne}$  out of the tape. We performed several lifetime measurements with different implantation depths in order to accentuate the effect, and we saw no evidence of diffusion (see Fig. 1.11).

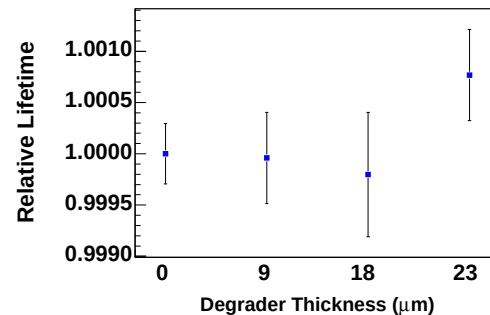


Figure 1.11: Diffusion from the tape is accentuated by degrading the energy of the particle beam before it is implanted. A 23  $\mu\text{m}$  degrader corresponds to the particles being implanted near the surface of the tape. Rate-dependent corrections are not yet fully understood, so only relative lifetimes are shown.

The rate-dependence of our data acquisition and analysis methods were studied in great detail both during and after the experiment. In order to minimize deadtime due to piled-up pulses or missed events, we digitized all of the shaped pre-amplifier pulses using the CAEN V1724 waveform digitizer. A constant-rate pulser used continuously throughout the experiment provided an in-situ measurement of deadtime, and extensive pulser studies were performed after the experiment to further explore the rate-dependence of the detection system. Event pulses are compared to a known average pulse shape, which improves time-resolution of distinct events to less than  $1\mu\text{s}$ . In order to minimize the uncertainty due to accidental coincidences, a fixed analysis deadtime of several  $\mu\text{s}$  is applied, and the form of the fitting function is corrected for deadtime. Finally, use of Gaussian or Poisson statistics for such a high-

precision measurement can introduce large biases into the extracted lifetime. We found that we could minimize bias and uncertainty by instead performing a least-squares minimization using the binomial distribution, and we performed a careful study of the statistical bias as a function of rate and fixed deadtime, using simulated data.

We have made significant progress towards understanding the rate-dependent systematics at our desired precision. Obtaining a 0.03% result for the lifetime of  $^{19}\text{Ne}$  would be a strong indication that our system is well-suited for more high-precision measurements using other mirror transitions. We have already performed some development work in minimizing contamination in the production of  $^{37}\text{K}$  and  $^{21}\text{Na}$ , and we hope to continue the program with high-precision measurements of the lifetimes of these and other mirror transitions.



# Neutrino and Dark Matter Physics

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Chapter 2

- $\beta\beta$  Decay Experiments
- Tritium  $\beta$  Decay
- Dark Matter Search

## 2.1 $\beta\beta$ Decay Experiments

### 2.1.1 The MAJORANA DEMONSTRATOR Neutrinoless Double-Beta Decay Experiment

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**The MAJORANA Collaboration is constructing the MAJORANA DEMONSTRATOR aimed at determining the feasibility of a tonne-scale  $^{76}\text{Ge}$ -based neutrinoless double-beta-decay experiment. The baseline design includes 15 kg of 86% enriched Ge detectors and 20 kg of natural Ge detectors. The measurement may be able to reveal whether neutrinos are Dirac or Majorana particles, while providing insights into both lepton number violation and the absolute mass scale of neutrinos. The DEMONSTRATOR with its low-energy sensitivity, is also expected to be capable of searching for dark matter.**

The primary goal of the MAJORANA Collaboration<sup>a</sup> is to develop a 1-tonne  $^{76}\text{Ge}$ -based neutrinoless-double-beta-decay experiment with the sensitivity to probe neutrino mass in the inverted hierarchy region (20 to 40 meV). The collaboration is building the MAJORANA DEMONSTRATOR, an array of high-purity  $^{\text{nat}}\text{Ge}$  and enriched  $^{76}\text{Ge}$  crystals that will be deployed in ultra-low-background electroformed Cu cryostats. The DEMONSTRATOR should be capable of reaching the ultra-low-background levels required for a 1-tonne scale experiment.

The DEMONSTRATOR will consist of 15–30 kg of 86% enriched  $^{76}\text{Ge}$  detectors and 10–20 kg of  $^{\text{nat}}\text{Ge}$  detectors. The HPGe detectors will be fabricated as P-type point-contact detectors, which have very low capacitance and excellent single-site to multi-site pulse-shape-discrimination capabilities. The detectors will be assembled into strings and housed in two ultra-pure electroformed Cu cryostats. These cryostats will be embedded in a passive layered shield of ultra-pure electroformed Cu, then Pb, all of which will be surrounded by an active cosmic-ray veto detector system and passive neutron shielding.

Significant progress has been made by the collaboration in moving forward with the construc-

tion of the DEMONSTRATOR and with additional R&D for a 1-tonne scale detector. Below is a brief summary of research activities carried out by TUNL collaborators. More details are available in sections that follow.

- **Assay:** The group has carried out both radiometric and neutron-activation-based materials assay at the Kimballton Underground Research Facility (KURF) and at the North Carolina State University reactor. Materials counted include Pb, plastics, and low-mass cables. An ultra-clean sample-preparation clean-room has been commissioned at the University of North Carolina at Chapel Hill (UNC). This facility allows materials to be prepared for counting or for assembly in prototype systems.
- **Detector Development:** A customized broad-energy germanium (BEGe) detector, mounted in a low-background cryostat has been installed in a TUNL-designed and TUNL-fabricated low-background shield at KURF. This Majorana low-background BEGe detector (MALBEK) is being used to investigate BEGe detector optimization, as well as low-energy (sub-keV) sensitivity. A

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number of additional Ge detectors, including a second BEGe detector that is similar to MALBEK but not in a low background shield, have been acquired. These detectors are being used for a variety of detector characterization and DAQ development tests. Work continues on the redeployment of the existing segmented enriched germanium detector.

- **Module Design and fabrication:** Significant design, fabrication, and construction of prototype string parts and their related assembly tooling have been completed. The collaboration is close to a final string design. Tests have also been completed on finding suitable low-activity materials to be used for the vacuum seals of the cryostat.
- **Data Acquisition:** The object-oriented real-time control and acquisition system is being used for prototype systems at LANL, LBNL, UNC, Univ. of Washington, and for underground detectors at Soudan, WIPP, and KURF. Evaluation of several different potential digitizer systems has been completed.
- **Ge refinement:** In conjunction with collaborators at the University of South Carolina and Oak Ridge National Laboratory, we have supported the development of a Ge refinement system that will produce electronic grade Ge crystals suitable for detector fabrication from enriched Ge material in the form of  $\text{GeO}_2$ . A commercial facility has been established in Oak Ridge, and a team of consultants working with MAJORANA collaborators have completed a detailed refinement plan.
- **Underground Facilities:** Working with collaborators at LANL and the engineering team from the Sanford Underground Laboratory at Homestake, a design has been completed for the main DEMONSTRATOR laboratory, and the cavity has been excavated. Space for a temporary electroforming facility that will also be located on the 4850-foot level at Sanford has been prepared, with beneficial occupancy expected in the fall of 2010.
- **Electroforming Facilities:** Equipment and material have been procured for an underground electroforming facility as part of a NSF Major Research Instrumentation grant. The facility is needed to produce the ultra-low-background Cu cryostat components as well as the inner-shield Cu sheets. In addition to the electroforming baths, this facility will host a full machine shop to allow fabrication of custom parts. Operating procedures have been developed and several readiness and safety reviews have been successfully completed.
- **Simulations and Analysis:** The TUNL group continues to make contributions to the MAJORANA-GERDA simulation development framework known as MaGe. Work is underway to implement the detailed design geometry in the simulation program framework.
- **Dark Matter Searches** When coupled with low-noise electronics, the low capacitance of the point-contact and BEGe detectors provides sensitivity to sub-keV energies. At these energies, one can perform searches for certain dark-matter candidates, such as WIMPS, with masses in the range of 1-10  $\text{GeV}/c^2$ . A search has been carried out with a point-contact detector as part of the CoGeNT collaboration, and the MALBEK detector is being optimized for a similar search.
- **Project Management** TUNL faculty and staff are guiding the management and engineering efforts of the DEMONSTRATOR and 1-Tonne Ge R&D activities. This past year the collaboration successfully completed a DOE/NSF Technical, Cost, Schedule, and Management Review and passed its Critical Design CD-1 review of the DEMONSTRATOR project. A NSF DUSEL panel review of its 1 Tonne Ge efforts was also passed successfully.

### 2.1.2 A Tonne-Scale Ge Neutrinoless Double-Beta Decay Experiment

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The 1TGe Collaboration is carrying out R&D aimed at the development of a tonne-scale  $^{76}\text{Ge}$ -based neutrinoless double beta decay experiment that could be sited at the Deep Underground Science and Engineering Laboratory (DUSEL). We describe what has been accomplished and outline our future R&D plans.

The motivation for a tonne-scale (1TGe) neutrinoless double beta decay ( $0\nu\beta\beta$ ) experiment is to determine the nature of the neutrino and reach a Majorana-neutrino-mass sensitivity indicated by atmospheric neutrino oscillation results. Worldwide there are currently two major efforts exploring the feasibility of a tonne-scale, Ge-based  $0\nu\beta\beta$  decay experiment: the MAJORANA DEMONSTRATOR and GERDA Phases I and II. These experiments are exploring two radically different approaches to shield against  $\gamma$  rays originating from primordial radioactivity external to the Ge diodes. GERDA, located at the Gran Sasso National Laboratory in Italy, is immersing Ge diodes in high purity liquid argon surrounded by a large water tank. The MAJORANA DEMONSTRATOR (See Sect. 2.1.1), to be located at the 4850-foot level at the Sanford Laboratory in South Dakota, utilizes a conventional layered design, in which ultra-pure electroformed copper and lead are used to shield a vacuum cryostat. In addition, the collaborations have also been exploring a number of alternative technologies related to HPGe detectors and their readout. The two collaborations have strong cooperative ties and intend to join efforts to build a single tonne-scale experiment. The eventual 1TGe experiment will utilize the best aspects of the DEMONSTRATOR and GERDA approaches.

The 1TGe Collaboration consists of the entire MAJORANA Collaboration and collaborators from the Max-Planck-Institut für Physik, Munich. In addition, we have had informal participation and contributions from a number of other GERDA collaboration members. The 1TGe experimental activities are being managed as a task within the MAJORANA Collaboration's existing management structure. Partial support is being provided by NSF as part of their DUSEL R&D activities.

During the past year our primary focus has

been to:

- define experimental-facilities requirements for the 1TGe experiment;
- identify possible major environmental, health, and safety hazards;
- develop preliminary layouts for the experimental hall;
- identify and begin to study DUSEL integration issues;
- justify the depth requirement for the 1TGe experiment at DUSEL;
- develop initial cost and schedule estimates;
- finalize plans for 1TGe simulation and engineering R&D;
- initiate the 1TGe experiment's simulation program;
- initiate the Ge recycling R&D activities.

We have developed two sets of preliminary conceptual designs and experimental layouts, based on the two different shielding approaches, to assist DUSEL facility planning. Our R&D plan includes simulation and design studies to compare the background suppression capabilities and technical feasibility of shielding approaches based on these two concepts. From the preliminary layouts, we have identified a set of issues related to the integration of the 1TGe experiment at DUSEL that require further study. The LAr/water shielding configuration may require excavation beyond the current 7400-foot-level laboratory-module baseline dimensions, depending on the outcome of our design and simulation studies. The transport of potentially large amounts of cryogen underground presents a logistical challenge that we will also study. A plan

for the underground fabrication and installation of the experiment will be developed, based on refined conceptual layouts.

Many of the underground facility requirements for the tonne-scale experiment are independent of the shielding configuration. In either configuration, 1TGe requires underground space for a copper electroforming laboratory, machine shop, germanium-detector fabrication facility, and an experimental hall. We have provided DUSEL with estimates for the requirements of these facilities, including environmental requirements, utilities needs such as power and water, lifting capacity, network capacity, and material transport. The primary hazards at these facilities arise due to the presence of (potentially large amounts of) cryogenics in the experimental hall and the use of acids in the electroforming and germanium laboratories. Part of our R&D scope includes the development of a Ge acquisition plan, in order to optimize the use of the enriched material. We are also exploring different scenarios for the underground purification, processing,

and fabrication of Ge diodes, in order to reduce cosmic-ray induced backgrounds.

The cost of a tonne-scale experiment is dominated by the procurement of enriched Ge isotope and the production of HPGe detectors. Based on our initial estimates, the cost of a tonne-scale experiment is therefore largely independent of the shielding configuration to be chosen. Cost and schedule estimates have been based on scaling up the actual or estimated costs for the MAJORANA DEMONSTRATOR and GERDA experiments. The preliminary schedule calls for installation of the tonne-scale experiment at DUSEL to begin in 2017.

As part of our education and outreach efforts, we are developing and will maintain a series of three public exhibits related to particle and nuclear astrophysics at the Morehead Planetarium and Science Center at the University of North Carolina. The first such exhibit, a cosmic-ray spark-chamber, is nearing completion and is scheduled to be operational by September 2010.

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### 2.1.3 Project Engineering for the MAJORANA DEMONSTRATOR Project

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M. BUSCH, R. HENNING, J.F. WILKERSON, *TUNL*;

Project engineering for the Majorana Demonstrator project (see Sect. 2.1.1) is being managed by engineers at TUNL. The primary responsibility of the project engineer is to provide design guidance and coordination for all Majorana Demonstrator hardware. This oversight is provided in three ways: (i) develop an engineering strategy and chair design reviews in accordance with this strategy, (ii) coordinate all engineering and design activities required to complete the project, and (iii) communicate and archive all design content to the collaboration.

#### 2.1.3.1 Engineering Strategy and Design Reviews

The project engineer is responsible for developing the engineering strategy, arranging and chairing design reviews, and documenting the review reports.

The engineering strategy outlines the design review process for the MAJORANA DEMONSTRATOR. There are three major review stages: conceptual design, preliminary design, and final design. Each design review clearly marks a milestone in the design process. The conceptual design review establishes a baseline configuration that allows engineers and designers to complete the necessary analysis and to specify all of the major components of the system. The preliminary design review serves as a way to lock in the configuration and specifications for a final configuration. The final design review brings together the final engineering calculations, safety analysis, fabrication drawings, and assembly procedures to ensure a quality finished product.

#### 2.1.3.2 Coordination of Design Activities

The MAJORANA DEMONSTRATOR engineering team consists of over twenty design contributors at seven institutions around the country. The project engineer is responsible for providing clear design guidance for all design contributors. The MAJORANA DEMONSTRATOR project has been divided into eleven major tasks. A task leader has been assigned to manage each task. The project engineer works with each task leader and with the project controls office to document major design activities and milestones in accordance with the engineering strategy. The implementation of the engineering strategy is re-

ferred to as the engineering plan. The engineering plan is documented as a subset of the overall project work breakdown structure, and is tracked monthly by the project engineer, task leaders, and the project office. Any discrepancy in the engineering plan and actual progress is addressed in the monthly status updates, and corrective actions are coordinated by the project engineer.

In developing the engineering plan, some aspects of the design have been identified as outside of the task leaders' area of expertise or as incorporating aspects of several tasks, and the project engineer takes a more direct role in the design development of these aspects of the project. An example of this is the detailed production plan for underground electro-forming of ultra-pure copper. This activity incorporates aspects of the infrastructure task, the electro-forming task, detector task, module task, and shielding task. In developing the electro-forming production plan, the project engineer has refined the underground machine shop tool specifications to meet the needs of the detector, module, and shielding design, and has developed a production plan to optimize the delivery of copper parts in accordance with the background goals of the project.

#### 2.1.3.3 Communicating Design Status

A series of weekly conference calls are utilized as a way of communicating and coordinating the design status and near term goals of the MAJORANA DEMONSTRATOR. The project engineer attends most weekly status calls and chairs a weekly engineering call to address engineering issues. Documents and images of the design are posted to a central conference-call-and-collaboration-meeting website in file formats that are readable by the entire collaboration.

All fabrication drawings, including prototypes and test parts, are assigned unique part numbers and posted in pdf format to an internal website. The drawing numbers follow a convention devised and managed by the project engineer. This convention is documented on the website.

All three-dimensional design content for the MAJORANA DEMONSTRATOR is produced using SolidWorks. Currently, SolidWorks models are exchanged periodically between designers. There

is a plan in place to implement a server-based archive and product-development management software tool called SolidWorks Enterprise PDM. This system will allow designers at any collaborating institution to update their model to the current version, check in and checkout design content, manage version and revision control, and have an automated mirrored archiving system. This software implementation and the necessary training required for this system will be managed by the project engineer.

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### 2.1.4 Copper Electroforming for the MAJORANA DEMONSTRATOR at the Sanford Underground Laboratory

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**The Copper Electroforming in a Temporary Cleanroom facility is a project to produce ultra-pure copper at the 1480-m level in the Sanford Underground Laboratory. This copper will be used as a construction material for the future MAJORANA DEMONSTRATOR project. We review recent progress on this facility and the roles of TUNL researchers.**

The Cu Electroforming in a Temporary Cleanroom facility (CETC) is a project to produce ultra-pure copper at the 1480-m level in the Sanford Underground Laboratory (SUL) in Lead, South Dakota. This copper will be used as a construction material for the future MAJORANA DEMONSTRATOR project, which will be located at the same level in the SUL. The copper is purified of natural trace radioactive contaminants using an electroforming process. Copper for the MAJORANA project must be electroformed underground to minimize cosmogenic isotopes, specifically  $^{60}\text{Co}$  that forms if it is exposed to cosmic rays at the surface of the earth. It will take a considerable amount of time to electroform all of the Cu needed for the MAJORANA DEMONSTRATOR. The CETC allows the necessary early start to this critical path process. MAJORANA collaborators at TUNL are responsible for the overall coordination and commissioning of the CETC, as well as the procurement of components using an NSF-MRI grant. In addition to the group at TUNL, E. Hoppe at PNNL is responsible for the design and operation of the electroforming baths, S. Elliott at LANL is responsible for the assembly and commissioning of the clean room building, and K. Jeskie at ORNL is responsible for the environmental, safety, and health aspects of the project.

The electroforming process purifies copper via the well-known process of electroplating. Electric current flows from a sacrificial anode of oxygen-free, high-conductivity copper stock, through a plating bath composed of sulfuric acid and copper sulfate, and onto a cathode, completing an electrical circuit. The current decomposes the sacrificial anode into copper ions that traverse the plating bath and are deposited on the cath-

ode. The cathode consists of a stainless steel mandrel of a size and shape driven by the desired final part. For the CETC, the mandrels are right cylinders 54 cm long and 33 cm in diameter. Figure 2.1 shows a mandrel that has copper electroformed on it. Once electroforming is complete, the electroformed Cu stock will be rinsed, left on the mandrel, double-bagged, and stored underground. The final removal from the mandrel, machining, and cleaning of the part will be performed at the MAJORANA Lab machine shop, once that facility is operational. This final procedure does not fall under the scope of the CETC. Until that time, the part will be stored in the vicinity of the CETC in sealed plastic drums.

The CETC consists of a modular, pre-fabricated cleanroom containing seven to ten electroforming baths and a small annex area (see Fig. 2.2). The building footprint is 40 ft by 12 ft, and the cleanroom area with the baths will be class 1000-10000. The CETC will become a significant production facility but is intended to be temporary. The future MAJORANA Lab itself will contain an electroforming facility with 16 baths.

The CETC had its initial readiness review at SUL in January 2010. The collaboration has followed up on the recommendations from the review and is generating the documentation required by the reviewers and SUL. The main documents include a project description, waste-stream management plan, oxygen-deficiency-hazard analysis, an emergency response and spill plan, an environmental monitoring plan, a memorandum of understanding between the MAJORANA project and SUL, detailed chemical inventories, detailed experimental operating procedures, material safety data sheets, a what-if type hazards analysis, liquid-nitrogen trans-

portation procedures, and a training check list for all MAJORANA collaborators who will work at the CETC. The MAJORANA group at TUNL has also procured the majority of the electroforming hardware for the CETC and has shipped it to SUL and PNNL.

We intend to commission the CETC during fall of 2010 and start operations at the end of CY 2010. The operating life of the CETC is intended to be at least two years.



**Figure 2.1:** A copper piece that the collaboration electroformed underground at the Waste Isolation Pilot Plant in Carlsbad, NM in 2007. The mandrel used is also visible. The pieces that will be electroformed at the CETC will be similar, but larger.

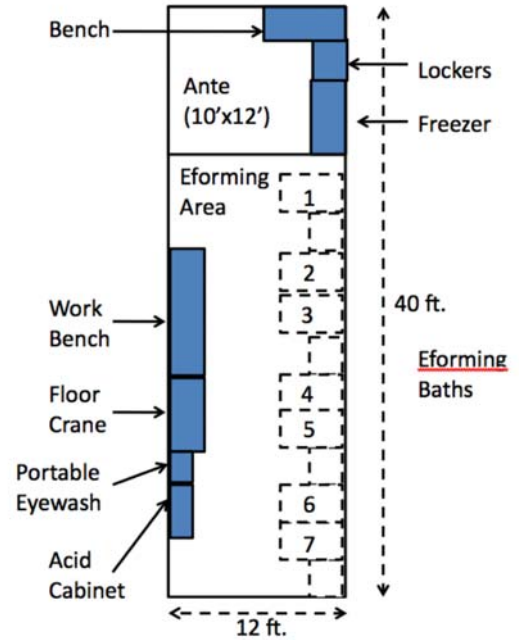


**Figure 2.2:** Functional layout of the temporary cleanroom. The electroforming area contains the seven electroforming baths on the right of the diagram. The annex or ante area will be used to change from dirty mine gear into cleanroom garb.

### 2.1.5 Deployment of the Majorana Low-Background Broad-Energy Germanium Detector at KURF

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**We have deployed a customized broad-energy germanium (BEGe) detector, the Majorana low-background BEGe at Kimballton (MALBEK) detector, in a low-background cryostat and shield at the Kimballton Underground Research Facility in Virginia.**

The operation of a new low-background detector in KURF required the development of a dedicated infrastructure. We obtained, modified, and deployed two connex trailers, one for the data acquisition system and one for the detector and shield. These trailers were deployed in June 2009 (see Fig. 2.3). Each trailer is outfitted with internal air filtration and dehumidifiers. For more information on the MALBEK detector deployment, see Ref. [Fin09]. The details on the infrastructure in place at KURF in the Kimballton mine are given in Ref. [Fin08].



**Figure 2.3:** (Color online) MALBEK detector and DAQ connex trailers being deployed at KURF in June 2009.

The detector and DAQ were deployed underground in January 2010. Figure 2.4 shows the detector in the shield stand with ancient lead below the cryostat. At this time, the lead house was stacked, all slow controls installed, the DAQ brought online, and the first data/calibration runs were taken. The implemented MALBEK DAQ is currently operating underground in a

production data-taking mode and is remotely accessible 24 hours per day. See Sect. 9.4.4 for more information regarding the MALBEK DAQ and Sect. 2.1.6 for details on the operating performance of the detector.



**Figure 2.4:** (Color online) MALBEK's low-background copper cryostat.

The lead shield is comprised of 2.54 cm of ancient lead and 20.32 cm of standard lead. The entire lead shield and internal cavity is continuously purged with LN<sub>2</sub> boil-off to reduce potential radon backgrounds (see Fig. 2.5). Additional neutron shielding is provided by 25.4 cm of polyethylene (see Fig. 2.6). The status of a soon-to-be-installed muon veto can be found in Sect. 9.3.4.1. For more information on the MALBEK shield, see Ref. [Fin09].



**Figure 2.5:** (Color online) MALBEK lead shielding and radon purge.



**Figure 2.6:** (Color online) MALBEK polyethylene shielding.

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[Fin08] P. Finnerty *et al.*, TUNL Progress Report, **XLVII**, 160 (2008).

[Fin09] P. Finnerty *et al.*, TUNL Progress Report, **XLVIII**, 156 (2009).

### 2.1.6 Initial Data from the Majorana Low-Background Broad-Energy Germanium Detector at KURF

P. FINNERTY, G.K. GIOVANETTI, R. HENNING, M.A. HOWE, S. MACMULLIN, J. STRAIN, J.F. WILKERSON, *TUNL*; J.I. COLLAR, *University of Chicago, Chicago, IL*; M.G. MARINO, M.L. MILLER, A.G. SCHUBERT, *University of Washington, Seattle, WA*; R.J. COOPER, D.C. RADFORD, *Oak Ridge National Laboratory, Oak Ridge, TN*; M. YOCUM, *Canberra Industries, Meriden, CT*

**We have deployed a customized broad-energy germanium (BEGe) detector, the Majorana low-background BEGe at Kimballton (MALBEK) detector, at the Kimballton Underground Research Facility. Currently, MALBEK has an energy threshold of  $\sim 1$  keV and a significant low-energy continuum. We hope to further reduce both the threshold and continuum in the near future.**

As part of the research and development efforts for the Majorana Demonstrator we have deployed MALBEK, a prototype BEGe detector similar to one described in Refs. [Aal08, Aal10], at the Kimballton Underground Research Facility in Ripplemead, VA (see Sect. 2.1.5). MALBEK is a 450 g natural Ge crystal housed in a low-background (LB) cryostat and outfitted with custom made LB components. MALBEK differs from commercial BEGe detectors in three respects: (1) absence of the typical thin front-entrance window, (2) the passivation ditch radius of 15 mm is almost a factor of two larger, and (3) the point-contact size of 4.0 mm is nearly a factor of two smaller. The reduction of the point contact should decrease the capacitance and hence the electronic noise. Simulations (see Fig. 2.7) indicate that the larger ditch radius should optimize the charge-collection and depletion regions within the crystal.

The physical dimensions of the crystal are 60 mm  $\times$  30 mm (diameter  $\times$  height), with a 15 mm ditch radius. The capacitance of MALBEK has been measured to be  $\sim 1.55$  pF, as shown in Fig. 2.8, and the noise corner is located at 6  $\mu$ s,  $\sim 165$  eV, as shown in Fig. 2.9.

Pulse shape analysis (PSA) of digitized waveforms (for information on the MALBEK data acquisition system see Sect. 9.4.4) allows the extraction of useful waveform characteristics, such as rise-time, baseline, peak height, extrema values, derivative, integral, etc. This is essential in order to remove non-physics backgrounds. Offline event-by-event processing also enables further digital processing of the waveform, for example pulse smoothing either by wavelet de-

noising or by performing a moving average (see Fig. 2.10). The MALBEK data analysis framework, based on a code developed Marino and others at the University of Washington, is as follows: (1) baseline removal, (2) smoothing (wavelets or moving average), (3) pole-zero compensation, and (4) extraction of waveform characteristics.

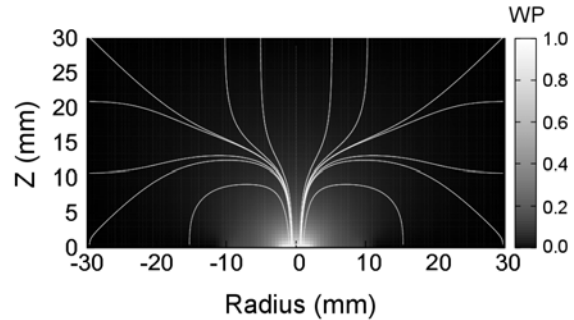


**Figure 2.7:** Weighting potential (WP) [Sch38] and charge-carrier (hole) drift paths for MALBEK. The WP quickly falls off nearly isotropically, resulting in long charge drift-times followed by rapid charge collection around the point contact (centered at the origin in the figure). This results in distinct current pulses for each interaction.

Energy calculations are done by performing a trapezoidal energy filter (TF). We are currently optimizing our choice of gap and peaking times in terms of resolution.

A 20-day spectrum with no cuts (runs in which LN2 fills are not used) is shown in Fig. 2.11. The detector threshold is  $\sim 1$  keV, but we expect significant improvement with the addition of cuts based on PSA to microphonics and other sources of background, such as

“slow” pulses from surface interactions. These slow pulses have rise times on the order of 1.5–2.0  $\mu\text{s}$  and result from interactions near the surface dead layer of the crystal.

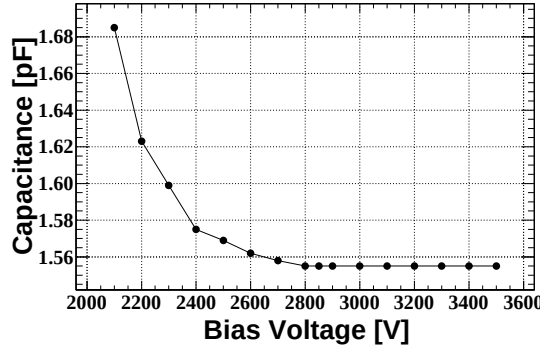


Figure 2.8: Detector capacitance vs. bias voltage (1.55 pF at depletion).

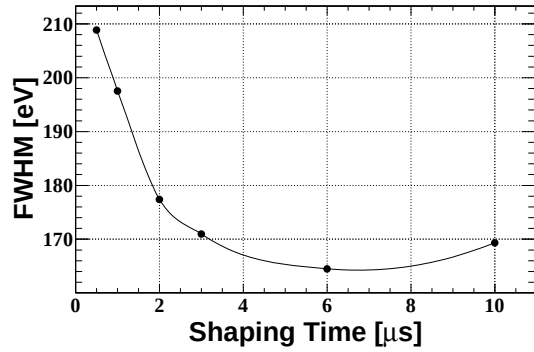


Figure 2.9: Electronic noise of MALBEK as measured by a pulser, showing the noise corner located at 6  $\mu\text{s}$ ,  $\sim 165$  eV.

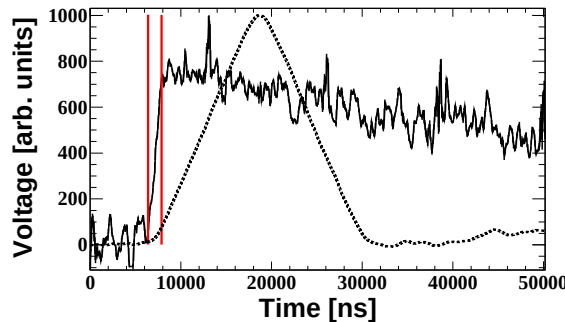


Figure 2.10: (Color online) Example of waveform processing on a 1.73 keV event. The solid black line represents the baseline corrected and smoothed waveform and the dashed black line represents a 100 kHz low-bandpass filter of a trapezoidal filtered waveform (gap time = 1.0  $\mu\text{s}$ , peaking time = 11.0  $\mu\text{s}$ ). Vertical bars indicate the extracted rise time start/stop of the pulse.

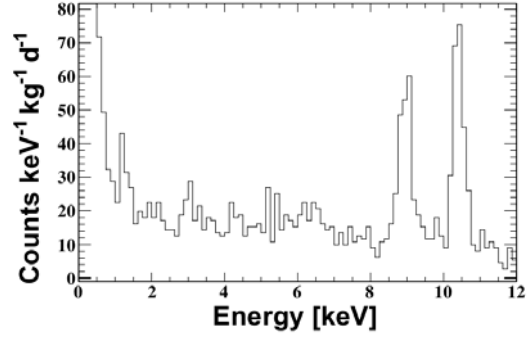


Figure 2.11: A 20-day spectrum for MALBEK with no cuts. Dominant features include cosmogenic peaks from K-shell electron capture in  $^{65}\text{Zn}$  (8.99 keV) and  $^{68,71}\text{Ge}$  (10.36 keV) and from L-shell peaks from  $^{68,71}\text{Ge}$  (1.1, 1.29 keV). The noise pedestal is located at  $\sim 1$  keV.

Even with only the LN2 fills removed, the continuum is within a factor of two of what is reported in Refs. [Aal08, Aal10]. Implementation of cuts to remove microphonic and surface interaction events will decrease the contribution to the continuum. We will also be commissioning a  $\sim 4\pi$  muon veto and 3.81 cm of borated polyethylene. We plan to investigate the performance of MALBEK at various operating temperatures. The temperature of the field effect transistor is directly proportional to the series noise, therefore the colder the detector is, the smaller the contribution from series noise. (Parallel noise also has a temperature component but is only relevant for resistive feedback preamplifiers.) Further refinement of the data analysis is also needed. We are pursuing several digital shaping methods, such as a dynamic TF that selects the optimal gap time based on pulse rise-time on an event-by-event basis.

[Aal08] C. Aalseth *et al.*, Phys. Rev. Lett., **101**, 251301 (2008).

[Aal10] C. E. Aalseth *et al.*, Arxiv preprint arXiv:1002.4703v2, (2010).

[Sch38] W. Shockley, J. Appl. Phys., **9**, 635 (1938).

## 2.1.7 Majorana Demonstrator Module Design Activities at TUNL

S. MACMULLIN, G. SWIFT, M. BUSCH, G. GIOVANETTI, W. PERKINS, *TUNL*; J. FAST, *PNNL*

Many portions of the Majorana Demonstrator modules are being developed at TUNL. The module task consists of the mechanical design of the cryostat vacuum enclosure, thermal management system, vacuum system, mechanical supports for the Ge crystals, and wiring. Also included in this task is designing the fabrication techniques and assembly techniques for these subsystems.

One of the most technically challenging aspects of the MAJORANA DEMONSTRATOR is to build the experiment using only the most radio-pure construction materials and follow an assembly process that leads to unprecedentedly low backgrounds.

### 2.1.7.1 String Design and Process Development

Each cryostat for the MAJORANA DEMONSTRATOR will be made almost entirely out of ultra-pure copper electro-formed underground and ultra-pure low-radioactivity PTFE plastic. Each cryostat houses up to 35 germanium crystals in 7 “strings” of up to 5 detectors in height (see Fig. 2.12). The detailed design of the detector mounts and strings is being completed at TUNL using Solidworks 3D modeling software.

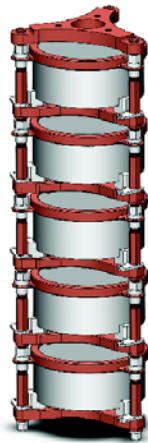


Figure 2.12: (Color online) Majorana string design

In addition to the string design, the manufacture of these parts must be in accordance with the background goals of the experiment. To

that end, a temporary cleanroom has been purchased for developing clean manufacturing techniques at UNC. TUNL and the UNC physics machine shop are collaborating to develop techniques for computer-numerical-controlled (CNC) machining in a cleanroom environment. This cleanroom will contain CNC machining equipment and other assembly tooling.

Building on techniques developed at PNNL, we will develop detailed procedures for cleaning the CNC machines and operating them in a way that minimizes contamination to the cleanroom environment and to the materials being machined. Commercially available copper and plastics will be used for the majority of these tests, but small samples of production materials are available to evaluate whether techniques will need to be modified for the production run. Special tools, work-holding and assembly fixtures are being developed to allow the clean handling and assembly of these parts. All of these tools (including the specially cleaned CNC machines) and detailed procedures will then be shipped to Sanford Underground Laboratory (SUL) for the underground production run. A Sodick VZ300L wire electric-discharge-machining (EDM) machine will be used in the manufacture of some of the copper string parts. A local manufacturer with a similar model Sodick wire EDM has been identified and has agreed to provide custom machining jigs and prototype parts in collaboration with TUNL and the UNC physics machine shop. These parts will then be shipped to SUL for installation on the Sodick VZ300L when it is installed in the underground-cleanroom machine shop.

### 2.1.7.2 Flange Test

Conventional vacuum seals such as indium wire and Viton O-rings cannot be used to seal the

MAJORANA cryostats because they can introduce radioactivity into the experiment. Alternatives consist of clean lead or gold wire, but since both are considerably harder than indium, it is difficult to attain the large pressures required for them to flow and seal with an all-copper cryostat. We have fabricated two 4-in.-diameter test cryostats made from commercial copper. Several flanges were designed and machined into each cryostat design to test vacuum sealing properties.

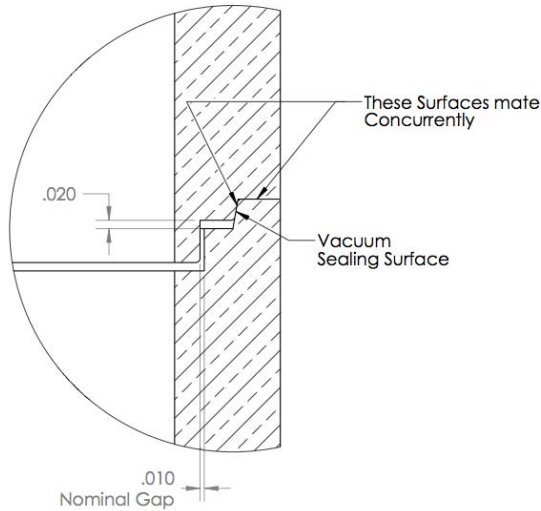


**Figure 2.13: Cryostat flange test design**

One design in particular, displayed in Fig. 2.13, showed no signs of vacuum leak when tested with a helium leak detector. An interface of 2-mil Parylene-C, provided by collaborators at the University of Washington, was placed

at the vacuum sealing surface to reinforce the seal. Parylene-C has the advantage of having low gas permeability and known radio-purity. A full-sized 13-in.-diameter test cryostat will be fabricated and tested using this design in the future.

### 2.1.7.3 Vacuum System Design

The vacuum system for the MAJORANA DEMONSTRATOR cryostats will be developed and prototyped at TUNL. This vacuum system must demonstrate high reliability with low intervention, due to the high monetary value of the detectors and the expense associated with manual intervention in a deep underground clean-room. Due to the likelihood of power failures at SUL, this system must also be designed to recover gracefully from a short (less than 24 h) power failure, and shutdown gracefully in the event of an extended power outage. Unique system requirements include the evaluation of UHV feedthroughs with low radon emanation and low vibration components to reduce microphonic noise.

### 2.1.7.4 Conclusions

The MAJORANA DEMONSTRATOR relies on achieving extremely low backgrounds. This is a difficult task and offers many unique design challenges. TUNL is leading the effort to design and fabricate the detector strings, using materials and techniques that satisfy the strict background criteria. In addition, we are developing the vacuum system and seal for the MAJORANA cryostat. The completion of these tasks will be crucial to the success of the DEMONSTRATOR.

### 2.1.8 A Monte-Carlo Background Model for the MALBEK Detector

A.G. SCHUBERT, M.G. MARINO, M.L. MILLER, *University of Washington, Seattle, WA*; P. FINNERTY, G.K. GIOVANETTI, R. HENNING, M.A. HOWE, S. MACMULLIN, J. STRAIN, J.F. WILKERSON, *TUNL*; P.S. BARBEAU, J.I. COLLAR, *University of Chicago, Chicago, IL*; R.J. COOPER, D.C. RADFORD, *Oak Ridge National Laboratory, Oak Ridge, TN*; J. ORRELL, *Pacific Northwest National Laboratory, Richland, WA*; M. YOCUM, *Canberra Industries, Meriden, CT*

**The MAJORANA low-background BEGe detector at KURF (MALBEK) is a custom low-background broad-energy germanium (BEGe) detector. MALBEK was modeled in MaGe, a geant4- and root-based simulation package. Results from MaGe simulations and radiopurity data for materials near the detector will be combined to create a background model for MALBEK.**

The MAJORANA Collaboration proposes a search for neutrinoless double-beta decay ( $0\nu\beta\beta$ ) of  $^{76}\text{Ge}$  using an array of enriched Ge detectors. The MAJORANA project will require an extremely low background rate to achieve high sensitivity to this decay. Radioactive decays and cosmogenically-induced radiation create backgrounds to the potential ( $0\nu\beta\beta$ ) signal.



**Figure 2.14:** (Color online) The MaGe/geant4 model of the MALBEK detector, shown in a cross-sectional view.

grounds is critical to the sensitivity of the MAJORANA experiment. The MAJORANA low-background BEGe at KURF (MALBEK) detector can be used to study these backgrounds. The MALBEK detector was modeled in MaGe, a GEANT4- and ROOT-based Monte-Carlo simulation package developed by the MAJORANA and Gerda collaborations [Hen05, Ago03, Ant09]. The MaGe model of MALBEK is shown in Fig. 2.14.

MaGe/GEANT4 will be used to simulate MALBEK's response to background radiation. The simulated response will be combined with information about the radiopurity of materials in the detector and experimental hall to predict the MALBEK background energy spectrum. The prediction can be compared to energy spectra collected at KURF in order to validate the simulation model and guide our understanding of the backgrounds for the MAJORANA experiment.

[Ago03] S. Agostinelli *et al.*, Nucl. Instrum. Methods Phys. Res., **A506**, 250 (2003).

[Ant09] I. Antcheva *et al.*, Comput. Phys. Commun., **180**, 2499 (2009).

[Hen05] R. Henning and the Majorana Collaboration, Nucl. Phys. B - Proc. Suppl., **143**, 544 (2005), NEUTRINO 2004.

Understanding and minimizing these back-



### 2.1.9 Creating a Muon Veto for MALBEK

J. STRAIN, G.K. GIOVANETTI, R. HENNING, A. LONG, J.F. WILKERSON, *TUNL*

**MALBEK (the Majorana low-background BEGe detector at KURF) is a broad-energy germanium (BEGe) detector in an ultra-low background cryostat from Canberra. One component of MALBEK's shielding is a muon veto made of plastic scintillator. The design and techniques used to prepare the muon veto for MALBEK are discussed.**

In January of 2010 MALBEK was commissioned at the Kimballton Underground Research Facility (KURF). The goal of MALBEK is to perform pulse-shape-analysis studies and characterize the prototype point-contact BEGe detector for the MAJORANA experiment [Fin09] (see also Sect. 2.1.6). Background suppression, and thus proper shielding, is important to achieve this goal. Working from the innermost to the outermost, MALBEK's shield includes 1 in. of Spanish galleon ancient lead, 8 in. of low-background lead, a  $^{222}\text{Rn}$  exclusion box, a muon veto, 1.46 in. of borated polyethylene, and 10 in. of polyethylene (see Sect. 2.1.5).

MALBEK's muon veto will surround the detector from all four sides and from above. Figure 2.15 shows a model of how the muon veto will be mounted to MALBEK's stand.

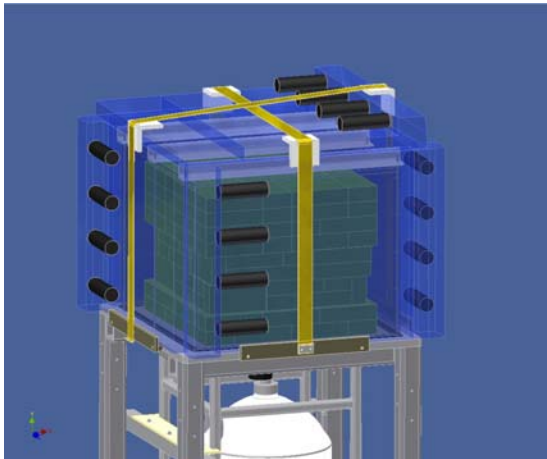


**Figure 2.15:** (Color online) The scintillator can be seen as the transparent blue paddles surrounding the detector's lead shielding (green). The black cylinders represent the PMTs. Figure drawn to scale.

The muon veto is composed of five plastic scintillator paddles. The scintillator material is

Saint Gobain's BC-412 with a polyvinyltoluene base, and the PMTs were made by Phillips. The scintillator and PMTs were acquired as surplus from KARMEN [Rei05]. The 2-in.-thick scintillator was delivered to UNC in 123.5 in. x 25.75 in. paddles, each with two lightguides attached, one at each end. From each end a 33 in. x 25.75 in. piece of scintillator was cut (with the attached lightguide) using a hand-held circular saw (see Fig. 2.16). A constant flow of clean water was maintained over the area being cut, to avoid overheating the scintillator and causing it to melt or craze.



**Figure 2.16:** (Color online) A piece of scintillator right before it was cut. Masking tape covers the area being cut to help protect the scintillator from being further scratched and so that a line could be drawn to help guide the saw.

Any scratching or crazing in the scintillator can lower the light collection efficiency. Therefore, after each piece of scintillator was cut, it was polished to remove any scratches and to help reduce some of the crazing.

Before any polishing was done on the scintillator for the muon veto, a detailed procedure was developed and the procedure was tested on small

scintillator test blocks. The polishing procedure consisted of dry sanding with progressively finer grits, wet sanding with finer grit Micro-Mesh, and then buffing. All sides of the scintillator were dry sanded down to a 400 grit. Generally, sides cut with the circular saw were sanded with a 36, 80, 220, and then 400 grit, while uncut sides were mostly just dry sanded with the 400 grit unless deeper scratches were found. The next step was wet sanding with a fine grit Micro-Mesh from Micro-Surface. All of the scintillator was wet sanded with 1500, 2400, 3600, and then 6000 grit Micro-Mesh. The final steps involved buffing all of the scintillator with a random orbital sander using a liquid abrasive, followed by hand buffing with an antistatic cream (see Fig. 2.17).



Figure 2.17: (Color online) A piece of scintillator in its final polishing stage, hand buffing with an antistatic cream.

After the scintillator was thoroughly polished, the PMTs were glued to it using Saint Gobain's BC-600 Optical Cement. It was then wrapped in aluminum foil and made light-tight with a black plastic ground cover (see Fig. 2.18).

Work is now being done to calibrate the scintillator paddle's spectrum and determine the light collection efficiency. The scintillator signal is read out by an object-oriented software program, ORCA (see Sect. 9.4.4). Figure 2.19 is an oscilloscope image of a scintillator signal after it has been through a discriminator and logic unit.

Once the scintillator spectrum has been characterized, future work will include bringing the

scintillator paddles underground and mounting them on the stand for MALBEK.



Figure 2.18: (Color online) A fully polished and wrapped piece of scintillator.

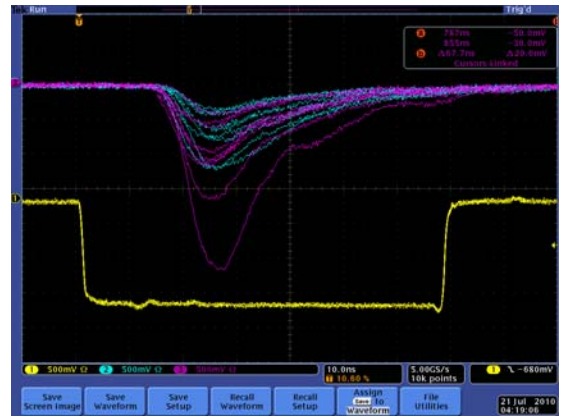


Figure 2.19: (Color online) The signal for two scintillator paddles in coincidence along with the GATE signal.

[Fin09] P. Finnerty *et al.*, TUNL Progress Report, **XLVIII**, 157 (2009).

[Rei05] J. Reichenbacher, *Final KARMEN-Results on Neutrino-Oscillations and Neutrino-Nucleus-Interactions in the Energy-Regime of Supernovae*, Technical Report Wissenschaftliche Berichte, FZKA-7093, Forschungszentrum Karlsruhe, 2005.

### 2.1.10 The SEGA Detector: A 1.4 kg, Segmented Germanium Ionization Detector Enriched to 85% $^{76}\text{Ge}$

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**We present progress in implementing a segmented, enriched-germanium-assembly detector (the SEGA detector), in analyzing segmentation and pulse-shape data to reconstruct single-site events, and in transforming SEGA into a low-background detector.**

The SEGA detector is a 1.4 kg, N-type Ge detector, with 6-fold azimuthal and 2-fold axial segmentation. This detector is unique, in that it is also enriched to 85%  $^{76}\text{Ge}$ , making it the first enriched, segmented Ge detector. The low-background SEGA detector will serve as a test-bench for (1) engineering low-background crystal mounts and detector cryostats and (2) determining known and previously unknown backgrounds (as well as methods for reducing them) for the one-tonne MAJORANA experiment designed to probe Majorana-neutrino mass scales down to roughly the 20 meV level. For further details, please see <http://majorana.npl.washington.edu>.

The strategy to eliminate background in the Majorana  $\beta\beta$ -decay experiment rests on four primary techniques: the high resolution achievable with Ge-diode technology, finely segmenting the detector, implementing pulse-shape analysis (PSA), and using ultra-low radioactive background materials. The first of these relies on the fact that neutrinoless  $\beta\beta$  ( $0\nu\beta\beta$ ) decay should normally result in the deposition of a monoenergetic line at 2.04 MeV in our detector. Thus, the intrinsically high resolution (nominally 0.2%) of Ge detectors allows an excellent rejection of most backgrounds present in a typical underground counting experiment. Segmentation and PSA rely on the fact that  $0\nu\beta\beta$  decay is a “single-site” event, in that all of the detected energy released in the decay is carried by two  $\beta$  particles with very small (less than 2 mm) range in the Ge. Many background events, on the other hand, are multi-site events, and can deposit energy at several points in the crystal separated by centimeters or more. Perhaps the most important example of these backgrounds comes from high-energy  $\gamma$  rays, which typically Compton scatter one or more times before depositing their full energy in the crystal.

SEGA’s 6-fold azimuthal and 2-fold axial segmentation is created with 6 azimuthally distributed outer electrical contacts (S1 through S6) and by segmenting the central electrical contact radially in two parts (C1 and C2), thereby dividing the crystal into 12 physical segments. SEGA’s unique geometry and segmentation serves as a powerful tool for rejecting multi-site events; however, in order to maximize the potential of the detector it is necessary to characterize each of the 12 physical segments thoroughly. During the past year, analysis of new source data has taken place, including studies of electronic noise, intrinsic peak efficiency, and system linearity.

In order to characterize the noise performance of SEGA, we used the methods of Betuccio and Pulic [Ber93] to represent the equivalent noise charge (ENC) in a given physical segment as  $(\text{ENC})^2 = \frac{h_1}{\tau} + h_2 + h_3\tau$ , where  $\tau$  is the peaking time of the shaping network, and where  $h_1$ ,  $h_3$ , and  $h_2$  are due to the series white noise, the parallel white noise, and the non-white series and parallel noises, respectively.

In order to quantify the noise sources, we varied the peaking time of our shaping network. Typically a pulser is used to decouple the additional contributing factors to the measured peak width, but since SEGA currently isn’t equipped with a pulser, we chose to place a  $^{60}\text{Co}$  source above the crystal and record data with very long (40- $\mu\text{s}$ ) traces. The long traces allowed us to apply an offline digital trapezoidal filter [Tan04] (the same filter implemented in the XIA module), while varying the shaping parameters. This eliminated the need for multiple data sets for which the shaping parameters were varied from run to run. FWHM values were measured by fitting the 1333-keV photopeak in the trapezoidal-filter-output spectra using a Gaussian function with

a linear background. To obtain only the electronic noise contribution to the photopeak width, all other components, including charge creation statistics and charge collection efficiency, were removed using the coefficients obtained from the previous resolution-versus-energy studies. The  $(\text{ENC})^2$  vs.  $\tau$  curves in Fig. 2.20 provide an understanding of how the three sources are contributing individually to the peak width.

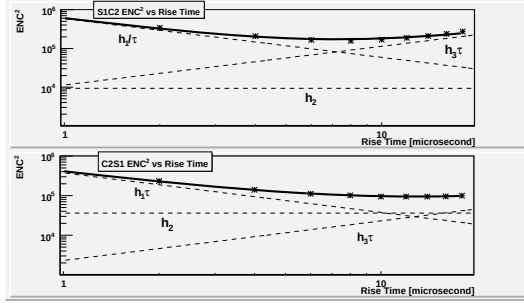


**Figure 2.20:** (Color online) Equivalent noise-charge vs. peaking time, along with the three individual noise components for the C2S1 segment. C2 and S1 refer to a central and outer contact respectively, thus labeling one of the twelve physical segments.

In order to assess the active volume within the detector, the intrinsic peak efficiency was measured using a  $3.15 \mu\text{Ci}$   $^{60}\text{Co}$  source. The source was placed approximately 25 cm above the top of the crystal, which was measured by scanning the detector with a  $^{57}\text{Co}$  source, and data were recorded for approximately 43 h to reduce the error in the sum-peak to less than 5%. To determine the full energy deposited within the detector for a given event, the outer S channels (S1-S6) energies were summed together. However, because the channels are electrically coupled, a cross-talk correction had to be applied to multi-segment events. By analyzing the number of counts in the sum-peak and the two  $^{60}\text{Co}$   $\gamma$ -ray peaks, it was possible to determine the intrinsic peak efficiencies for the 1173 keV and 1333 keV  $\gamma$  rays. These were 14% and 13% respectively. Sum-coincidence and angular correlation effects were accounted for within this study, while the effect of system dead time was avoided by using the sum-peak method.

In addition to the electronic noise and efficiency studies, the system linearity was quickly analyzed using the data-set from the efficiency study and fitting the various background and source lines using a Gaussian function with a linear background. The extent of the linearity can be seen in the energy response curve in Fig. 2.21 along with the residuals from the fit.

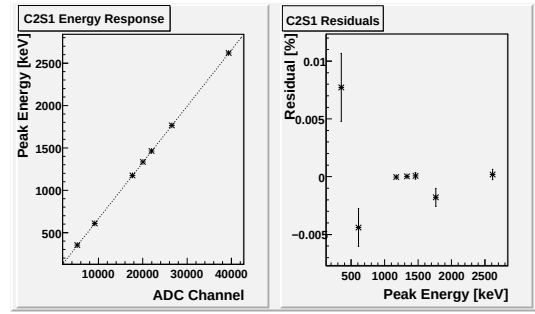


**Figure 2.21:** (Color online) Energy response of the C2 channel for C2S1 events from a  $^{60}\text{Co}$  source (left) along with the residuals from the fit (right).

These studies complete the evaluation phase of SEGA in its current cryostat. Together with our measurements of leakage currents, the resolution vs. deposited  $\gamma$ -ray energy, peak energy vs. bias voltage, integral crosstalk, and segmentation performance, these studies provide a solid basis for characterizing the basic performance of the SEGA detector.

The next step in the SEGA project is to transfer the detector into a low-background cryostat and move it to an underground counting laboratory. In the past year, SEGA served to exercise the first MAJORANA-dedicated electroforming bath at PNNL in the production of the low-background contact assembly (made entirely of electroformed copper and Duponts NXT-85 plastic). All components of this contact assembly and a transfer cryostat have been fabricated, and the plastic has been screened for radiopurity using neutron activation analysis at NCSU's PULSTAR reactor to determine the uranium and thorium content. The test/transfer cryostat was designed at the University of Washington and built at NCSU. The preamplifier electronics were developed at LBNL and are being sent to TUNL for integration into the new cryostat.

At present, we are finalizing details of the wire-routing in the test and transfer cryostat and attempting to schedule the crystal transfer, which will take place at AMETEK's facility in Oak Ridge, TN. We are also completing design details of the final low-background cryostat, which has been mostly designed, and will be installed in the DOE's Waste Isolation Pilot Plant in Carlsbad, NM.

[Ber93] G. Bertuccio and A. Pullis, *Rev. Sci. Instrum.*, **64** (1993).

[Tan04] H. Tan *et al.*, *IEEE Trans. Nucl. Sci.*, **51** (2004).

### 2.1.11 Differential Cross-Section Measurements for Elastic and Inelastic Scattering of Neutrons from Neon

S. MACMULLIN, M. KIDD, W. TORNOW, R. HENNING, M. BROWN, C.R. HOWELL, *TUNL*

**We have measured the absolute partial cross sections for elastic scattering of neutrons from  $^{nat}\text{Ne}$  at the TUNL NTOF facility. Neutron energies were chosen to correspond to those produced from  $(\alpha, n)$  reactions due to  $^{238}\text{U}$  and  $^{232}\text{Th}$  decays in borated photo-multiplier-tube glass. These measurements will help to enrich the nuclear databases, identify backgrounds in dark-matter experiments, and refine Monte Carlo simulations and background estimates.**

#### 2.1.11.1 Introduction

The next generation of low-background physics experiments, including direct detection of weakly-interacting-massive-particle (WIMP) dark matter and searches for neutrinoless double-beta decay ( $0\nu\beta\beta$ ), may provide significant insight into physics beyond the Standard Model. The successful detection of WIMP interactions will provide valuable information about the mass, cross section, and nature of dark matter. Many of the next generation large-scale detectors designed to search for WIMP dark matter will make use of large volumes of noble liquids (Ne, Ar, Xe). These experiments will search for the scintillation light generated from WIMP-nuclear scattering. Neutron-induced nuclear recoils are a particularly dangerous background for these experiments, as it is difficult to distinguish them from WIMP events. Experimental data for elastic and inelastic cross sections of neutrons with neon were previously unavailable. We have performed measurements of these cross sections for use as inputs to Monte Carlo simulations of such neutron backgrounds in these low-background experiments, especially MiniCLEAN [Bou04]. These data will also be added to existing simulation databases.

#### 2.1.11.2 Experimental Details

The neutron time-of-flight (NTOF) facility at TUNL was used to measure the partial elastic and inelastic scattering cross sections of  $^{nat}\text{Ne}$ . The 10 MV Tandem Van de Graaff accelerator is capable of producing pulsed, mono-energetic neutron beams with energies of about 5–15 MeV using the  $^2\text{H}(d, n)^3\text{He}$  reaction [Hut07]. Neutron energies of specific interest are determined by where the  $^{238}\text{U}$ - and  $^{232}\text{Th}$ -induced  $\alpha$ -neutron

yields are the largest in Ar, Ne and Xe [Mei09]. Neutrons are generated by bombarding a small deuterium gas cell with a deuteron beam pulsed at 2.5 MHz with a 2 ns width. Typical deuteron beam current on target is about 1.0–1.5  $\mu\text{A}$ .

The gas target cell is described fully in [Rup09]. It is a 21.0 mm diameter stainless steel sphere with 0.5 mm wall thickness. The cell is filled using a coupling device connected to a high pressure filling station at TUNL. For the neon experiment, the pressure was maintained at around 170 atm, corresponding to a steel-to-neon ratio of about 4:1. The cell was operated well below its maximum pressure rating of 550 atm. This was limited by the ability to condense the gas in the cell at the filling station. The amount of gas in the cell is determined by measuring the weight before and after filling. The pressure in the cell was stable, with no measurable difference during the course of a run, sometimes up to 48 hours.

The scattered neutrons are detected by two NE-213 and NE-218 liquid scintillation detectors, placed at symmetric angles with respect to the beam axis. The detectors are shielded from external backgrounds by copper, lead and polyethylene. A time-of-flight spectrum is acquired for each angle at each neutron energy. After each “sample in” measurement, an identical run is done with an unfilled gas cell, so that backgrounds may be subtracted. Pulse shape discrimination is utilized to discriminate accidental  $\gamma$ -ray backgrounds that may fall into the neutron time-of-flight window. The background-subtracted yields are corrected for dead time and multiple scattering, and normalized to a neutron counter which has a direct line of sight to the neutron production cell. To determine the cross section, these yields are normalized to  $^1\text{H}(n, n)^1\text{H}$  scattering using a polyethylene ( $\text{C}_2\text{H}_4$ ) and car-

bon scatterer. For each neutron energy, a differential elastic scattering and inelastic scattering cross section may be obtained.

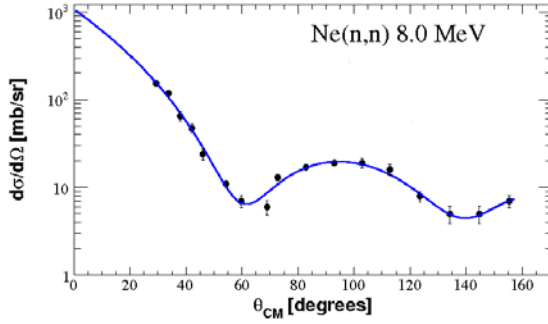


**Figure 2.22:** (Color online)  $\text{Ne}(n,n)$  elastic-scattering differential cross section at 8.0 MeV. The curve is a fifth-order Legendre polynomial fit.

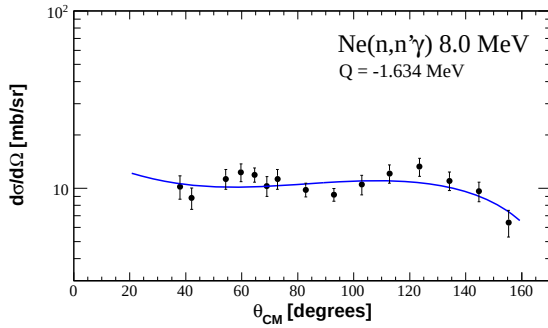


**Figure 2.23:** (Color online)  $\text{Ne}(n,n'\gamma)$  inelastic scattering differential cross section at 8.0 MeV, with the residual nucleus in its first excited state. The curve is a third-order Legendre polynomial fit.

In September 2009, an experiment was performed for 8.0 MeV neutrons scattering from  $^{nat}\text{Ne}$ , and additional 8.0 MeV data were taken in March 2010. Several data points at 5.0 MeV were taken in June 2010, and these measurements are scheduled to continue in August 2010. The differential cross sections for  $^{nat}\text{Ne}(n,n)$  and  $^{nat}\text{Ne}(n,n'\gamma)$  were measured. Results are shown in Figs. 2.22 and 2.23.

### 2.1.11.3 Conclusions

The lack of experimental data for some neutron cross sections in Ne, Ar and Xe pose a significant problem to dark-matter experiments that rely on Monte Carlo simulations to model expected backgrounds. Elastic and inelastic neutron-scattering cross sections were measured for neon and will be measured for argon and xenon in the future. These cross sections will help to enrich the cross section databases in the neutron energy range in which the Monte Carlo simulations rely on data. These measurements will make new information available for Monte Carlo simulations and background estimates for current and future experiments.

- 
- [Bou04] M. Boulay *et al.*, Arxiv preprint arXiv:nucl-ex/0410025, (2004).
  - [Hut07] A. Hutcheson *et al.*, Nucl. Instrum. Methods, **B261**, 369 (2007).
  - [Mei09] D.-M. Mei *et al.*, Nucl. Instrum. Methods, **A606**, 651 (2009).
  - [Rup09] G. Rupp *et al.*, Nucl. Instrum. Methods, **A608**, 152 (2009).

### 2.1.12 Double-Beta Decay of $^{150}\text{Nd}$ to the First Excited Final State of $^{150}\text{Sm}$

M. F. KIDD, J. H. ESTERLINE, S. FINCH, W. TORNOW, *TUNL*;

We report the first measurements from the TUNL double-beta decay effort at the Kimballton Underground Research Facility (KURF). We investigated the decay of  $^{150}\text{Nd}$  to the first excited  $0^+$  state of  $^{150}\text{Sm}$  by detecting the 333.9 keV and 406.5 keV deexcitation  $\gamma$  rays in coincidence. After an exposure of 21.2 kg-days, we observed 21 net coincidence events, which corresponds to a half-life of  $T_{1/2} = 0.76^{+0.33}_{-0.18}(\text{stat}) \pm 0.04(\text{syst}) \times 10^{20}$  y.

Studying two neutrino double-beta ( $2\nu\beta\beta$ ) decay is an excellent test of theoretical models used to predict the half-lives of neutrinoless double-beta decay ( $0\nu\beta\beta$ ). Therefore results from studying  $2\nu\beta\beta$  decay can aid in the search for  $0\nu\beta\beta$  decay, which in turn can provide information on the fundamental properties of the neutrino and serve as an excellent probe for physics beyond the Standard Model. For example, the presence of  $0\nu\beta\beta$  decay would show that the neutrino is its own antiparticle, (*i.e.*, that it is a Majorana particle). Detecting  $0\nu\beta\beta$  decay is the most viable experiment known to verify this conjecture. Evidence of this process would also indicate violation of lepton number conservation.

In addition,  $0\nu\beta\beta$  decay is currently a promising method of obtaining the neutrino mass. The half-life of  $0\nu\beta\beta$  decay can be related to the mass of the neutrino using the relation

$$[T_{1/2}^{0\nu}]^{-1} = G_{0\nu} |M_F^{0\nu} - (g_A/g_V)^2 |M_{GT}^{0\nu}|^2 |\langle m_{\beta\beta} \rangle|^2$$

Here  $G_{0\nu}$  is the two-body phase-space factor with the coupling constant;  $|\langle m_{\beta\beta} \rangle|$  is the effective Majorana electron neutrino mass;  $g_V$  and  $g_A$  are, respectively, the vector and axial-vector coupling constants; and  $M_F^{0\nu}$  and  $M_{GT}^{0\nu}$  are the Fermi and Gamow-Teller nuclear matrix elements, respectively. Extracting the mass from the half-life measurement is not as straightforward as it appears. Knowledge of the  $0\nu\beta\beta$  decay nuclear matrix elements is currently based on calculations using techniques from quasi-particle random phase approximations, the nuclear shell model, and the interacting boson model. The parameters in these calculations (in particular, the strength of the particle-particle interaction  $g_{pp}$ ) in turn are adjusted using measured half-lives from  $2\nu\beta\beta$  decay. Because the behavior of the  $g_{pp}$  parameter is different for transitions to

the ground state and transitions to excited states, studying  $2\nu\beta\beta$  decay to excited final states is an excellent test of the theoretical calculations.

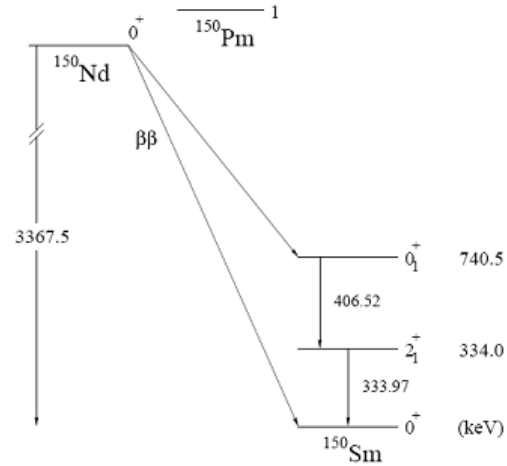


Figure 2.24: Level scheme of  $^{150}\text{Sm}$ , the daughter nucleus of the double-beta decay process of  $^{150}\text{Nd}$ .

To date,  $2\nu\beta\beta$  decay to the ground state of the daughter nucleus has been observed in 10 different nuclei, but  $2\nu\beta\beta$  decay to excited final states has only been observed in  $^{100}\text{Mo}$  and  $^{150}\text{Nd}$ .  $^{150}\text{Nd}$  is an excellent candidate for  $\beta\beta$ -decay study for several reasons. Its high Q-value, even for decay to excited final states, makes it a viable isotope for the TUNL-ITEP (Institute for Theoretical and Experimental Physics)  $\beta\beta$ -decay setup, though very little information is currently available regarding the nuclear matrix elements of  $^{150}\text{Nd}$ . Finally,  $^{150}\text{Nd}$  is the nuclide of choice for the next phase of the Solar Neutrino Observatory, called SNO+, which will attempt to measure  $0\nu\beta\beta$  decay of  $^{150}\text{Nd}$ . In this case, the  $2\nu\beta\beta$

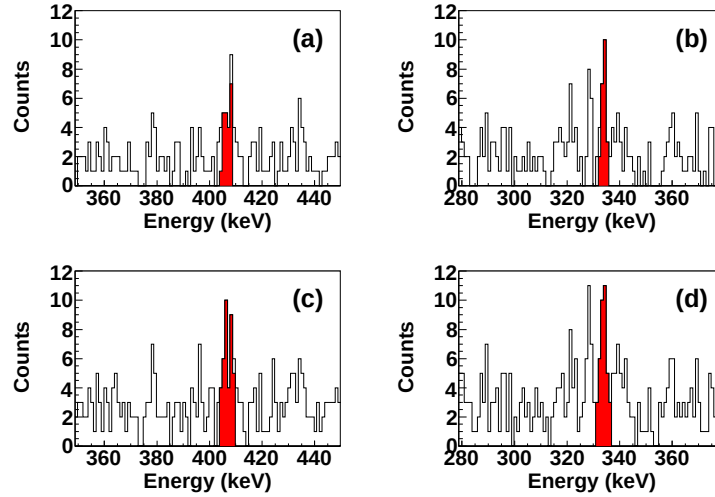


Figure 2.25: (Color online) Coincidence data from 529 days of runtime. Spectra (a) and (c) are in coincidence with 333.9 keV, and (b) and (d) are in coincidence with 406.5 keV. Spectra (a) and (b) show an energy coincidence cut of  $\pm 2.5$  keV while (c) and (d) have an energy coincidence cut of  $\pm 3.0$  keV.

decay will be a large background factor and must be well-understood.

The recent result obtained by Barabash *et al.* for the  $2\nu\beta\beta$  decay of  $^{150}\text{Nd}$  to the first excited  $0^+$  state is  $T_{1/2} = [1.33^{+0.36}_{-0.23}(\text{stat})^{+0.27}_{-0.13}(\text{syst})] \times 10^{20}$  y. This measurement was performed at Modane Underground Laboratory by observing single  $\gamma$ -ray transitions. Though an excess of counts was seen at the de-excitation energies of 333.9 keV and 406.5 keV, the level of background in these measurements is comparatively high [Bar09]. The background lines of greatest concern in this measurement are listed in Table 2.1 and coincide with the  $\gamma$ -ray transitions of interest. The associated isotopes are present in the natural decay chains shown in the table. Because of the coincidence technique employed in the experiment described here, none of these decays can mimic the  $2\nu\beta\beta$  signature, despite the  $^{228}\text{Ac}$  contamination from a  $^{232}\text{Th}$  impurity in our enriched  $^{150}\text{Nd}$  source.

50.00 grams of powdered neodymium oxide ( $\text{Nd}_2\text{O}_3$ ) enriched to 93.60%  $^{150}\text{Nd}$  were leased from Oak Ridge National Laboratory. This corresponds to 42.87 g Nd metal and 40.13 g  $^{150}\text{Nd}$ . The  $\text{Nd}_2\text{O}_3$  is sealed in an acrylic holder with a cavity measuring 5.72 cm in diameter and 0.72 cm deep. Using the technique outlined in [Kid09], we used a pair of HPGe detectors surrounding the source to detect the two coincident  $\gamma$  rays resulting from the decay of the  $^{150}\text{Sm}$  excited  $0^+$  state

via  $0^+_1 \rightarrow 2^+_1 \rightarrow 0^+_{gs}$  (see Fig. 2.24). The TUNL-ITEP  $\beta\beta$ -decay setup is located at KURF. The depth of the present facility is 518 meters, which corresponds to approximately 1450 meters water equivalent.

Table 2.1: Background Contamination

| Isotope           | Intensity (%) | Energy (keV) | Decay Chain       |
|-------------------|---------------|--------------|-------------------|
| $^{214}\text{Bi}$ | 0.065         | 333.37       | $^{238}\text{U}$  |
| $^{214}\text{Bi}$ | 0.036         | 334.78       | $^{238}\text{U}$  |
| $^{214}\text{Bi}$ | 0.169         | 405.72       | $^{238}\text{U}$  |
| $^{228}\text{Ac}$ | 0.40          | 332.37       | $^{232}\text{Th}$ |
| $^{227}\text{Th}$ | 1.54          | 334.37       | $^{238}\text{U}$  |
| $^{211}\text{Pb}$ | 3.78          | 404.853      | $^{238}\text{U}$  |

After counting for 529 days, the spectra shown in Fig. 2.25 were obtained. The shaded bins are those within the event gates. An excess of 21 events has been seen, corresponding to a half-life of  $T_{1/2} = 0.76^{+0.33}_{-0.18}(\text{stat}) \pm 0.04(\text{syst}) \times 10^{20}$  y. This is lower than the result of Barabash *et al.* [Bar09] but still in agreement with it within the error bars.

[Bar09] A. S. Barabash *et al.*, eprint arXiv:0904.1924v1, 2009.

[Kid09] M. F. Kidd, J. H. Esterline, and W. Tornow, Nucl. Phys. A, **821**, 251 (2009).

### 2.1.13 Double-Beta Decay of $^{150}\text{Nd}$ to Excited Final States of $^{150}\text{Sm}$

M.F. KIDD, J.H. ESTERLINE, S.W. FINCH, W. TORNOW, *TUNL*

During the first measurements from the TUNL double-beta ( $\beta\beta$ ) decay effort at the Kimballton Underground Research Facility, we investigated the decay of  $^{150}\text{Nd}$  to the higher excited states of  $^{150}\text{Sm}$  by detecting the deexcitation  $\gamma$  rays in coincidence. After an exposure of 21.2 kg-days, we were able to set limits on the double-beta decay to higher excited final states of  $^{150}\text{Sm}$ .

The  $\beta\beta$  decay of  $^{150}\text{Nd}$  to higher excited states of  $^{150}\text{Sm}$  was studied using the technique described in Sect 2.1.12. The decay scheme in Fig. 2.26 shows the coincidence energies for these three cascades to be 712.2 keV - 333.9 keV, 859.9 keV - 333.9 keV, and 921.2 keV - 333.9 keV. Note that both the 712.2 keV and 859.9 keV transitions are in  $2^+ \rightarrow 2^+ \rightarrow 0^+$  decays, and the efficiency must be adjusted accordingly. As seen in Fig. 2.27, no events were detected above background for any of these decays, meaning that half-life limits may be set for  $\beta\beta$  decay to these states. The half-life limit is given by

$$T_{1/2} > \frac{\ln 2 N_0 t f_b \epsilon_{\gamma\gamma}^{\text{tot}}}{N_d}, \quad (2.1)$$

where  $N_0$  is the number of  $^{150}\text{Nd}$  nuclei in the sample,  $\epsilon_{\gamma\gamma}^{\text{tot}}$  is the coincidence efficiency,  $t$  is the counting time, and  $f_b$  is the branching ratio for the particular cascade. The value of  $N_d$  is recommended by the Particle Data Group [Par09] and is determined by a statistical estimator derived for a process obeying Poisson statistics.  $N_d$  is defined as the desired upper limit on the signal above background, and it depends on the chosen level of certainty. For  $\beta\beta$ -decay half-life limits, reporting the 90% confidence level (CL) has become standard. For the 90% CL,  $N_d$  is the maximum signal that will be observed in 90% of all random repeats of the experiment, so that there is less than a 10% chance of observing a count rate above  $N_d$ .

The first case to be considered is the  $2_2^+ \rightarrow 2_1^+ \rightarrow 0_{gs}^+$  transition, which proceeds through the emission of a 712.2 keV  $\gamma$  ray in coincidence with the 333.9 keV  $\gamma$  ray. The  $\epsilon_{\gamma\gamma}$  for this transition is  $(0.275 \pm 0.014)\%$ , and the branching ratio is 89%. The accumulated data can be seen in Fig. 2.27 (a.) and (b.). The background is 2.5 counts per keV. The large peak seen at 707.4 keV in spec-

trum (a.) is a coincidence peak in the  $^{228}\text{Ac}$  decay to  $^{228}\text{Th}$  (the associated  $\gamma$  ray in the decay has an energy of 332.0 keV). The peak labeled at 1001.0 keV in spectrum (b.) is a Compton scattering peak (*i.e.* the energy deposited in the detector is 1001.0 keV minus 712.2 keV) from the decay of  $^{234m}\text{Pa}$  to  $^{234}\text{U}$ . The typical Compton scattering coincidence (CSC) peaks mentioned in Sect. 2.1.14 at 328 keV and 338 keV can also be seen. With 16 counts in the region of interest, a positive signal is not detected. The half-life limit is found to be  $T_{1/2} > 5.40 \times 10^{19}$  y.

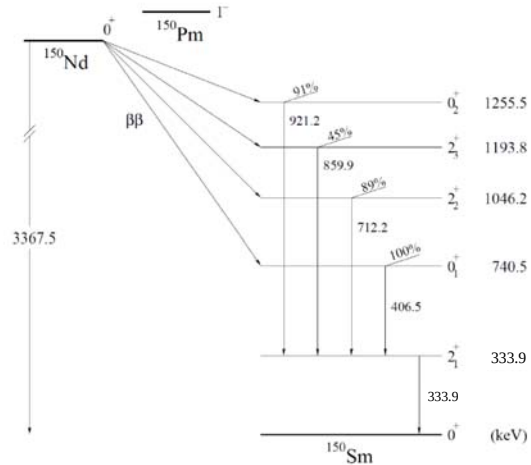


**Figure 2.26: Level scheme of  $^{150}\text{Nd}$   $\beta\beta$  decay to higher excited states of  $^{150}\text{Sm}$ .**

The next case is the  $2_3^+ \rightarrow 2_1^+ \rightarrow 0_{gs}^+$  transition, which proceeds through the emission of a 859.9 keV  $\gamma$  ray in coincidence with the 333.9 keV  $\gamma$  ray. The accumulated data are shown in Fig. 2.27 (c.) and (d.). The  $\epsilon_{\gamma\gamma}$  for this transition is  $(0.275 \pm 0.014)\%$ , and the branching ratio is 45%. The background is 0.8 counts per keV. In spectrum (b.), another coincidence peak

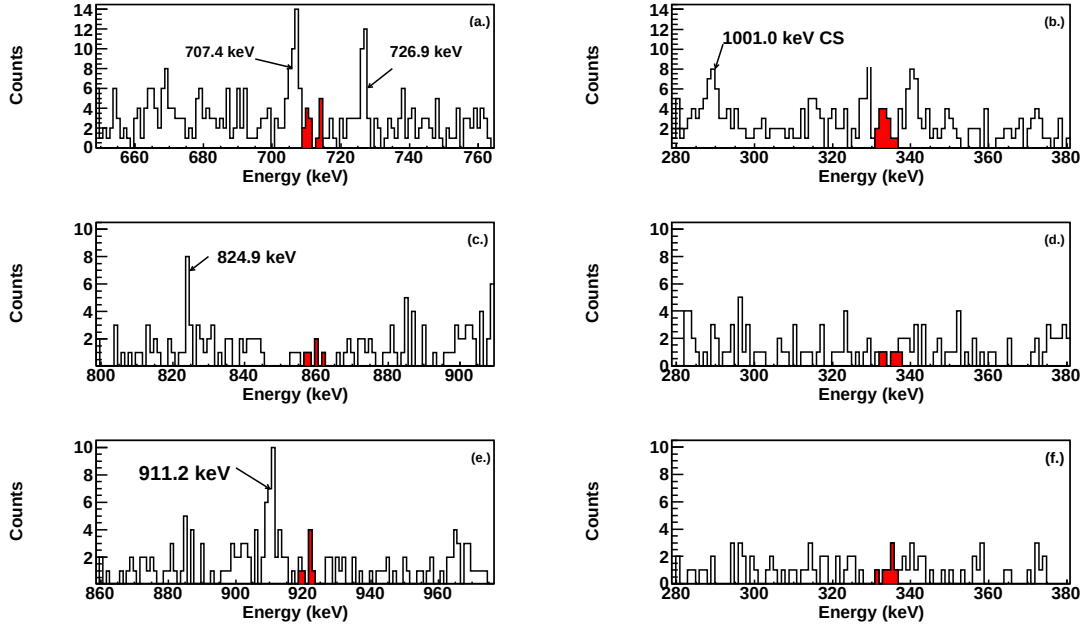


Figure 2.27: Coincidence data for the higher excited states. Spectra (a.) and (b.) are in coincidence with 333.9 keV and 712.2 keV, respectively, (c.) and (d.) are in coincidence with 333.9 keV and 859.9 keV, respectively, and (e.) and (f.) are in coincidence with 333.9 keV and 921.2 keV, respectively. The coincidence-energy window is  $\pm 3.0$  keV.

associated with the 332.0 keV  $\gamma$  ray in the decay of  $^{228}\text{Ac}$  can be seen at 824.9 keV. With 5 counts in the region of interest, a positive signal is not detected. The half-life limit is found to be  $T_{1/2} > 8.28 \times 10^{19}$  y.

Finally, the transition  $0_2^+ \rightarrow 2_1^+ \rightarrow 0_{gs}^+$  proceeds through the emission of a 921.1 keV  $\gamma$  ray in coincidence with the 333.9 keV  $\gamma$  ray. The accumulated data are shown in Fig. 2.27 (e.) and (f.). The  $\epsilon_{\gamma\gamma}$  for this transition is  $(0.595 \pm 0.030)\%$ , and the branching ratio is 91%. The background is 0.8 counts per keV. The only peak in this spectrum is at 911.0 keV which is a CSC peak. With 7 counts in the region of interest a positive signal is not detected. The half-life limit is found to be  $T_{1/2} > 1.48 \times 10^{20}$  y.

The limits determined here were also mea-

sured by Barabash *et al.* [Bar09], and their limits are about an order of magnitude better than those from the present work. Roughly, this can be accounted for by comparing the exposure time  $\times$  efficiency for each transition in Ref. [Bar09] and the present work. Their exposure is 1732 kg-h, compared to about 509 kg-h in the present experiment. In addition, the efficiency in a singles experiment is considerably higher than in a coincidence measurement.

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[Bar09] A. S. Barabash *et al.*, eprint arXiv:0904.1924v1, 2009.

[Par09] Particle Data Group, *Probability Review*, <http://pdg.lbl.gov/2009/reviews/rpp2009-rev-probability.pdf>, 2009.

### 2.1.14 Background Sources Observed in Long-Duration Counting of an Enriched Sample of $^{150}\text{Nd}$

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**We report the backgrounds observed over 529 days of counting an enriched  $^{150}\text{Nd}$  sample with high-purity germanium detectors in coincidence. Such information is valuable for other low-background experiments, especially those involving  $^{150}\text{Nd}$ .**

In the measurement reported in Sect. 2.1.12, a neodymium sample enriched to 93.60%  $^{150}\text{Nd}$  was counted for 529 days in order to observe the two-neutrino double-beta decay. Such a long counting period also leads to observation of background radiation that is not always seen in high count rate systems. This radiation, both natural and due to source enrichment, can be a problem for other low-background experiments involving  $^{150}\text{Nd}$ , such as the next phase of the Solar Neutrino Observatory (SNO), called SNO+.

All materials, unless processed to remove them, naturally contain some amount of potassium, thorium, and uranium, all of which have isotopes that contribute to natural background radiation. Since the TUNL-ITEP (Institute for Theoretical and Experimental Physics)  $\beta\beta$ -decay setup is located in a limestone mine, typical concentrations of these isotopes in limestone are listed in Table 2.2.

Radon can also be a worrisome contaminant as it is a gas and can plate out on surfaces in the detector setup.  $^{220}\text{Rn}$ ,  $^{222}\text{Rn}$ , and  $^{219}\text{Rn}$  are byproducts of natural decay chains and have half lives of 55.6 s, 3.82 d, and 3.92 s, respectively.  $^{220}\text{Rn}$  is also definitely present in the sample due to  $^{232}\text{Th}$  contamination; any decay-chain contamination from  $^{220}\text{Rn}$  is in addition to the sample contamination. It is unlikely that there will be noticeable contamination from  $^{219}\text{Rn}$  because the concentration of its parent,  $^{235}\text{U}$ , is substantially smaller than that of the parent of  $^{222}\text{Rn}$ .

Evidence of  $^{222}\text{Rn}$  is found by detecting  $\gamma$ -ray emissions from its daughters, specifically in the  $\beta^-$  decay of  $^{214}\text{Bi}$  to  $^{214}\text{Po}$ . In Fig. 2.28, the characteristic 609.320 keV  $\gamma$ -ray emission was monitored over time. The decay rate seen in the detector was corrected for the  $\gamma$ -ray intensity of 45.49%. The radon contamination does not lead to specific coincidence events in the regions of interest, but it does produce some  $\gamma$  rays uncom-

fortably close to the region of interest (ROI). It also increases the Compton continuum and thus the constant background in the ROI.

**Table 2.2:** Typical concentrations of naturally occurring radioactive isotopes in limestone [The96].

| Nuclide           | Radiation (Bq/kg) |
|-------------------|-------------------|
| $^{40}\text{K}$   | 90                |
| $^{238}\text{U}$  | 27                |
| $^{232}\text{Th}$ | 7                 |

In the experiment described in Sect. 2.1.12, detection of a coincidence between 333.9 keV and 406.5 keV  $\gamma$  rays indicated an event. Thus, the most important backgrounds are those which can mimic that event. In the  $^{238}\text{U}$  decay chain, the metastable state of  $^{234m}\text{Pa}$ , which  $\beta^-$  decays to  $^{234}\text{U}$ , produces a weak  $\gamma$  ray with energy 742.8 keV and intensity 0.11%. This  $\gamma$ -ray transition is notable because it can Compton scatter directly into the ROI.

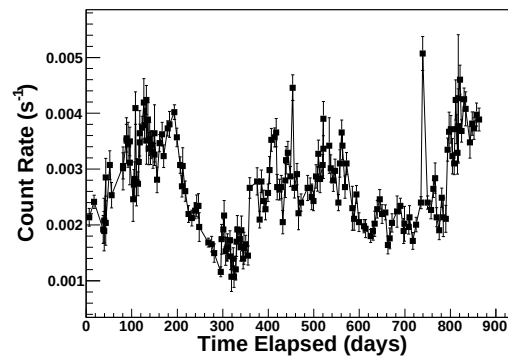


**Figure 2.28:** The radon contamination measured in decays of  $^{214}\text{Bi}$  starting from April 2008. The seasonal dependence is especially noticeable.

In the  $^{234}\text{U}$  decay chain, though a multitude of  $\gamma$  rays is produced, those which interfere with the ROI include those associated with the  $\beta^-$  decay of  $^{214}\text{Bi}$  to  $^{214}\text{Po}$ . Their energies and abundances are 333.37 keV (0.065%), 334.78 keV (0.018%), 405.72 keV (0.169%), and 768.4 keV (4.895%). Because neither of the transitions accompanied by the  $\gamma$  rays near 333.9 keV occur in coincidence with the one at 405.72 keV, they are not expected to contribute to the regions of interest. The 768.4 keV  $\gamma$  ray, however, can Compton scatter into the ROI. [Nat09].

The largest source of background from a natural decay chain is the  $^{150}\text{Nd}$  sample itself. This sample was leased from Oak Ridge National Laboratory (ORNL) where it was enriched in the calutrons. The enrichment process also resulted in a contamination of  $^{232}\text{Th}$  decay products. This contamination manifests itself in a multitude of  $\gamma$ -ray emissions from the  $\beta^-$ -decay of  $^{228}\text{Ac}$  to  $^{228}\text{Th}$ . Three of these characteristic  $\gamma$ -ray emissions are in close proximity to the ROI of the 333.9–406.5 keV coincidence. Their energies and intensities are 328.000 keV (2.95%), 338.320 keV (11.27%), and 409.462 keV (1.92%) [Nat09], though none of these  $\gamma$ -ray energies occur in coincidence with each other. However, the 328.000 keV and the 338.320 keV  $\gamma$  rays do appear as excesses of counts to the left and right of the ROI at 333.9 keV.

Further down the  $^{232}\text{Th}$  decay chain, the  $^{212}\text{Bi}$   $\beta^-$  decay to  $^{212}\text{Po}$  produces a 727.3 keV  $\gamma$  ray at 6.67% intensity which can create a Compton scattering peak near the ROI. This decay chain can also contribute to the areas surrounding the regions of interest via true coincidences which will form peaks in the one-dimensional summed event spectrum. Because the statistics are so low, and the intensities of these coincidences often so small, it is difficult to verify that they explain any excesses of counts in the areas around the ROI.

A rare-earth contaminant that has been found in this  $^{150}\text{Nd}$  sample is  $^{152}\text{Eu}$ . Europium forms the same oxide structure as neodymium,  $\text{Eu}_2\text{O}_3$ , and  $^{152}\text{Eu}$   $\beta^-$  decays to  $^{152}\text{Gd}$  and emits (among others) a  $\gamma$  ray at 344.3 keV (26.6%) in coincidence with a  $\gamma$  ray at 411.1 keV (2.24%). The energy cut that defines the 406.5 keV ROI includes part of the tail of this coincidence, which thus appears in the two-dimensional spectrum. This seems to account for an excess of counts near 344 keV.

The background discussed above cannot be removed; its contribution in and around the ROI

must be understood. The first natural background lines to be discussed are the 742.8 keV  $\gamma$  ray emitted in the decay of  $^{234m}\text{Pa}$ , the 768.4 keV  $\gamma$  ray emitted in the decay of  $^{214}\text{Bi}$ , and the 727.3 keV  $\gamma$  ray emitted in the decay of  $^{212}\text{Bi}$ .

Examining the singles spectrum near these energies, it is apparent that the 742.8 keV full-energy peak is substantially smaller than the surrounding 727.3 keV and 768.4 keV full-energy peaks. If the one-dimensional coincidence spectrum is then examined, the “full-energy Compton-scattering peaks” (i.e. peaks in the coincidence spectrum due to a full-energy  $\gamma$  ray depositing part of its energy in one detector in one region of interest and the rest in the other detector) attributed to 727.3 keV and 768.4 keV can be identified. By comparing the intensity of these peaks to the intensity of the full-energy singles peak, it can be seen that the 742.8 keV full-energy Compton-scattering peak would not contribute above background in the ROI.

The other background that contributes in the areas surrounding the ROI for 333.9 keV are the  $\gamma$  rays emitted in the decay of  $^{228}\text{Ac}$  to  $^{228}\text{Th}$ . These have energies of 328.000 keV and 338.320 keV. They contribute in the ROI when the full energy of a  $\gamma$ -ray transition is deposited in one detector in coincidence with a Compton-scattered  $\gamma$  ray in the other detector that does not deposit its full energy. Thus an excess of counts at 328.000 and 338.320 keV can occur.

It must then be considered whether a peak can be expected in the other one-dimensional spectrum from a Compton-scattering coincidence with the 409.5 keV peak in the decay of  $^{228}\text{Ac}$  to  $^{228}\text{Th}$ . It can be found that 2.9% of all such decays proceed in coincidence with the 328.000 keV transition and with energies large enough to Compton scatter into the 406.5 keV ROI. Similarly, the percentage of decays in coincidence with the 338.320 keV transition is 2.3%, and for the 409.5 keV transition it is only 0.26%. Thus, it makes sense that the excesses of counts in the 328.000 keV and 338.320 keV areas are of a comparable size, and it can be deduced that only one-tenth of that number of counts are expected at 409.5 keV.

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[Nat09] National Nuclear Data Center, *Chart of the Nuclides*, 2009.

[The96] P. Theodórsson, *Measurement of Weak Radioactivity*, World Scientific, Singapore, 1996.

## 2.2 Tritium $\beta$ Decay

### 2.2.1 The Karlsruhe TRItium Neutrino (KATRIN) Experiment

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**The Karlsruhe TRItium Neutrino (KATRIN) experiment will directly probe absolute neutrino masses via precise observations of the decay kinematics of nuclear  $\beta$  decay. Construction of the apparatus is proceeding, with full data-taking expected in 2012. An operational data-acquisition system has been developed and is being used for focal-plane-detector commissioning (Seattle) and pre-spectrometer testing (Karlsruhe). Detailed studies are also underway of the electron transport properties of the apparatus.**

The Karlsruhe TRItium Neutrino (KATRIN) experiment, a next-generation tritium  $\beta$ -decay experiment with a sensitivity to sub-eV neutrino masses, is being constructed at the Karlsruhe Institute of Technology (KIT), in Karlsruhe, Germany [Ott08, Rob08]. KATRIN employs a 10 m diameter solenoidal retarding electrostatic spectrometer ( $\Delta E = 0.93$  eV) coupled to a windowless gaseous molecular tritium source. After 5 years of data-taking, KATRIN expects to reach an estimated sensitivity of  $m_\beta = 0.20$  eV (90 % C.L.) and have a discovery potential ( $5\sigma$ ) of 350 meV. Here  $m_\beta$  is the neutrino mass determined from  $\beta$ -decay measurements in the quasi-degenerate region. Full data-taking is expected to commence in 2012.

The TUNL group is responsible for one of the major KATRIN tasks, data acquisition (Task 50). Figure 2.29 provides an overview of the controls and data-acquisition systems for KATRIN. Basic machine control is implemented with programmable logic controllers (PLCs), in order to ensure secure operation of the tritium material and source. The physics monitoring and control system, which is independent of the PLC system, provides system monitoring, direct control and acquisition of physics data, and an interface to the slow control systems. There are two applications: ZEUS for slow control and ORCA for fast detector readout. The ZEUS system, developed by collaborators at KIT, is implemented in LabVIEW and integrates various PC-based controllers. The Object-oriented Real-time Control and Acquisition (ORCA) data-acquisition system (DAQ), developed and supported by UNC [How08], is responsible for controlling and read-

ing out the focal-plane detector and veto electronics, while creating a data stream that is merged with the information from the slow controls system.

The DAQ is capable of taking data from the 148-pixel detector at rates that vary from mHz (neutrino running) to MHz (calibration), as well as from a separate 32 channel veto system that runs at hundreds of Hz. All fast signals are digitized and recorded using an electronics design from the Institut für Prozessdatenverarbeitung und Elektronik (IPE). The hardware incorporates extensive field-programmable gate arrays (FPGAs) that allow acquisition either in an event-by-event mode or with fast histogramming of data at very high rates.

The following is a brief summary of highlights and accomplishments during the past year. More detailed sections follow.

- *Data Acquisition:* This past year we worked with collaborators at IPE at KIT to implement full support of a new version of the electronics system that will be used to read out the segmented PIN-diode focal-plane detector. The new Mark 4 version of the hardware, consisting of first level trigger cards, a second level trigger card, and a custom 6U crate and power supply, was delivered from KIT to UNC in the fall of 2009. Initial work concentrated on shaking down the FPGA firmware, the ORCA software, and the various acquisition modes. The operational system was shipped to Seattle in the winter of 2010, where it is now being used for commissioning of the focal-plane detector.

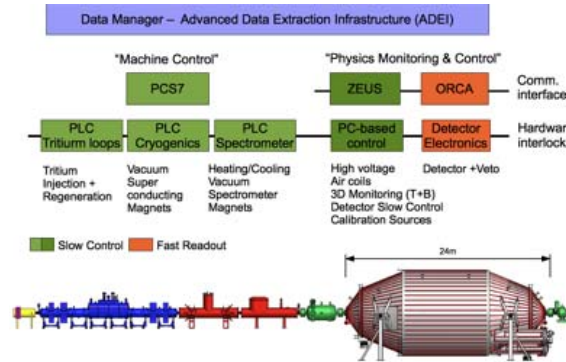


Figure 2.29: (color online) The KATRIN apparatus and schematic view of the experimental control and data acquisition systems.

- *IPE Hardware Verification:* We are undertaking a careful validation of the operation of the KATRIN Mark 4 hardware system (see Sect. 9.4.3). In addition to the system now in Seattle, a small mini-crate Mark 4 system is being used at UNC to facilitate these tests. Thus far the system has been shown to meet the specifications needed for the experiment.
- *EMD Main Spectrometer Tests:* We are working towards providing a fully integrated DAQ system for the electromagnetic design (EMD) tests of the main spectrometer scheduled for 2011. A number of requested run-control and scripting capabilities have been added and are currently in use as part of the focal-plane-detector commissioning taking place in Seattle (see Sect. 9.4.1).
- *Data Structure and Database:* We are working with collaborators at Münster and IPE to define the database that will be used by KATRIN. This activity involves a number of major groups, including the DAQ, detector, slow controls, simulations, and analysis groups. Implementation of the database is proceeding, following guidelines developed and agreed to this past year.
- *Focal-Plane-Detector and Veto-Detector Commissioning:* Working in collaboration with the UW and MIT groups, we are involved in the focal-plane-detector commissioning activities, and assisting where needed in the commissioning process. In addition to providing off-site DAQ support, we have made multiple trips to UW to facilitate the commissioning process. We are also working with KIT and MIT to develop and implement FPGA support for the Veto detector.
- *Simulations:* Detailed electromagnetic field calculations are being developed to facilitate our understanding of potential backgrounds to the observed signal (see Sects. 2.2.3 and 2.2.2).

[How08] M. Howe, M. Marino, and J. Wilkerson, In *Nuclear Science Symposium Conference Record, NSS '08. IEEE*, pp. 3562–3567, 2008.

[Ott08] E. W. Otten and C. Weinheimer, *Rep. Prog. Phys.*, **71**, 086201 (2008).

[Rob08] R. G. H. Robertson and KATRIN Collaboration, *J. Phys. Conf. Ser.*, **120**, 052028 (2008).

## 2.2.2 Automated Penning Trap Searches in the KATRIN Experiment

T.J. CORONA, J.F. WILKERSON, *TUNL*

A possible background in the Karlsruhe TRitium Neutrino (KATRIN) experiment is from electric breakdown due to Penning discharge, where a charged particle confined within a Penning trap (a potential well along a magnetic field line) ionizes residual gas molecules. Using simulation tools developed to locate potential Penning traps within a given magnet and electrode configuration, it is possible to characterize and eliminate or minimize this source of background.

The use of high-field ( $\sim 6$  T) magnetics, electrodes held at differing potentials, and large regions of ultra high ( $\sim 10^{-11}$  mbar) vacuum in the KATRIN experiment introduced the possibility that potential wells may exist along the trajectory of a charged particle within the experimental apparatus. These potential wells, known as Penning traps, can trap charged particles, dramatically increasing their path length and, therefore, the probability of ionizing residual gas molecules (known as Penning discharge).

If ions emitted during Penning discharge enter the fiducial region of the KATRIN beamline, they can produce an aperiodic background that is difficult to decouple from the true signal. Additionally, arcing due to Penning discharge causes

fluctuations in electrode potentials and can damage the experimental apparatus. It is for these reasons that it is critical to fully characterize and hopefully minimize the presence of Penning traps within the KATRIN experiment.

Simulation software designed to compute both the electrostatic and magnetostatic fields of complicated electrode, dielectric, and magnet configurations can be used to locate and quantify the dimensions of existing Penning traps within the KATRIN experiment (see Sect. 2.2.3). This information is useful for understanding background signals due to Penning discharge and can also help to alter design configurations to minimize the presence of such traps.

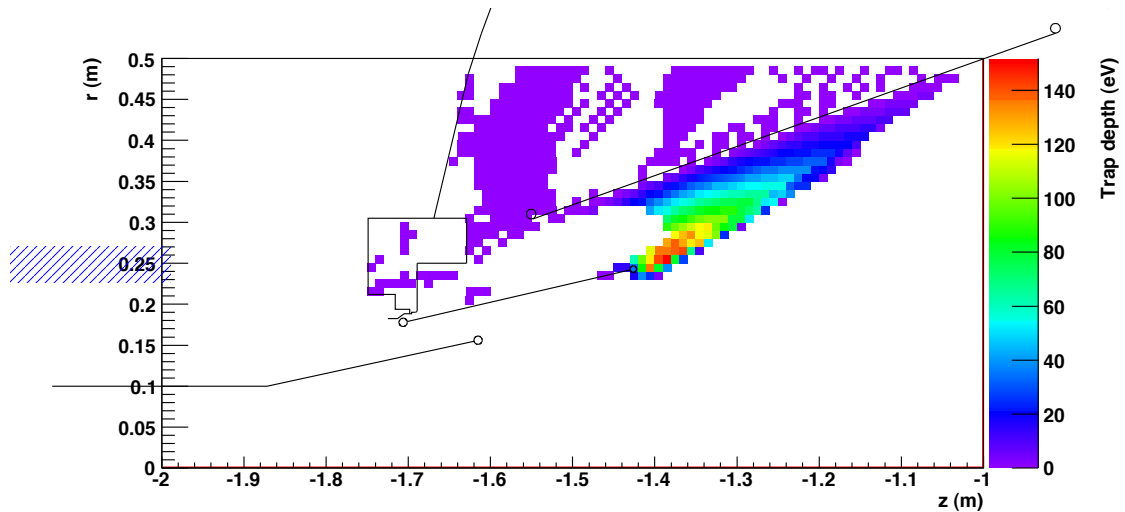


Figure 2.30: (Color online) An example of a graphical representation of a Penning trap in an axially symmetric electrode system. Each point is colored according to the depth (in eV) of the Penning trap at that location, and the electrode geometry is overlaid in black.

The task of developing software to aid in Penning trap characterization is ongoing within the KATRIN experiment, and is led by F. Glück of Karlsruhe Institute of Technology. As techniques for electrostatic and magnetostatic field simulation continue to improve, it becomes possible to apply Penning trap characterization methods to a broader range of geometrical configurations and, as a result, to achieve a more accurate representation of Penning trap characteristics.

Currently, software designed to automate the detection and characterization of Penning traps in an arbitrary electrode, dielectric and magnet configuration is being developed at UNC (see Fig. 2.30). With this tool in place, it will be possible to perform near-online analysis of potential Penning traps due to the most current electrode configurations, allowing operators to inspect potential Penning traps caused by a given electrode configuration as data are being collected.

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### 2.2.3 BEM Techniques for Computing Electric Fields in the KATRIN Experiment

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**The measurement of the  $\nu$  mass in the KARlsruhe TRItium Neutrino experiment requires a thorough understanding of electrostatic fields resulting from complex electrode configurations. The boundary element method is employed to simulate these fields for various geometries, and the recent addition of triangular electrode primitives facilitates the simulation of general three-dimensional geometries.**

Due to the complex interplay of electrostatic and magnetostatic fields in the Karlsruhe TRItium Neutrino (KATRIN) experiment, special care must be taken to precisely understand the electric fields resulting from various electrode configurations. The characterization of these fields is critical for determining the experiment's overall sensitivity to the  $\nu$  mass, as well as for minimizing systematic errors due to such background effects as ionization from Penning discharge.

A suite of tools for simulating electrostatic and magnetostatic fields has been in development at Karlsruhe Institute of Technology, and this code has been ported into C++ and developed further. A critical step in the computation of electrostatic fields is the implementation of the boundary element method (BEM), where the Laplace equation is solved over a discretized surface containing mixed Neumann-Dirichlet boundary conditions. This technique requires an analytic form for the electric potential from a uniformly charged geometry primitive.

Using mathematical techniques based on the work of A. Birtles et. al (Ref. [Bir73]), an analytic form for the electric potential due to a uniformly charged triangle has been developed, allowing for

the use of triangle primitives in the discretization of electrode geometries. The addition of triangular electrodes facilitates the description of a much broader set of three-dimensional geometries and, when used in conjunction with surface meshing algorithms, allows for the computation of electrostatic fields from electrode configurations in an automated fashion.

Since both the accuracy and computation time of the BEM are proportional to the granularity of the boundary discretization, it is helpful to employ multi-threading and grid computing techniques for high-precision measurements of electric fields. To this end, both the OpenMP API and Message Passing Interface (MPI) library specification are used to increase computational efficiency. Measurements for the KATRIN experiment that exploit these features are currently underway using the UNC Topsail computer cluster. Tools for the design and near-online analysis of the KATRIN electrode system based on these techniques are in continued development. A sample discretized representation of KATRIN electrodes is shown in Fig. 2.31.

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[Bir73] A. B. Birtles, B. J. Mayo, and A. W. Bennett, *Proc. IEEE*, **120**, 213 (1973).

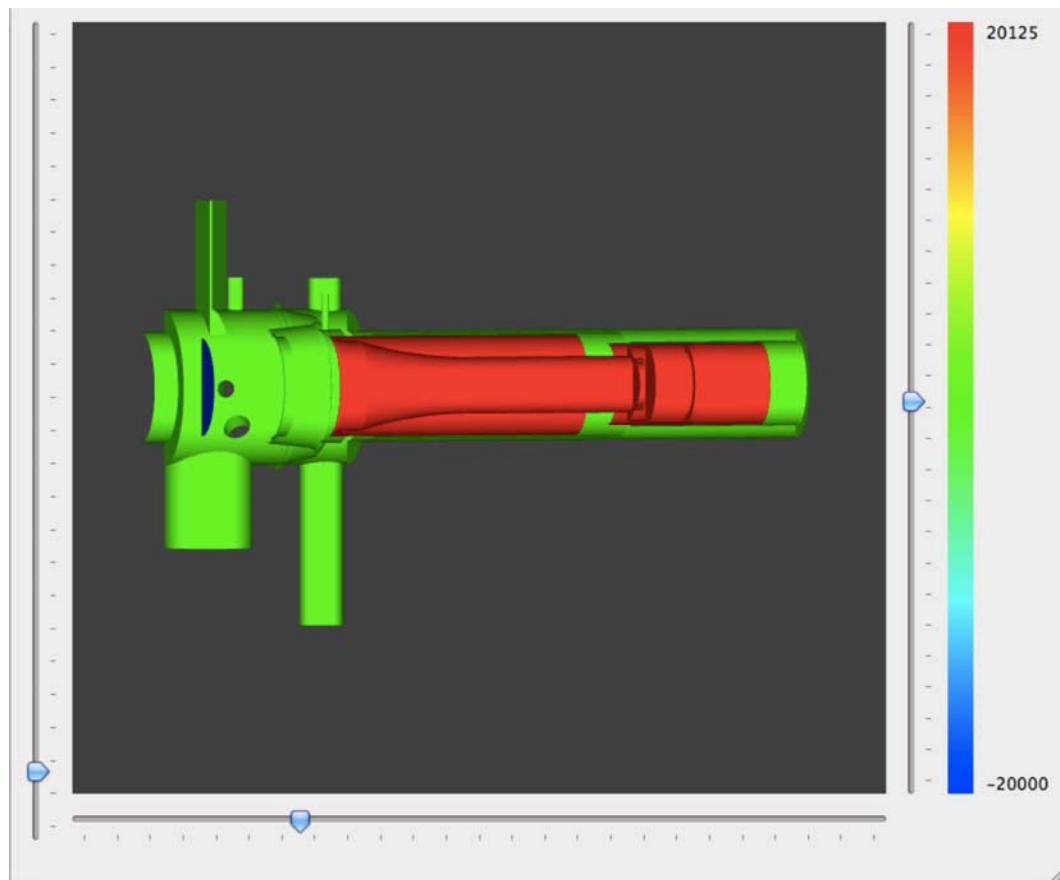


Figure 2.31: (Color online) A discretized representation of the electrodes in the KATRIN internal detector region, colored by electric potential. The geometry is constructed using rectangular and triangular sub-elements.

## 2.3 Dark Matter Search

### 2.3.1 DEAP/CLEAN Activities

M.C. AKASHI-RONQUEST, L.T. EVANS, R. HENNING, G. SWIFT, *TUNL*

**The DEAP/CLEAN project will search for weakly-ionizing-massive-particle (WIMP) dark matter via the observation of nuclear recoils in noble liquids. TUNL activities include construction of the MiniCLEAN calibration system, work on Monte Carlo simulations, and analysis of data from the DEAP-1 prototype detector.**

The DEAP (Dark Matter Experiment using Argon Pulse-Shape Discrimination)/CLEAN (Cryogenic Low Energy Astrophysics with Noble Gases) collaboration's near term goal is to develop a dark-matter detector with a sensitivity to the spin-independent WIMP-nucleon cross section of  $10^{-46}$  cm<sup>2</sup> for a WIMP mass  $M_{\text{WIMP}} \approx 100$  GeV. The DEAP/CLEAN concept is to observe only the scintillation light from the noble liquid target, removing the need for time-projection chambers, which can lower the light yield and make larger-scale experiments a challenge. The ratio of prompt-to-total scintillation light provides an excellent means to discriminate background electrons from signal nuclear recoils. Currently the collaboration is running two smaller R&D detectors: MicroCLEAN and DEAP-1. MicroCLEAN, situated at Yale University, is used to measure the scintillation characteristics of liquid argon (LAr) [Lip08] and liquid neon (LNe) [Nik08] and to study a number of engineering issues. DEAP-1 has been used to further probe pulse-shape discrimination (PSD) in LAr [Bou09]. Having been moved underground to SNOLab, it is about to embark on a preliminary dark-matter search.

Our involvement centers on the next step in the DEAP/CLEAN project: MiniCLEAN. MiniCLEAN will have a sensitivity to the WIMP-nucleon cross section of approximately  $10^{-45}$  cm<sup>2</sup> for  $M_{\text{WIMP}} \approx 100$  GeV when running with a target mass of approximately 500 kg of LAr. In the event of a possible dark matter signal, the target can be exchanged for LNe, which will allow the expected  $A^2$  dependence of the cross section to be probed and will produce very different intrinsic background characteristics. An analytic model of PSD based on DEAP-1 data [Bou09] indicates that MiniCLEAN will be able to completely eliminate the dominant <sup>39</sup>Ar background

via PSD.

In addition to the focus on MiniCLEAN, we are also involved in DEAP-1 operations, analysis and simulations. DEAP-1 is a 7 kg LAr prototype detector developed in order to measure background rejection via PSD to the  $10^{-9}$  level. We also participate in the design and simulation of the DEAP-3600 detector, which will run with 3600 kg of LAr. This experiment is expected to begin taking data in 2011 and should push the sensitivity down to the collaboration's near-term goal. The next logical step would then be the construction of a 10-100 ton dark-matter detector at the Deep Underground Science and Engineering Laboratory. This detector would also be capable of measuring the  $pp$  solar- $\nu$  flux to the 1% level.

#### 2.3.1.1 Calibration System

Our main responsibility is the design and construction of the calibration systems for MiniCLEAN. During the previous year we had pursued the development of an articulated source manipulator that would allow the placement of a source at an arbitrary location within the sensitive volume in order to map out the detector response. After detailed study, we have determined that such a system is too complicated within the current budget constraints. We have developed a more modest calibration program that consists of:

- A transfer-module light-injection system that uses LEDs to inject light directly into the sensitive volume and the PMTs. This will directly determine the PMT responses.
- A dedicated input into the process system for injection of radioisotope spikes into the

cryogen. A candidate isotope that has been studied is  $^{83}\text{Kr}$ .

- Naturally occurring  $^{39}\text{Ar}$  present in the argon.
- Four calibration ports that penetrate the cryostat vacuum volume but not the sensitive volume. Three of these ports will consist of penetrating, insulated tubes that are filled with water from the shield tank. Figure 2.32 shows one of these tubes, and Fig. 2.33 shows the location of the tube within the MiniCLEAN cryostat. The fourth tube will consist of a penetrating insulated tube filled and purged with air, nitrogen, or a similar dry, clean cover gas. Sources will be deployed into these ports via a mechanical winch system from the deck through deployment tubes into the OV nozzles. The sources include standard  $\gamma$ -ray sources and a miniature pulsed DD neutron generator.

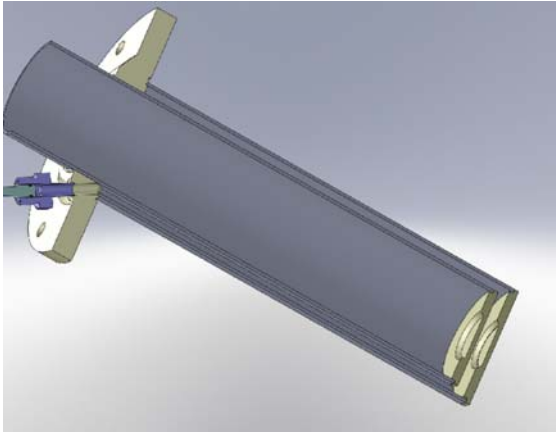


**Figure 2.32:** Concept for calibration port tube. Additional thermal insulation will be wrapped around the outside of the tube and will further mitigate the thermal load from the shield water inside the tube. A VCR fitting and a vacuum pump may be used to create and maintain an insulating vacuum. The tube assembly is about 40 cm in length.

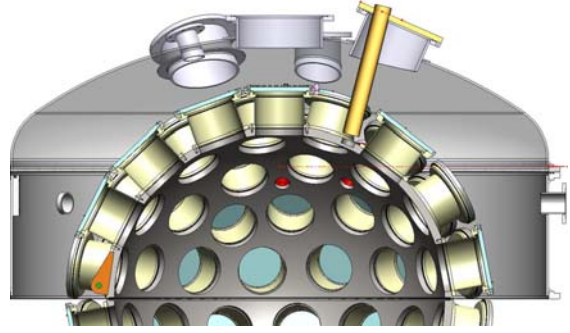


**Figure 2.33:** The calibration tube (yellow, top right) location.

### 2.3.1.2 Other Activities

Another thrust of our research program is the further development of the DEAP/CLEAN Monte Carlo program named RAT, which is, in turn, based on GEANT4 and co-developed by the SNO+ collaboration. Another important aspect of our simulation work is the validation within GEANT4 of neutron transport. This is important in understanding MiniCLEAN's background due to neutron interactions within the liquid cryogen. We have participated in the ongoing validation effort within the collaboration.

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[Bou09] M. G. Boulay *et al.*, arXiv:astro-ph, **IM/0904.2930** (2009).

[Lip08] W. H. Lippincott *et al.*, Phys. Rev., **C78**, 035801 (2008).

[Nik08] J. A. Nikkel *et al.*, Astropart. Phys., **29**, 161 (2008).

### 2.3.2 Searches for Direct Detection of Dark Matter with a MAJORANA Prototype Detector

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**P-type point-contact (P-PC) germanium detectors present an exciting detector technology, yielding sub-keV thresholds and intrinsically-low electronic noise. These characteristics make them sensitive to low-mass WIMPs and axioelectric interactions. Limits on the strength of these processes using data from a P-PC detector deployed at Soudan Underground Laboratory are presented.**

P-type point contact (P-PC) germanium detectors will be used in the MAJORANA DEMONSTRATOR because their low-noise and long charge-drift times make them well suited for background reduction. The low noise of these detectors also allows a very low threshold ( $\sim 0.5$  keV), making them sensitive to low-mass ( $\leq 10$  GeV) weakly interacting massive particles (WIMPs).

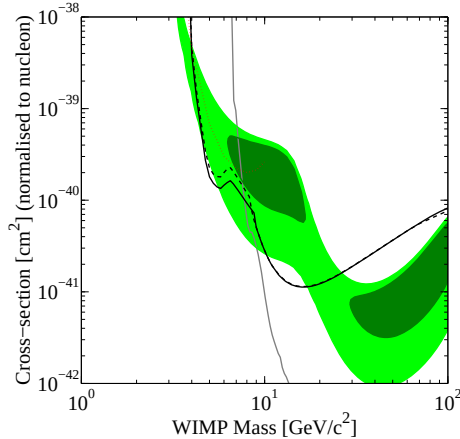


**Figure 2.34:** (color online) Constraints on spin-independent scattering cross sections from various experiments. Limits are calculated at 90% CL. Black lines are from these results with rise-time cuts applied with 95% (dashed) and 70% (solid) acceptance efficiency. Other limits are from CDMS [Ahm09a] (solid grey line) and CoGeNT, which uses a similar P-PC detector [Aal08] (red dotted). The green shaded regions are DAMA/LIBRA acceptance regions at  $3\sigma$  and  $5\sigma$  [Sav09].

ilar to those to be used in the MAJORANA DEMONSTRATOR, was deployed underground at the Soudan Underground Laboratory in Soudan, MN. Care was taken to reduce backgrounds, and some critical components internal to the detector cryostat were replaced with clean versions. This 0.44 kg detector was placed underground in a shielded environment within a 2-inch inner shield of clean Pb from the University of Chicago and an 8-inch outer shield of less radiopure lead, all inside a Rn-exclusion box. For mitigation of neutrons from cosmic-ray interactions in the rock walls of the laboratory,  $\sim 8$  inches of borated polyethylene was placed surrounding the radon-exclusion box. The detector has been taking data underground since December 2009 and has demonstrated a threshold of less than 0.5 keV.

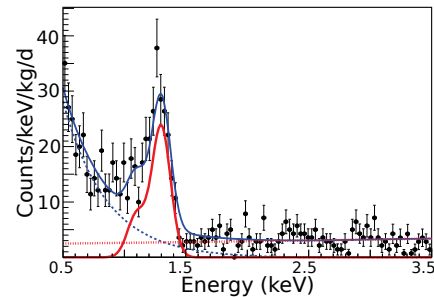


**Figure 2.35:** (color online) Example fit showing an excluded signal at 90% CL from an 8 GeV WIMP (dashed, decreasing blue line) and background components: L-capture lines from  $^{65}\text{Zn}$  and  $^{68}\text{Ge}$  (red solid-line peaks), and an exponential plus flat background (fairly flat red dotted line). The solid blue curve is the overall fit to the data.

A custom P-PC BEGe (broad-energy germanium) detector from Canberra Industries, sim-

Analysis techniques using wavelet de-noising were developed to remove slow-rise-time pulses

arising from poor charge drift and collection due to weak electric fields near the  $n^+$  Li outer contact on the crystal [Aal10]. Because the two-dimensional rise-time vs. energy distribution is *a priori* unknown for slow-rise-time pulses, simulations were used to calculate cuts with different acceptance efficiencies for “good” pulses with fast rise-times. Since it removes events near the outer surface, the cut on slow-rise-time pulses provides an effective fiducial volume cut on the crystal, reducing the active mass to 0.33 kg.

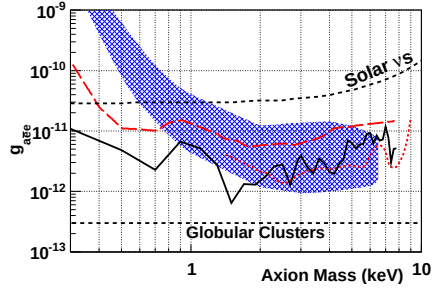


Figure 2.36: (color online) Axioelectric limits from these results (solid black curve) as well as CDMS [Ahm09b] (red dotted) and CoGeNT [Aal08] (red dashed). A corrected interpretation of the DAMA acceptance region [Col09], as well as cosmological limits from solar neutrinos [Gon09] and red giant stars in globular clusters [Raf95] are also shown.

Limits on dark matter interactions, including nuclear recoils from WIMPs and axioelectric interactions from keV-mass axions, have been calculated using data with 150.6 days of live-time. Limits on the spin-independent cross section of WIMP interactions are shown in Fig. 2.34, where current results are compared to those from the CDMS experiment [Ahm09a], past results

from a similar P-PC detector [Aal08], and allowed regions from the DAMA/LIBRA experiment [Sav09]. An example of an exclusion fit to a WIMP signal is shown in Fig. 2.35. Limits on the strength of the axioelectric effect have also been derived from these data and are shown in Fig. 2.36, where they are compared to constraints from other direct detection experiments as well as those from cosmological observations. The DAMA acceptance region is currently disfavored due to considerations of the velocity dependence of the axioelectric interaction [Pos08].

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- [Aal08] C. E. Aalseth *et al.*, Phys. Rev. Lett., **101**, 251301 (2008), Erratum: *ibid.* 102 (2009) 109903.
  - [Aal10] C. E. Aalseth *et al.*, arXiv:1002.4703, (2010).
  - [Ahm09a] Z. Ahmed *et al.*, arXiv:0912.3592, (2009).
  - [Ahm09b] Z. Ahmed *et al.*, Phys. Rev. Lett., **103**, 141802 (2009).
  - [Col09] J. I. Collar and M. G. Marino, arXiv:0903.5068, (2009).
  - [Gon09] P. Gondolo and G. G. Raffelt, Phys. Rev. D, **79**, 107301 (2009).
  - [Pos08] M. Pospelov, A. Ritz, and M. B. Voloshin, Phys. Rev. D, **78**, 115012 (2008).
  - [Raf95] G. Raffelt and A. Weiss, Phys. Rev. D, **51**, 1495 (1995).
  - [Sav09] C. Savage *et al.*, J. Cosm. Astro. Phys., **0904**, 010 (2009).



# Nuclear Astrophysics

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Chapter 3

- Nucleosynthesis in Hydrostatic and Explosive Environments
- $^{26}\text{Al}$  in the Interstellar Medium
- Thermonuclear Reaction Rates

### 3.1 Nucleosynthesis in Hydrostatic and Explosive Environments

#### 3.1.1 Measurement of $^{17}\text{O}(p,\gamma)^{18}\text{F}$ Between the Narrow Resonances at $E_r^{\text{lab}} = 193$ and 519 keV

J.R. NEWTON, C. ILIADIS, A.E. CHAMPAGNE, J.M. CESARATTO, S. DAIGLE, R. LONGLAND, TUNL

The  $^{17}\text{O}(p,\gamma)^{18}\text{F}$  reaction is important to nucleosynthesis in several stellar sites, including classical novae. These are close binary systems which exhibit thermonuclear explosions. The explosions attain temperatures between 0.1 and 0.4 GK, where the thermonuclear reaction rate of  $^{17}\text{O}(p,\gamma)^{18}\text{F}$  is currently believed to be dominated by direct capture. We measured the cross section at six energies between the resonances at  $E_r^{\text{lab}} = 193$  and 519 keV. Our extracted direct-capture cross section differs significantly from previous, less accurate measurements.

Hydrogen burning of  $^{17}\text{O}$  is important for a variety of stellar environments such as red giants, AGB stars, massive stars, and classical novae. The latter occur in a close binary system, where the accretion of hydrogen-rich material onto the surface of a white dwarf results in a thermonuclear explosion. The temperature range of interest in these explosions is  $T = 0.1\text{--}0.4$  GK. Because  $^{17}\text{O}$  represents a major branch point in the CNO cycles, the relative reaction rates for the  $^{17}\text{O}(p,\gamma)^{18}\text{F}$  and  $^{17}\text{O}(p,\alpha)^{14}\text{N}$  reactions are crucial to our understanding of the nucleosynthesis of the oxygen isotopes and the production of radioactive  $^{18}\text{F}$  in these sites [Fox05].

In recent progress reports, we reported on preliminary experimental results. Here, we briefly summarize our final findings. The experiment was carried out at LENA using the JN Van de Graaff to supply protons ranging in energy from  $E_p^{\text{lab}} = 275$  to 500 keV. The targets were made by anodizing 91% enriched  $^{17}\text{O}$  water onto 0.5 mm thick tantalum backings.  $^{18}\text{O}$  targets were also used to calibrate the beam energy and detection efficiencies using the well known  $E_r^{\text{lab}} = 151$  keV resonance in  $^{18}\text{O}(p,\gamma)^{19}\text{F}$ . A lead shield was designed to almost completely surround the large volume HPGe detector by at least 5 cm of lead on all sides. The detector is inserted into the lead shield at an angle of  $55^\circ$  with respect to the incident beam direction at a distance of 3.5 cm from the target. Data were taken at six different energies with this arrangement. Because of the close running geometry, coincidence summing corrections had to be performed

on all spectra.

Results are displayed in Fig. 3.1 and show astrophysical S-factors in the relevant bombarding energy range. Measured *total* S-factors from Refs. [Rol73, Cha07] and from the present work are shown. The data points from Ref. [Rol73] gave rise to the previous estimate of the direct-capture S-factor (dotted line), also from Ref. [Rol73]. The single data point by Chafa et al. [Cha07], obtained via the activation technique, has a rather large uncertainty bar and is not useful for constraining the direct-capture S-factor. The present data clearly show the influence of the tails of two broad resonances at  $E_r^{\text{cm}} = 557$  and 677 keV. Our measured total S-factors can be used to extract the direct-capture contribution. To this end, we subtract the calculated S-factor arising from the two well-known broad resonances from our measured total S factor. The extracted direct-capture S-factor is nearly energy independent and is well described by a constant S-factor below  $E_{\text{cm}} = 500$  keV:  $S_{\text{DC}}(E) = 4.6$  keV b ( $\approx 23\%$ ).

Our extracted direct-capture S-factor disagrees with the result of Rolfs (dotted line) by a factor of  $\approx 2$ . We improved the uncertainty of the direct-capture S-factor from an assumed value of  $\pm 50\%$  in Ref. [Rol73] to an experimental value of  $\pm 23\%$  in the present work. Our results are in good agreement with the predictions of Ref. [Fox05].

This work has now been published. For detailed results, see Ref. [New10]. We are now in the process of performing reaction network simu-

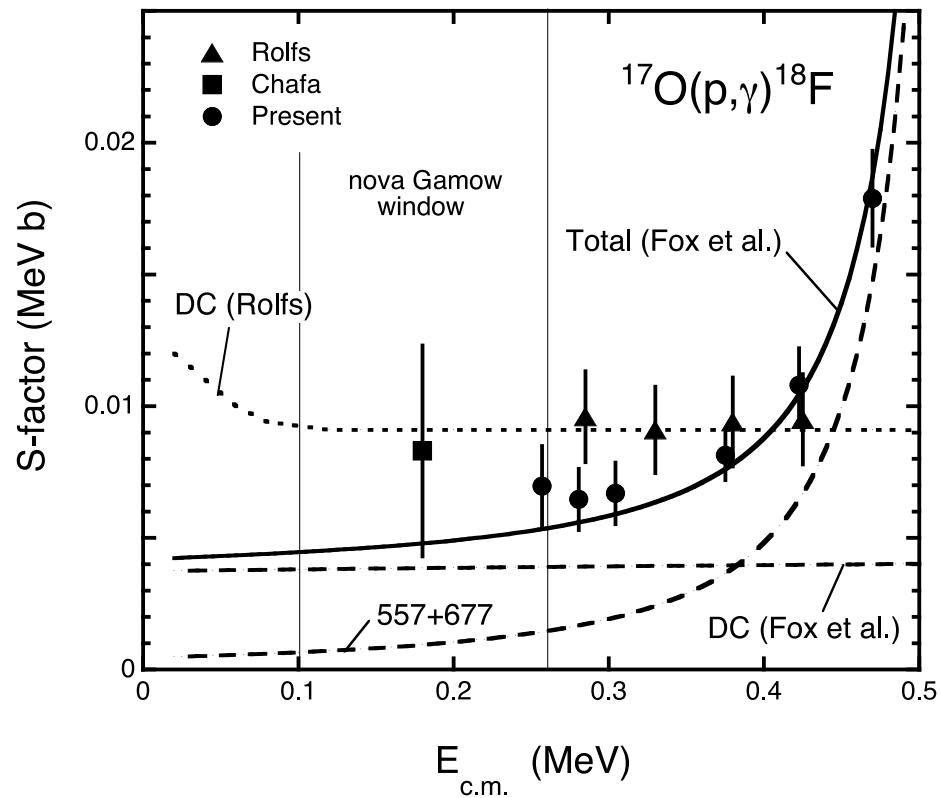


Figure 3.1: Astrophysical S-factors at low energies in  $^{17}\text{O}(p,\gamma)^{18}\text{F}$ . The data from the present work, corrected for efficiencies and coincidence summing, are shown as circles. The two vertical lines mark the energy region of primary interest for classical novae. The dotted line is the prediction of Rolfs [Rol73]. The dashed lines show the direct-capture and resonance contributions from Fox *et al.* [Fox05], and the solid line is their sum.

lations for classical novae using our newly derived [Fox05] C. Fox *et al.*, Phys. Rev. C, **71**, 055801 (2005).  
reaction rates for the  $^{17}\text{O}+p$  reactions.

[Cha07] A. Chafa *et al.*, Phys. Rev. C, **75**, 035810 (2007).

[New10] J. Newton *et al.*, Phys. Rev. C, **81**, 045801 (2010).

[Rol73] C. Rolfs, Nucl. Phys., **A217**, 29 (1973).

### 3.1.2 Resonance Strength in $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$ from Depth Profiling in Aluminum

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TUNL

**A novel method for extracting absolute resonance strengths has been investigated. By implanting  $^{22}\text{Ne}$  ions into a thick aluminum backing and simultaneously measuring the  $^{22}\text{Ne}+p$  and  $^{27}\text{Al}+p$  reactions, the strength of the  $E_r^{\text{lab}} = 479$  keV resonance in  $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$  was determined to be  $\omega\gamma = 0.524(51)$  eV. This result has significantly smaller uncertainties than earlier work. Our results are important for the absolute normalization of resonance strengths in the  $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$  hydrogen-burning reaction and in the  $^{22}\text{Ne}+\alpha$   $s$ -process neutron-source reactions.**

Nuclear reaction rates of many important stellar-burning processes are dominated by resonances in the reaction cross section. In order to improve the accuracy in these rates, recent evaluations [Ili10] have determined resonance strengths relative to a backbone of accurately measured *standard strengths* [Ili07]. Those strengths have been determined relative to elastic scattering, where many systematic effects, such as those from detector efficiency, beam charge, and target stoichiometry, cancel out. Consequently standard resonance strengths measured in this way depend only on the measured count rates and Rutherford scattering cross sections. However, as is apparent from Table 1 in Ref. [Ili01], there are no proposed standard resonance strengths for proton-induced reactions involving noble-gas targets.

The  $^{22}\text{Ne}+p$  reaction is one example, which is important for hydrogen-burning, particularly in the Ne-Na cycle. Many resonance strengths for capture reactions involving noble gases have been measured previously using implanted targets, where in most cases the target backing was a thin tantalum sheet. In reactions such as  $^{22}\text{Ne}+p$ , it is notoriously difficult to obtain absolute strengths because the stoichiometry of the implanted region must be known in order to extract a strength from a thick-target excitation function. There is currently one measured absolute strength in  $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$  corresponding to the  $E_r^{\text{lab}} = 1278$  keV resonance [Kei77]. For this resonance, the stoichiometry of the implanted  $^{22}\text{Ne}$  targets was obtained with Rutherford back-scattering, but the measurement has never been independently verified. In addition,

this resonance is beyond the reach of most low-energy accelerators, necessitating the need for a standard resonance strength at low energy.

Here, we report on an absolute resonance strength measurement of the  $E_r^{\text{lab}} = 479$  keV resonance in  $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$ . The experiment utilizes a target composed of  $^{22}\text{Ne}$  ions implanted into an aluminum substrate. By measuring the well-known  $E_r^{\text{lab}} = 406$  keV resonance in  $^{27}\text{Al}(p,\gamma)^{28}\text{Si}$  and the  $E_r^{\text{lab}} = 479$  keV resonance in  $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$  simultaneously, the absolute strength of the latter resonance can be obtained, independent of the absolute beam current, absolute detector efficiency, or target stoichiometry. Obtaining a resonance strength independent of the target stoichiometry is a significant advantage of this method. Our new method is not specific to  $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$  but could also be useful for other reactions. Note that an accurately measured  $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$  resonance strength will also improve estimates of  $\alpha$ -particle-induced reactions on  $^{22}\text{Ne}$ , since the targets for the latter cases were previously characterized using  $^{22}\text{Ne}+p$  resonances [Gie93].

In brief, we implanted  $^{22}\text{Ne}$  ions into a thick aluminum sheet and measured the yields of the narrow resonances at  $E_r^{\text{lab}} = 406$  keV in  $^{27}\text{Al}(p,\gamma)^{28}\text{Si}$  and at  $E_r^{\text{lab}} = 479$  keV in  $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$  simultaneously. Since the implanted  $^{22}\text{Ne}$  ions are concentrated near the surface of the aluminum sheet, we expect a well-defined peak-shape for the  $^{22}\text{Ne}+p$  yield curve. On the other hand, the  $^{27}\text{Al}+p$  yield curve will reveal an interesting structure. In the pure aluminum region, beyond the implanted  $^{22}\text{Ne}$  depth, the  $^{27}\text{Al}+p$  yield will be at a maximum. How-

ever, in the  $^{22}\text{Ne}$  implanted region the yield will be reduced. Therefore, we expect a step in the excitation function caused by the implanted region near the surface of the target. The general strategy was the following: (i) fit the measured  $^{27}\text{Al}+p$  yield curve, including the step on the front edge, allowing us to extract the stoichiometry; (ii) with the stoichiometry and the absolute yield normalization factor determined from the previous step, fit the measured  $^{22}\text{Ne}+p$  yield curve with the resonance strength in  $^{22}\text{Ne}+p$  left as a free parameter.

All previously measured strengths for the  $E_r^{\text{lab}} = 479$  keV resonance in  $^{22}\text{Ne}+p$  were normalized relative to higher-lying resonances in the same reaction. In our work, we have obtained the resonance strength independently of other resonances in  $^{22}\text{Ne}+p$ , with no dependence on absolute detector efficiencies or absolute beam-charge integration. The result is  $\omega\gamma = 0.524(51)$  eV. We have significantly improved the uncertainty of the resonance strength from the previous value of around 30% [Kei77] to 10%. Our new technique removes any systematic uncertainty due to the target stoichiometry, which is difficult to quantify using traditional methods. It was already mentioned above that our new value for the  $E_r^{\text{lab}} = 479$  keV resonance strength in  $^{22}\text{Ne}+p$  is important in two respects. First, it will reduce the

rate uncertainties of the  $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$  reaction, since the strengths of the low-energy resonances can be renormalized relative to our precisely measured strength for  $E_r^{\text{lab}} = 479$  keV, thus improving predictions of hydrogen-burning nucleosynthesis. Secondly, our precise strength can be used to determine more reliable stoichiometries for implanted  $^{22}\text{Ne}$ -Ta targets, which have been employed in measurements of the important  $s$ -process neutron-source reactions involving  $^{22}\text{Ne}$ .

This work has now been published. For detailed results, see Ref. [Lon10].

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- [Gie93] U. Giesen *et al.*, Nucl. Phys., **A561**, 95 (1993).
  - [Ili01] C. Iliadis *et al.*, Astrophys. J. Suppl., **134**, 151 (2001).
  - [Ili07] C. Iliadis, *Nuclear Physics of Stars*, Wiley-VCH, Weinheim, 2007.
  - [Ili10] C. Iliadis *et al.*, Nucl. Phys., **A841**, 31 (2010).
  - [Kei77] J. Keinonen and M. Riihonen, Phys. Rev. C, **15**, 579 (1977).
  - [Lon10] R. Longland *et al.*, Phys. Rev. C, **81**, 055804 (2010).

### 3.1.3 Target Development for a Measurement of $^{23}\text{Na}(p,\gamma)^{24}\text{Mg}$ at Astrophysical Energies

J.M. CESARATTO, A.E. CHAMPAGNE, T.B. CLEGG, C. ILIADIS, *TUNL*

In preparation for a measurement of the  $^{23}\text{Na}(p,\gamma)^{24}\text{Mg}$  reaction at energies relevant for novae, significant effort was devoted to target development. Sodium was implanted into four different metal backings using an ion implanter located on the UNC campus. In this report we describe the motivation for investigating implanted targets and the characteristics of these targets. The conclusion is that this type of target is inferior to evaporated targets in terms of overall yield and structure.

Low-energy charged-particle reactions important for nuclear astrophysics have exceedingly small cross sections. Measuring these cross sections requires using intense beam currents, high-efficiency detection systems, and isotopically pure targets. The former two requirements are fulfilled at LENA, while the latter can be accomplished at UNC using an Eaton positive-ion implanter. This implanter is capable of producing beams from both gaseous and solid materials. More details about the implanter can be found in [Cot06, Ces09].

A measurement of the expected but unobserved resonance at  $E_R^{\text{lab}} = 144$  keV in  $^{23}\text{Na}(p,\gamma)^{24}\text{Mg}$  prompted the need for high yield, uniform, and stable targets. The decision to pursue implanted  $^{23}\text{Na}$  (hereafter referred to as Na) targets was two-fold. First, previous results [Seu87] for Na implanted into nickel reported both uniform structure and high yield. The authors state that a pure Na layer could be achieved with  $1.1 \times 10^{18}$  atoms/cm<sup>2</sup> at a bombarding energy of 30 keV. Second, a previous study of  $^{23}\text{Na}(p,\gamma)^{24}\text{Mg}$  showed that evaporated targets were not stable under proton beam loads of  $> 50$   $\mu\text{A}$ . Evaporated targets composed of NaCl, NaBr, and Na<sub>2</sub>Ti<sub>3</sub>O<sub>7</sub> all proved to be unstable under such beam loads [Row04]. However, targets evaporated with Na<sub>2</sub>WO<sub>4</sub> proved sufficiently stable for that experiment as well for other experiments [Zij90]. In the previous measurement, typical beam currents on target were limited to 50  $\mu\text{A}$  to minimize target degradation and preserve the life of the target. However, that measurement failed to meet its goal in observing the  $E_R^{\text{lab}} = 144$  keV resonance in  $^{23}\text{Na}(p,\gamma)^{24}\text{Mg}$ . It was determined that more beam current inci-

dent on target was needed in order to boost the signal rate over the background.

It was believed that an increase in beam current would surely cause these evaporated targets to degrade, so implanted targets seemed like a wiser choice to produce more robust targets with high yield. Sodium was implanted into several different backings: Ta, Ni, Cu, and Ni evaporated onto Ta (NiTa). Target backing dimensions (in mm) were 38 x 38 x 0.5 thick. The goal for the thickness of the active target material was 15 keV at a proton energy of 144 keV. Stopping powers from SRIM [Zie08] were used to calculate the necessary dose and energy required for the implant into each target backing. The implanted region had a diameter of 25 mm, as determined by a collimator located 0.5 m upstream in the implanter beam line. Table 3.1 shows a listing of target backing and associated implant parameter for 15 keV thick targets with assumed stoichiometry of 1 to 1 (active to backing). The calculated doses assumed no losses of implanted particles.

**Table 3.1: Backings used for Na implantations with associated Na bombarding energies for 15 keV thick targets (at  $E_p = 144$  keV) and calculated dose assuming a ratio of active to backing atoms of 1:1**

| Backing | $E_b$<br>(keV) | implanted dose<br>( $10^{18}$ ions/cm <sup>2</sup> ) |
|---------|----------------|------------------------------------------------------|
| Ta      | 94             | 0.15                                                 |
| Ni      | 51             | 0.3                                                  |
| Cu      | 54             | 0.3                                                  |

After implantation, the targets were tested for yield (stoichiometry) and uniformity by probing the 309 keV resonance in  $^{23}\text{Na}(p,\gamma)^{24}\text{Mg}$ . Thick-target yield curves (excitation functions) were measured over the thickness of the targets.

Excitation curves of Na implanted into different host backings are shown in Fig. 3.2. For each of these targets, the yield over the implanted region is not uniform. For the Ta and Cu backings, Na seemed to migrate to the surface of the target, whereas for the Ni backing, the migration seemed to be further into the backing. Because of the non-uniform nature of the targets, the stoichiometry of the target changed depending on the depth into the target. At the maximum, the stoichiometry for Na in a Ni backing was Na:Ni = 1:1. In Ta, it is not appropriate to estimate the stoichiometry based on the narrow surface peak. However, the stoichiometry based on the region past the surface peak, was Na:Ta = 1:6.

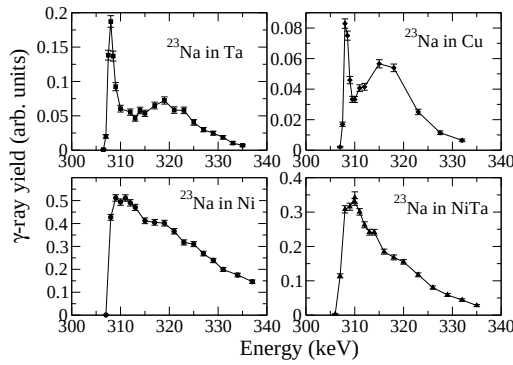


**Figure 3.2:** Thick-target yield curves for the reaction  $^{23}\text{Na}(p,\gamma)^{24}\text{Mg}$  at  $E_r = 309$  keV. Sodium was implanted into Ta, Cu, Ni, and Ni evaporated onto Ta backings (NiTa). The lines connecting the data points are included to guide the eye.

We tried different methods to obtain the most uniform targets: implanting at different energies and varying the dose. We learned that it was possible to over-implant the targets, actually ending up with less active target material than we started with. Changing energies did not improve

the quality of the implant.

Although the Ni backing produced the best target, we were not able to reproduce the results of Ref. [Seu87]. We were able to reproduce the structure for Na implanted into Ta, which also compared well in structure what is described in a new paper from the University of Washington [Bro09].

Although much effort went into this development, it was ultimately decided that Na-implanted targets would not be suitable for measurement because of the non-uniformity and low yield exhibited for Na implanted into Ni, Ta, Cu, and Ni evaporated onto Ta. Ultimately, we resorted to targets evaporated with  $\text{Na}_2\text{WO}_4$  for the experiment, since these targets were far more uniform, had higher yield, and showed the best resiliency to degradation in previous measurements.

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[Bro09] T. A. D. Brown *et al.*, Nucl. Instrum. Methods, **B267**, 3302 (2009).

[Ces09] J. M. Cesaratto, T. B. Clegg, and A. E. Champagne, TUNL Progress Report, **XLVIII**, 135 (2009).

[Cot06] A. Cotrell and C. Ugalde, TUNL Progress Report, **XLV**, 113 (2006).

[Row04] C. Rowland, Ph.D. thesis, University of North Carolina at Chapel Hill, Chapel Hill, NC, 2004.

[Seu87] S. Seuthe *et al.*, Nucl. Instrum. Methods, **A260**, 33 (1987).

[Zie08] J. F. Ziegler and J. P. Biersack, *SRIM: The Stopping Range of Ions in Matter*, computer program SRIM available at <http://www.srim.org>, 2008.

[Zij90] F. Zijderhand *et al.*, Nucl. Instrum. Methods, **A286**, 490 (1990).

### 3.1.4 Resonant Proton Capture on $^{23}\text{Na}$ at Stellar Burning Temperatures

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The motivation for and details of a new search for the predicted 144 keV resonance in the  $^{23}\text{Na}(p,\gamma)$  reaction at stellar burning temperatures are presented. Measurements were carried out at LENA using twenty times the proton beam current of previous measurements. The data are being analyzed.

Globular clusters are simple stellar populations that are assumed to contain stars of the same age and chemical composition. They have been used as a testing ground for stellar evolution and nucleosynthesis. All galactic globular clusters studied have shown star-to-star elemental variations of light elements (C, N, O, Na, Mg, and Al) in their surface compositions, pointing to the simultaneous operation of the CNO, NeNa, and MgAl cycles of hydrogen burning [Car08]. This is contrary to what is seen in halo field stars, which do not exhibit the extreme elemental variations of globular clusters [Ven06]. There exists a pronounced anti-correlation between O and Na among evolved RGB stars [Kra97] as well as unevolved stars slightly above and below the main sequence turn-off in globular clusters [Gra01]. The origin of these variations is thought to arise either from evolutionary effects within a star—effects involving extra physics beyond standard stellar theory—or from primordial differences in the material from which a star was created.

The  $^{23}\text{Na}+p$  reaction is a branching point where material can be either recycled back into the NeNa cycle with emission of an  $\alpha$  particle, or advanced to the MgAl cycle with emission of a  $\gamma$  ray. The competing reaction rates between the two exit channels determine the most probable path for material to follow. Figure 3.3 shows the ratio of the reaction rates of the two competing exit channels. The uncertainties of the current reaction rate of  $^{23}\text{Na}(p,\gamma)^{24}\text{Mg}$  are dominated by an expected but unobserved resonance at  $E_r^{\text{lab}} = 144$  keV. In the temperature regions for the environments of interest, it is apparent that the rate is uncertain by several orders of magnitude.

An explosive environment where the  $^{23}\text{Na}(p,\gamma)^{24}\text{Mg}$  reaction influences the yields of

other elements is in classical novae. A classical nova is a binary star system comprised of a white dwarf and a main sequence star. As the white dwarf accretes hydrogen-rich material from its companion onto its surface, a thermonuclear outburst occurs. A study completed in Iliadis *et al.* [Ili02] showed that the  $^{23}\text{Na}(p,\gamma)^{24}\text{Mg}$  reaction affects many abundances for ONe core nova models. It has also been thought that classical novae might contribute to the production of  $^{26}\text{Al}$ , since type II supernovae cannot produce the amount detected in the interstellar medium [Pra04].

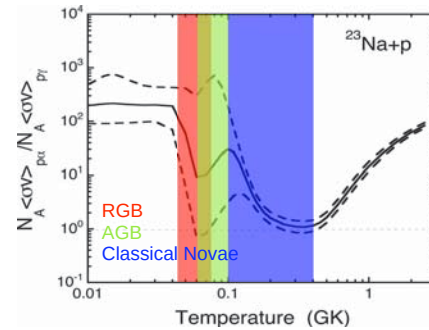


**Figure 3.3:** (Color Online) Current reaction rate ratio for the  $^{23}\text{Na}(p,\alpha)$  and  $^{23}\text{Na}(p,\gamma)$  reactions. The solid line represents the ratio of recommended rates for the two exit channels. The upper and lower dashed lines represent the uncorrelated uncertainties of the rates. The astrophysical sites relevant for this reaction and their associated hydrogen burning temperatures are also shown.

The current upper limit of the resonance strength for this reaction is  $\omega\gamma \leq 0.15$   $\mu\text{eV}$

- [Row04]. A new search for this resonance was conducted at LENA utilizing the high-beam-intensity ECR ion source. The ECR ion source was able to produce >1 mA of proton beam on target, an increase in beam current by a factor of 20 compared to the previous measurement. Results of this measurement are forthcoming.
- 
- [Car08] E. Carretta, *Memorie della Societa Astronomica Italiana*, **79**, 508 (2008).
- [Gra01] R. G. Gratton *et al.*, *Astron. Astrophys.*, **369**, 87 (2001).
- [Ili02] C. Iliadis *et al.*, *Astrophys. J. Suppl. Ser.*, **142**, 105 (2002).
- [Kra97] R. P. Kraft *et al.*, *Astron. J.*, **113**, 279 (1997).
- [Pra04] N. Prantzos, *Astron. and Astrophys.*, **420**, 1033 (2004).
- [Row04] C. Rowland *et al.*, *Astrophys. J.*, **615**, L37 (2004).
- [Ven06] P. Ventura and F. D’Antona, *Astron. Astrophys.*, **457**, 995 (2006).

### 3.1.5 The Effects of Thermonuclear-Reaction-Rate Variations on Nucleosynthesis in Classical Novae

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The effects of thermonuclear-reaction-rate variations on the production of  $^{20}\text{Ne}$ ,  $^{28}\text{Si}$ ,  $^{31}\text{P}$ , and  $^{32}\text{S}$  in classical novae were investigated. To determine the sensitivity of nucleosynthesis to these variations, post-processing nucleosynthesis calculations were performed on temperature-density-time profiles obtained from hydrodynamic nova simulations. The goal of this research is to demonstrate the extent to which nova nucleosynthesis calculations rely on uncertain thermonuclear reaction rates and to guide future measurements.

A classical nova occurs in a binary star system consisting of a main sequence star and a white dwarf. A thermonuclear explosion occurs as a result of accretion of hydrogen-rich material onto the white dwarf. The isotopic abundances observed in nova ejecta are of particular importance for constraining models of stellar evolution and explosion [Sta98, Sta00].

A total of 12,720 nuclear network reaction calculations were performed. Six temperature-density-time profiles of the hottest hydrogen-burning zone were obtained from hydrodynamic nova simulations and used for our calculations. These profiles pertain to white dwarfs primarily composed of oxygen and neon (ONe) with peak temperatures ranging from 0.231 to 0.567 GK and masses from 1.15 to 1.35 solar masses [Ili02]. STARLIB, a new reaction rate library based on a recent evaluation of experimental Monte-Carlo reaction rates, provided most of the recommended reaction rates for 1 MK through 10 GK, the temperature range of this study [Ili10, Lon10].

The post-processing approach used in this research is capable of completing a single network calculation in less than a minute, whereas directly-coupled reaction network and hydrodynamic calculations require significantly more computing time. Decoupling the hydrodynamics and the reaction network effectively ignores convection and its effect on final nova abundances [Ili02]. For this reason, this approach cannot be used to calculate accurate absolute isotopic abundances, but it can be used to obtain quantitative results on abundance changes. Therefore, the recommended rates for 265 reactions were individually multiplied by factors of 0.01, 0.1, 0.2, 0.5, 2, 5, 10, and 100 for each profile. Reaction

rates were analyzed for their impact on the abundances of  $^{20}\text{Ne}$ ,  $^{28}\text{Si}$ ,  $^{31}\text{P}$ , and  $^{32}\text{S}$  by comparing the final abundance of an isotope calculated using the recommended reaction rate with the abundance calculated using the rate multiplied by a factor. The three reactions with the strongest impact on the nucleosynthesis of each of these isotopes are listed in Table 3.2.

Table 3.2: Significant reactions given by isotope.

| Isotope          | Reaction                                 |
|------------------|------------------------------------------|
| $^{20}\text{Ne}$ | $^{20}\text{Ne}(p,\gamma)^{21}\text{Na}$ |
|                  | $^{23}\text{Na}(p,\alpha)^{20}\text{Ne}$ |
|                  | $^{23}\text{Na}(p,\gamma)^{24}\text{Mg}$ |
| $^{28}\text{Si}$ | $^{28}\text{Si}(p,\gamma)^{29}\text{P}$  |
|                  | $^{20}\text{Ne}(p,\gamma)^{21}\text{Na}$ |
|                  | $^{23}\text{Na}(p,\alpha)^{20}\text{Ne}$ |
| $^{31}\text{P}$  | $^{31}\text{P}(p,\gamma)^{32}\text{S}$   |
|                  | $^{28}\text{Si}(p,\gamma)^{29}\text{P}$  |
|                  | $^{30}\text{P}(p,\gamma)^{31}\text{S}$   |
| $^{32}\text{S}$  | $^{28}\text{Si}(p,\gamma)^{29}\text{P}$  |
|                  | $^{31}\text{P}(p,\gamma)^{32}\text{S}$   |
|                  | $^{32}\text{S}(p,\gamma)^{33}\text{Cl}$  |

A sensitivity study for the effects of reaction-rate variations on the isotopes of interest has been completed for reactions resulting in a final abundance change of 20% or more. Currently, the relationships between the isotopic abundances are being investigated, as are the effects that reaction rate changes and peak temperatures have on these relationships. We plan to submit this work for publication by late fall 2010.

[Ili02] C. Iliadis *et al.*, *Astro. J. Suppl. Ser.*, **142**, 105 (2002).

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- [Ili10] C. Iliadis *et al.*, unpublished article, 2010.
- [Sta98] S. Starrfield *et al.*, Mon. Not. R. Astron. Soc., **296**, 502 (1998).
- [Lon10] R. Longland *et al.*, Nucl. Phys., **A841**, 1 (2010).
- [Sta00] S. Starrfield *et al.*, Astro. J. Suppl. Ser., **127**, 485 (2000).

### 3.1.6 Hydrodynamic Models of Type I X-Ray Bursts: Metallicity Effects

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Type I x-ray bursts (XRBs) are thermonuclear stellar explosions driven by charged-particle reactions. In the regime for combined H/He-ignition, the main nuclear flow is dominated by the  $rp$ -process, the  $3\alpha$ -reaction, and the  $\alpha p$ -process. We performed a detailed hydrodynamic study of the nucleosynthesis and nuclear processes powering type I XRBs. In total, 11 bursts have been computed by means of a spherically symmetric (one-dimensional) Lagrangian hydrodynamic code, linked to a nuclear reaction network that contains 325 nuclides (from  $^1\text{H}$  to  $^{107}\text{Te}$ ) and 1392 nuclear processes. These evolutionary sequences, followed from the onset of accretion up to the explosion and expansion stages, have been performed for two different metallicities to explore the dependence between the extension of the main nuclear flow and the initial metal content.

Type I X-ray bursts (XRBs) are cataclysmic stellar events. They are powered by thermonuclear runaways (TNRs) in the H/He-rich envelopes accreted onto neutron stars in close binary systems. These events constitute the most frequent type of thermonuclear stellar explosion in our galaxy, in part because of their short recurrence period (hours to days). About 90 galactic low-mass X-ray binaries exhibiting such bursting behavior have been found since the discovery of XRBs. Type I XRBs and their associated nucleosynthesis have previously been extensively modeled, reflecting the astrophysical interest in determining the nuclear processes that power the explosion, determining the light curve, and providing reliable estimates for the chemical composition of the neutron star surface.

With a neutron star hosting the explosion, the temperatures and densities in the accreted envelope reach high values ( $10^9$  K and  $\rho = 10^6$  g cm $^{-3}$ ). As a result, detailed nucleosynthesis studies require the use of hundreds of nuclides, linked by thousands of nuclear interactions, extending all the way up to the SnSbTe-mass region. Because of computational constraints, XRB nucleosynthesis studies have traditionally been performed using limited nuclear reaction networks. Until recently, it has not been possible to couple hydrodynamic stellar calculations (in one dimension) and detailed networks. This has prompted a detailed analysis of the nuclear activity powering the bursts.

Clearly, the identification of the most relevant reactions in the mass region  $A = 65$ -100 remains

to be addressed in detail within the framework of hydrodynamic simulations. This is particularly relevant since proton captures on heavy nuclei have a dramatic effect on the shape of XRB light curves. To this end, we computed a new set of type I XRBs using a one-dimensional, spherically symmetric, hydrodynamic, implicit, Lagrangian code (see José and Hernanz 1998 [Jos98]). The code has been linked to a fully updated nuclear reaction network containing 324 nuclides and 1392 nuclear processes, including the most relevant charged-particle-induced reactions occurring between  $^1\text{H}$  and  $^{107}\text{Te}$ , as well as their corresponding reverse processes. Experimental rates are available for a small subset of reactions (adopted from Angulo et al. 1999 [Ang99], Iliadis et al. 2001 [Ili01], and some recent updates for selected reactions). For all other reactions for which experimental rates are not available, we used the rates from Hauser-Feshbach codes.

Computations of evolutionary sequences, followed from the onset of accretion up to the explosion and expansion stages, have been performed for two different metallicities to explore the dependence between the extension of the main nuclear flow and the initial metal content. We carefully analyzed the dominant reactions and the products of nucleosynthesis, together with the physical parameters that determine the light curve (including recurrence times, ratios between persistent and burst luminosities, and the extent of the envelope expansion). Results are in qualitative agreement with the observed properties of some well-studied bursting sources. Production

of  $^{12}\text{C}$  (and its implications for the mechanism that powers superbursts) and light p-process nuclei, and the amount of H left over after the bursting episodes have also been investigated.

This extensive work has now been published. For detailed results, see Ref. [Jos10].

(1999).

[Ili01] C. Iliadis *et al.*, *Astrophys. J. Suppl.*, **134**, 151 (2001).

[Jos98] J. Jose and M. Hernanz, *Astrophys. J.*, **494**, 680 (1998).

[Jos10] J. Jose *et al.*, *Astrophys. J. Suppl.*, **189**, 204 (2010).

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[Ang99] C. Angulo *et al.*, *Nucl. Phys.*, **A656**, 3

## 3.2 $^{26}\text{Al}$ in the Interstellar Medium

### 3.2.1 Theoretical Evaluation of the Reaction Rates of $^{26}\text{Al}(n,p)^{26}\text{Mg}$ and $^{26}\text{Al}(n,\alpha)^{23}\text{Na}$

B.M. OGinni, A.E. CHAMPAGNE, C. ILIADIS, *TUNL*;

The reactions that destroy  $^{26}\text{Al}$  have significance in a number of astrophysical contexts. The reaction rates of  $^{26}\text{Al}(n,p)^{26}\text{Mg}$  and  $^{26}\text{Al}(n,\alpha)^{23}\text{Na}$  have been evaluated using cross sections obtained from the nuclear reaction codes *empire* and *talys*. These have been compared with the rates obtained from the *non-smoker* code, the compilation of Caughlan and Fowler, and some experimental data. We show that the results obtained from *empire* and *talys* are comparable and similar to those from *non-smoker*, whereas the rates tabulated in Caughlan and Fowler are systematically lower.

The nucleus  $^{26}\text{Al}$   $\beta$ -decays to the first excited state of  $^{26}\text{Mg}$ , which emits a  $\gamma$  ray of 1809 keV. These  $\gamma$  rays were first detected by the HEAO3 satellite [Mlw84], and also by the Solar Maximum Mission Satellite [Skk85], the Gamma-Ray Imaging Spectrometer [Tbg91], and others. Subsequently, an all-sky image of  $^{26}\text{Al}$   $\gamma$ -ray emission at 1809 keV was derived from the COMPTEL instrument on board the Compton Gamma Ray Observatory [Pds01, Ilc07]. This map provides information about star formation and nucleosynthesis over a time period comparable to the half-life of  $^{26}\text{Al}$  ( $7.17 \times 10^5$  y).

The observed overabundance of  $^{26}\text{Mg}$  in meteorite materials is attributed to the decay of  $^{26}\text{Al}$ , which implies that the latter was present during the formation of the meteorites [Sww07]. Since, meteorites were formed during the early stages of the solar system, this observation should provide information about the last nucleosynthesis events that contributed material to the solar nebula. The abundance of  $^{26}\text{Al}$  depends largely on the reactions which lead to its production and destruction. The main production mechanism in a variety of sites is the  $^{25}\text{Mg}(p,\gamma)^{26}\text{Al}$  reaction, while the main destruction mechanisms at higher temperatures are the  $^{26}\text{Al}(n,p)^{26}\text{Mg}$  and  $^{26}\text{Al}(n,\alpha)^{23}\text{Na}$  reactions [Wwg01].

In this study, we have used the codes *EMPIRE* [Hcc07] and *TALYS* [Khd08] to evaluate the cross sections for the  $^{26}\text{Al}(n,p)$  and  $^{26}\text{Al}(n,\alpha)$  reactions. The cross sections were then used to evaluate reaction rates, which have been compared with the results from *NON-SMOKER* [Rat00, Rat01] and Caughlan and Fowler (here-

after, CF88) [Cfo88].

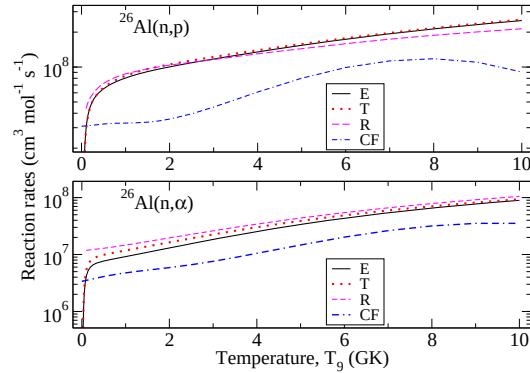


**Figure 3.4:** (Color online) (upper)  $^{26}\text{Al}(n,p)$  reaction rates calculations using *EMPIRE* (E), *TALYS* (T), *NON-SMOKER* [Rauscher] (R) and Caughlan (CF); (lower) similar calculations for  $^{26}\text{Al}(n,\alpha)$ .

In Fig. 3.4, we show the reaction rates for  $^{26}\text{Al}(n,p)^{26}\text{Mg}$  and  $^{26}\text{Al}(n,\alpha)^{23}\text{Na}$  as calculated by the *EMPIRE*, *TALYS*, *NON-SMOKER* codes and as compiled by Caughlan. In the  $^{26}\text{Al}(n,p)$  case, the ratios of the maximum reaction rate to the minimum reaction rate for the *EMPIRE*, *TALYS* and *NON-SMOKER* results were less than a factor of 1.2 at temperatures from 0.2 GK to 10 GK. When the Caughlan results were included, the ratios increased but were still generally less than 2. Similar ratios were determined for  $^{26}\text{Al}(n,\alpha)$  for the *EMPIRE*, *TALYS* and *NON-SMOKER* results.

The ratios varied from 1.7 to 3 between 0.2 GK and 10 GK, but the ratios increased to between 2.5 and 3.4 when the CF88 results were included.

This result indicates that the Caughlan results for these reactions were underestimated, at least when compared with the other reaction codes used in this study. This is a very important observation, because the Caughlan compilations are often used in nucleosynthesis calculations. Koehler *et al.* [Kkv97] made a similar observation. Their measurements of the reaction rates for the  $^{26}\text{Al}(n,\alpha)$  reaction were two to three times larger than the rates given by Caughlan over much of the relevant range of nucleosynthesis calculations. The reaction rates from EMPIRE, TALYS, and NON-SMOKER are about the same factor larger than rates from Caughlan.

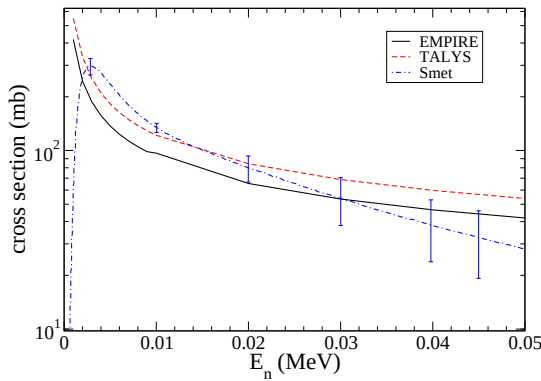


**Figure 3.5:** (Color online) A comparison between the Maxwellian averaged cross section for  $^{26}\text{Al}(n,\alpha_0 + \alpha_1)^{23}\text{Na}$  and calculations using the empire and talys codes.

Only a few experimental data are available for the reactions we studied, and most of them are partial cross sections, i.e., the production cross section for a certain energy level in a nucleus. However, Smet [Sww07] evaluated the Maxwellian averaged cross section for  $^{26}\text{Al}(n,\alpha_0 + \alpha_1)^{23}\text{Na}$ , where 0 and 1 in the  $\alpha$  sub-

script indicate the ground state and first excited state, respectively, of the residual nucleus. We compare those results with our calculations from EMPIRE and TALYS in Fig. 3.5. Though, the data fall within a small energy range, there was consistency between the data and the two theory codes in at least three of the six data points.

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- [Cfo88] G. R. Caughlan and W. A. Fowler, *At. Data Nucl. Data Tables*, **40**, 283 (1988).
  - [Hcc07] M. Herman *et al.*, *Nucl. Data Sheets*, **108**, 2655 (2007).
  - [Ilc07] C. Iliadis, *Nuclear Physics of Stars*, Wiley-VCH, 2007.
  - [Khd08] A. J. Koning, S. Hilaire, and M. C. Duijvestijn, In *Proceedings of the International Conference on Nuclear Data for Science and Technology*, p. 211, 2008.
  - [Kkv97] P. E. Koehler *et al.*, *Phys. Rev. C*, **56**, 1138 (1997).
  - [Mlw84] W. A. Mahoney *et al.*, *Astrophys. J.*, **286**, 578 (1984).
  - [Pds01] S. Pluschke *et al.*, In *Space Debris, Proceedings of the Third European Conference*, volume ESA SP 459, p. 55. European Space Agency, 2001.
  - [Rat00] T. Rauscher and F. Thielemann, *At. Data Nucl. Data Tables*, **75**, 1 (2000).
  - [Rat01] T. Rauscher and F. Thielemann, *At. Data Nucl. Data Tables*, **79**, 47 (2001).
  - [Skk85] G. H. Share *et al.*, *Astrophys. J.*, **292**, L61 (1985).
  - [Sww07] D. L. Smet *et al.*, *Phys. Rev. C*, **76**, 045804 (2007).
  - [Tbg91] B. J. Teegarden *et al.*, *Astrophys. J.*, **375**, L9 (1991).
  - [Wwg01] J. Wagemans *et al.*, *Nucl. Phys.*, **A696**, 31 (2001).

### 3.2.2 The Effects of Thermonuclear Reaction-Rate Variations on $^{26}\text{Al}$ Production in Massive Stars

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**We investigate the effects of thermonuclear reaction-rate variations on  $^{26}\text{Al}$  production in massive stars. The dominant production sites in such events were recently investigated by using hydrodynamic simulations and were found to be explosive neon-carbon burning, convective shell carbon burning, and convective core hydrogen burning. Post-processing nucleosynthesis calculations are performed for each of these sites by adopting temperature-density-time profiles from recent hydrodynamic models. For each profile, we individually multiplied the rates of all relevant reactions by factors of 10, 2, 0.5, and 0.1 and analyzed the resulting abundance changes of  $^{26}\text{Al}$ . Our simulations are based on a next-generation nuclear physics library, called STARLIB, which is partially based on a new evaluation of Monte Carlo reaction rates.**

The radioisotope  $^{26}\text{Al}$  is of outstanding importance for  $\gamma$ -ray astronomy and cosmochemistry. It has been discovered in three distinct sites: (i) the galactic interstellar medium, via detection of its decay emission line at 1809 keV [Mah82, Die95]; (ii) meteorites, via observed excesses of its radioactive-decay (daughter) product  $^{26}\text{Mg}$  [Mac95], implying an injection of live  $^{26}\text{Al}$  into the early solar system nebula; and (iii) presolar dust grains that are uncontaminated by solar system material and thus are of likely stellar origin, again via observed  $^{26}\text{Mg}$  excesses [Hop94, Hus97]. Identification of the main sources of  $^{26}\text{Al}$  would have far-reaching implications, ranging from questions related to the circumstances and conditions of the solar system's birth to imposing strong constraints on the chemical evolution of the galaxy. A number of different sources have been suggested over the years: AGB stars, classical novae, Wolf-Rayet stars, and type II supernovae.

However, the origin of  $^{26}\text{Al}$  remains controversial. The observation of galactic  $\gamma$ -rays from  $^{26}\text{Al}$  is important since it provides unambiguous direct evidence for the theory of nucleosynthesis in stars. The half-life of  $^{26}\text{Al}$  amounts to  $7.17 \times 10^5$  y and is small compared to the time scale of galactic chemical evolution ( $\approx 10^{10}$  y). Consequently, nucleosynthesis is currently occurring in the interstellar medium and, in particular,  $^{26}\text{Al}$  is synthesized throughout the galaxy. From the observed  $\gamma$ -ray intensity, it is estimated that the production rate of  $^{26}\text{Al}$  in the galaxy, depend-

ing on the assumed density distribution, amounts to  $\approx 1 - 3 M_{\odot}$  per  $10^6$  y. The observational evidence in this case favors massive stars as a source. First, the all-sky map of the 1809 keV  $\gamma$ -ray line detected by the COMPTEL instrument onboard CGRO showed that  $^{26}\text{Al}$  is confined along the Galactic disk and that the measured intensity is clumpy and asymmetric; second, the measurement of the 1809-keV-line Doppler shift by the SPI spectrometer onboard INTEGRAL demonstrated that  $^{26}\text{Al}$  co-rotates with the galaxy and hence supports a galaxy-wide origin.

Massive stars may produce  $^{26}\text{Al}$  during several different phases of their evolution: (i) during pre-supernova stages in the C/Ne convective shell, where a fraction of the  $^{26}\text{Al}$  survives the subsequent explosion and is ejected into the interstellar medium; (ii) during core collapse via explosive Ne/C burning; and (iii) in Wolf-Rayet stars, i.e., stars with masses in excess of about  $30 M_{\odot}$ , during core hydrogen burning, where  $^{26}\text{Al}$  may appear via convection at the surface and subsequently be ejected by strong stellar winds. These  $^{26}\text{Al}$  production mechanisms were recently analyzed in detail by Limongi and Chieffi [Lim06] by using extensive hydrodynamic simulations of solar metallicity massive stars. In that work they also emphasized the impact of rate uncertainties for selected reactions on the final  $^{26}\text{Al}$  yields.

In the present work we expand this effort by presenting a comprehensive investigation of the impact of nuclear reaction-rate uncertainties on the synthesis of  $^{26}\text{Al}$ . The general strategy

consists of varying the rates of many reactions by different factors (in this work, 10, 2, 0.5, and 0.1) and analyzing the impact of each individual reaction-rate change on the final  $^{26}\text{Al}$  yields. At present it is not feasible to perform this computationally intensive procedure with a self-consistent stellar model. Instead, we extract a few representative temperature-density-time evolutions from recent hydrodynamic models of massive stars and execute a large number of post-processing reaction-network sensitivity calculations using these profiles. Our goal is two-fold. On the one hand, we would like to quantify to what degree predictions of  $^{26}\text{Al}$  yields depend on currently uncertain nuclear-physics input. On the other hand, by identifying the *most important nuclear reactions*, our results represent a guide for future measurements.

There are a number of novel aspects about the present work. First, we employ a new-generation library, called STARLIB (see Sect. 3.3.1), of nuclear-reaction and weak-interaction rates. This library is partially based on a recent evaluation of experimental Monte Carlo reaction rates [Ili10]. In fact, this work represents the first application of STARLIB. Second, we carefully investigate the equilibration effects of  $^{26}\text{Al}$ . At least two species of  $^{26}\text{Al}$ , the ground state and the isomeric state, take part in nucleosynthesis. In all previous investigations, either a single species or two species of  $^{26}\text{Al}$  were taken into account, depending on whether thermal equilibrium is achieved or not. Obviously, these are two extreme assumptions, and in a hot stellar plasma the ground and isomeric state may *communicate* via  $\gamma$ -ray transitions involving higher-lying  $^{26}\text{Al}$  levels.

Our study has some obvious limitations. Since we perform post-processing calculations, we necessarily focus our investigation on the effects of nuclear reaction rates. In other words, the important effects of convection, mass loss, rotation, and so on are outside the scope of the present work. This also implies that our simulations are unsuitable for defining absolute  $^{26}\text{Al}$  yields. Instead, we claim that our procedure is useful for exploring the effects of  $^{26}\text{Al}$  abundance changes that result from reaction rate variations. We only explore a few temperature-density-time evolutions that are representative of solar metallicity stars. A more comprehensive study covering a broad range of stellar masses and metallicities is also beyond the scope of this work. The present investigation is ongoing, and first results will be presented soon.

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- [Die95] R. Diehl *et al.*, *Astron. Astrophys.*, **298**, 445 (1995).
  - [Hop94] P. Hoppe *et al.*, *Astrophys. J.*, **430**, 870 (1994).
  - [Hus97] G. Huss *et al.*, *Geochim. Cosmochim. Acta*, **61**, 5117 (1997).
  - [Ili10] C. Iliadis *et al.*, *Nucl. Phys.*, **A841**, 31 (2010).
  - [Lim06] M. Limongi and A. Chieffi, *Astrophys. J.*, **647**, 483 (2006).
  - [Mac95] G. MacPherson *et al.*, *Meteoritics*, **30**, 365 (1995).
  - [Mah82] W. Mahoney *et al.*, *Astrophys. J.*, **262**, 742 (1982).

### 3.3 Thermonuclear Reaction Rates

#### 3.3.1 STARLIB: A Next-Generation Reaction-Rate Library for Nuclear Astrophysics

C. ILIADIS *TUNL*

**We have recently completed a new charged-particle thermonuclear-reaction-rate evaluation for  $A = 14$ -40 target nuclei. These results were obtained using an entirely different approach from the one used in previous evaluations. A Monte-Carlo technique was employed, with special emphasis on reliability and the presentation of meaningful reaction-rate uncertainties. This data set represents the backbone of a new kind of reaction-rate library for nuclear astrophysics. The library is presently under construction.**

The reaction-rate library most widely used for stellar model simulations is called REACLIB, originally constructed by F.-K. Thielemann. A number of updated versions exist. Reaction rate libraries such as REACLIB typically contain the rate for nuclear reactions or the decay constant for weak decays on a specified temperature grid. In the particular case of the REACLIB, the information is available as an analytical (fit) expression.

We recently began construction of a new kind of library, called STARLIB. It originated from a previous version of REACLIB that we modified over the years and that was used for all of the reaction network calculations presented in Ref. [Ili07]. At that point in time, several important changes occurred. A recent evaluation of reaction rates for the  $A = 14$ -40 target range was completed and is scheduled for publication in October of 2010 [Ili10]. These 62 *experimental* rates are based on a Monte Carlo technique, described in Ref. [Lon10], allowing for a rigorous statistical definition of recommended reaction rates and their associated uncertainties. The Monte Carlo procedure provides, *for the first time*, for any given temperature the (output) reaction-rate probability-density function that is based on the (input) probability densities of measured nuclear-physics quantities such as S-factors, resonance energies, resonance strengths, and upper limits in spectroscopic factors. From the cumulative distributions of the rate probability densities, a low rate, median rate, and high rate can then be defined as the 0.16, 0.50 and 0.84 quantiles, respectively, assuming a coverage probability of 68%. The meaning of these rates in general differs from the commonly reported, but statisti-

cally meaningless, literature expressions “lower limit,” “nominal value,” and “upper limit” of the total reaction rate. Furthermore, it has been shown [Lon10] that in the majority of cases the Monte-Carlo-rate probability-density function can be approximated by a lognormal distribution, that is determined by only two parameters: the lognormal location parameter  $\mu$  and the lognormal spread parameter  $\sigma$ . The former parameter determines the recommended reaction rate via  $N_A \langle \sigma v \rangle_{\text{rec}} = e^\mu$ , while the latter parameter corresponds to the rate factor uncertainty via  $f.u. = e^\sigma$ .

The information on the rate probability density was not available previously and opens interesting windows of opportunity for Monte Carlo studies of nucleosynthesis and energy generation in stars. However, it becomes clear from the above discussion that three quantities ( $T$ ,  $N_A \langle \sigma v \rangle_{\text{rec}}$ , lognormal  $\sigma$ ) instead of the traditional two ( $T$  and  $N_A \langle \sigma v \rangle_{\text{rec}}$ ) need to be reported, so that the user can calculate the rate probability density for each reaction at each temperature. Therefore, it was decided to convert our 2007 version of the REACLIB, which lists the recommended reaction rates as analytical functions of temperature by employing a number of rate fitting parameters, to a tabular format. The new format consists of three columns and lists for each reaction the temperature, the recommended rate, and the rate factor uncertainty on a grid of 60 temperatures between 1 MK and 10 GK. At this stage, the rate factor uncertainty for each reaction was set equal to a nominal value of 10. In a subsequent step, the rates and factor uncertainties of 62 reactions in the  $A = 14$ -40 region were replaced with their exact Monte Carlo

results. In addition, the rates of the following interactions were replaced with more recent information: (i) 10 Big Bang reactions, using the rates of Ref. [Des03], which were derived from an R-matrix description of the available data; (ii) 30 reactions in the mass range of  $A = 1$ –26 from the NACRE evaluation of experimental rates [Ang99]; (iii)  $(n, \gamma)$  reactions based on the KADoNiS v0.2 evaluation of experimental rates [Dil06]; (iv) a number of special reactions, such as  $^{14}\text{N}(p, \gamma)^{15}\text{O}$  and  $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ ; and (v) 550 experimental rates for  $\beta$  decays and  $\beta$ -delayed particle decays, including associated uncertainties calculated from the half lives and branching ratios compiled in Ref. [Aud03]. All experimental reaction rates were corrected for the effects of thermal target excitations using the stellar enhancement factors and partition functions of Rauscher and Thielemann [Rau00]. For all other reactions for which insufficient experimental information is available to compute reliable experimental rates, the results of statistical model calculations [Rau00] were adopted. The present version of the new library described above extends up to antimony. A number of features still need to be implemented. Publication of this library, which is expected to become the foundation of

many stellar models (e.g., for massive stars, AGB stars and classical novae) is anticipated for the near future.

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- [Ang99] C. Angulo *et al.*, Nucl. Phys., **A656**, 3 (1999).
- [Aud03] G. Audi, A. H. Wapstra, and C. Thibault, Nuclear Physics A, **729**, 337 (2003).
- [Des03] P. Descouvemont *et al.*, At. Data Nucl. Data Tables, **88**, 1 (2003).
- [Dil06] I. Dillmann *et al.*, In *AIP Conf. Proc.*, volume 819, p. 123, 2006.
- [Ili07] C. Iliadis, *Nuclear Physics of Stars*, Wiley-VCH, Weinheim, 2007.
- [Ili10] C. Iliadis *et al.*, Nucl. Phys., **A841**, 31 (2010).
- [Lon10] R. Longland *et al.*, Nucl. Phys., **A841**, 1 (2010).
- [Rau00] T. Rauscher and F.-K. Thielemann, At. Data Nucl. Data Tables, **75**, 1 (2000).



# Few-Nucleon Interaction Dynamics

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Chapter 4

- Sub-Nucleonic Degrees of Freedom
- The  $A=2$  System
- The  $A=3$  System
- Reaction Dynamics of Light Nuclei

## 4.1 Sub-Nucleonic Degrees of Freedom

### 4.1.1 Measurement of Single Target-Spin Asymmetry in Semi-Inclusive Pion Electroproduction on a Transversely Polarized $^3\text{He}$ Target

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A first measurement of single-target spin asymmetry (SSA) from semi-inclusive electroproduction of charged pions from a transversely polarized  $^3\text{He}$  target in deep-inelastic scattering kinematics was completed in Hall A at Thomas Jefferson National Accelerator Facility in early 2009. Such SSAs will allow the extraction of much-desired information on the Collins and Sivers asymmetry from the “neutron” in order to probe the quark transversity distributions. The Medium Energy Group at TUNL has been playing a leading role in this experiment. Preliminary results on the SSAs from  $^3\text{He}$  have been reported at various conferences and workshops this summer. A first paper reporting on these results will be submitted to *Physical Review Letters* in the near future.

There are eight transverse-momentum-dependent distribution functions (TMDs) at leading twist [Mul96, Boe98]. TMDs describe the parton distribution beyond the collinear approximation. They depend not only on the longitudinal momentum fraction  $x$ , but also on the transverse momentum  $k_T$  of the quark. Among these eight TMDs, three survive upon integration over the quark transverse momentum. They are  $f_1$ ,  $g_1$  and  $h_1$ .

After several decades of experimental and theoretical efforts, the unpolarized parton distribution function (PDF),  $f_1(x, Q^2)$ , has been extracted with excellent precision over a large range of  $x$  from deep inelastic scattering (DIS), Drell-Yan, and other processes. In recent years, the longitudinal polarized parton distribution function,  $g_1(x, Q^2)$ , has been determined with significantly improved precision over a large region of  $x$  and  $Q^2$  from polarized DIS experiments. What remains elusive among these three leading-twist parton distribution functions is the transversity function,  $h_1(x, Q^2)$ . In the parton picture, the nucleon transversity distribution describes the net quark transverse polarization in a transversely polarized nucleon. In the non-relativistic limit, the transversity distribution function is the same as  $g_1(x, Q^2)$ . Therefore, the transversity distribution function probes the relativistic na-

ture of the quarks inside the nucleon.

Because of its chiral-odd nature, the experimental determination of transversity requires processes where an additional chiral-odd function is involved. Double-polarized Drell-Yan processes, which involve two transversity distributions, and single target-spin azimuthal asymmetries from semi-inclusive DIS pion electroproduction, in which transversity is convoluted with a chiral-odd fragmentation function, the Collins function [Col93], are two methods to measure transversity. The Collins fragmentation function describes the probability for a transversely polarized quark to fragment into an unpolarized hadron.

Considering the differential cross section in a single-spin semi-inclusive DIS (SIDIS) ( $e, e'h$ ) reaction with a transversely polarized target, the transversity function convoluted with the Collins fragmentation function gives rise to an azimuthal asymmetry in  $\sin(\phi_h + \phi_S)$ , where the azimuthal angles of both the hadron ( $\phi_h$ ) and the target spin ( $\phi_S$ ) are about the virtual photon axis and relative to the lepton scattering plane. Two more leading-twist TMDs contribute to the single-spin azimuthal asymmetry: the Sivers function [Siv91], which gives rise to the azimuthal asymmetry of  $\sin(\phi_h - \phi_S)$  due to the correlation between the nucleon's transverse

spin and the quark's transverse momentum, and the pretzelosity, with a  $\sin(3\phi_h - \phi_S)$  asymmetry in SIDIS, which measures the quark polarization perpendicular to both the transverse polarization of the nucleon [Ava08] and the longitudinal direction. The orthogonal nature of these three azimuthal asymmetries gives them an unambiguous separation in SIDIS. The HERMES Collaboration [tHC05] and the COMPASS Collaboration [tCC05, tCC07, tCC08] reported results on single-spin asymmetries from SIDIS on transversely polarized proton and deuteron targets. The asymmetry related to the Collins fragmentation function and the quark transversity distribution was also measured by the BELLE Collaboration [tBC06] in the  $e^+e^- \rightarrow h_1 h_2 X$  reaction. In order to extract the transversity for the  $u$  and  $d$  quarks, a measurement on the neutron is essential.

The first experiment on the SIDIS neutron single-spin asymmetry using transversely polarized  $^3\text{He}$  finished taking data in February 2009 in Jefferson Lab Hall A. Details on the experimental conditions are given in Ref. [Che09]. Xin Qian, a graduate student from Duke, worked on this experiment for his Ph.D. thesis. He was in charge of the large acceptance BigBite spectrometer. His work included the background study, wire chamber preparation, tracking-related software development, on-line data quality check, wire-chamber alignment, and BigBite optics calibration. The BigBite wire chamber successfully survived from the extreme 60 MHz rate with a 15  $\mu\text{A}$  electron beam, and the optics calibration has reached the design goal. Yi Qiang, a former postdoctoral fellow in our group, also played a key role by leading the polarized- $^3\text{He}$ -target effort for this experiment as well as for a number of experiments employing the polarized  $^3\text{He}$  target after the neutron

transversity experiment. Since the experiment, both Yi and Xin have been actively involved in the data analysis, with Xin leading the overall analysis effort of the entire collaboration. Recently, Xin successfully defended his Ph.D. thesis based on his work on this experiment. Xin is also the lead author on the first paper from this experiment on SSAs, which will be submitted to Physical Review Letters this year.

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- [Ava08] H. Avakian *et al.*, Phys. Rev., **D78**, 114024 (2008).
  - [Boe98] D. Boer and P. Mulders, Phys. Rev., **D57**, 5780 (1998).
  - [Che09] W. Chen *et al.*, TUNL Progress Report, **XLVIII**, 53 (2009).
  - [Col93] J. Collins, Nucl. Phys., **B396**, 161 (1993).
  - [Mul96] P. Mulders and R. Tangerman, Nucl. Phys., **B461**, 197 (1996).
  - [Siv91] D. Sivers, Phys. Rev., **D43**, 261 (1991).
  - [tBC06] the Belle Collaboration, Phys. Rev. Lett., **26**, 232002 (2006).
  - [tCC05] the COMPASS Collaboration, Phys. Rev. Lett., **94**, 202002 (2005).
  - [tCC07] the COMPASS Collaboration, Nucl. Phys., **B765**, 31 (2007).
  - [tCC08] the COMPASS Collaboration, Proceeding for Transversity 2008 Workshop, Ferrara, (2008).
  - [tHC05] the HERMES Collaboration, Phys. Rev. Lett., **94**, 012002 (2005).

## 4.2 The A=2 Systems

### 4.2.1 Final Neutron-Proton Analyzing Power Data at $E_n=7.6$ MeV

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**We present new corrections for the polarization dependent efficiency of previously reported  $n$ - $p$   $A_y(\theta)$  data at 7.6 MeV. These data indicate that only "complete" angular distributions of  $A_y(\theta)$  data provide a stringent test of phase-shift analysis and nucleon-nucleon potential model predictions. They confirm our earlier conclusion that an accurate determination of the low-energy  ${}^3P_j$  nucleon-nucleon interactions has not been achieved yet.**

The motivation for collecting high-precision neutron-proton ( $n$ - $p$ ) analyzing power,  $A_y(\theta)$ , data is to test the accuracy of nucleon-nucleon (NN) phase-shift analysis (PSA) predictions for this observable. PSA results are often the database for fitting NN potential models parameters. At low energies, the  $n$ - $p$   $A_y(\theta)$  is very small, typically well below 1%, and it depends greatly on the  ${}^3P_0$ ,  ${}^3P_1$  and  ${}^3P_2$  NN phase shifts. The high-precision data of Holslin *et al.* [Hol88] at  $E_n=10.03$  MeV are in very good agreement with the Nijmegen PSA results [Sto93]. However, the Holslin *et al.* data set contains only one datum at angles below  $65^\circ$  c.m., while the more accurate data of Braun *et al.* [Bra08] at 12.0 MeV extend all the way down to  $30^\circ$  c.m., where considerable discrepancies have been observed between the PSA predictions of the Nijmegen group and the experimental data. This observation indicates that only "complete" angular distributions of the  $n$ - $p$   $A_y(\theta)$ , including sufficient forward angle data points, provide an accurate comparison of PSA predictions and experimental data. Besides the 12 MeV  $n$ - $p$   $A_y(\theta)$  angular distribution referred to above, only the 7.6 MeV data set of Braun [Bra98] covers a large enough angular range to be considered "complete".

This is the reason why considerable effort has been spent on the polarization dependent efficiency (PDE), which is endemic to the organic scintillator based neutron side detectors used in  $n$ - $p$   $A_y(\theta)$  experiments. In each side detector, polarized neutrons can scatter first from a carbon nucleus and then from a proton. As is known from the work of Galati *et al.* [Gal72], the  $A_y(\theta)$  of  ${}^{12}\text{C}(n,n){}^{12}\text{C}$  shows large fluctuations with energy in the range between 3 and 7 MeV. Because of the kinematic variation of the neutron energies

over the face of the side detectors, the  ${}^{12}\text{C}$ - $p$  double scattering events can introduce a false asymmetry into the  $n$ - $p$   $A_y(\theta)$  measurement [Hol89]. This false asymmetry does not cancel with the usual spin-flip technique used in  $A_y(\theta)$  measurements. The only way that the PDE effect can be accounted for is by using Monte-Carlo techniques, which employ an accurate  $n$ - ${}^{12}\text{C}$  scattering library. In order to improve this library, Roper *et al.* [Rop05] gathered 33 angular distributions of  ${}^{12}\text{C}(n,n){}^{12}\text{C}$   $A_y(\theta)$  data from 2.2 to 8.5 MeV. Further details about the  ${}^{12}\text{C}(n,n){}^{12}\text{C}$  library used in the present work are given in [Bra08, Wei10].

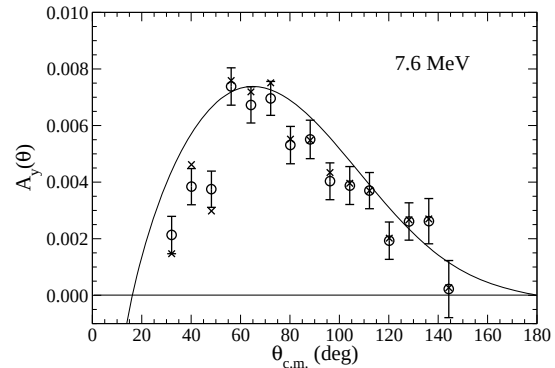


**Figure 4.1:** The  $n$ - $p$   $A_y(\theta)$  data at  $E_n=7.6$  MeV. The crosses use the original PDE corrections, while the circles use the PDE corrections of the present work. The solid curve is the Nijmegen PSA prediction.

Results for the  $n$ - $p$   $A_y(\theta)$  at  $E_n=7.6$  MeV after the PDE corrections are displayed in Fig. 4.1. Here the crosses use the original PDE correction [Bra98], while the circles use the PDE corrections of the present work. The difference between the two corrections is very small for scattering an-

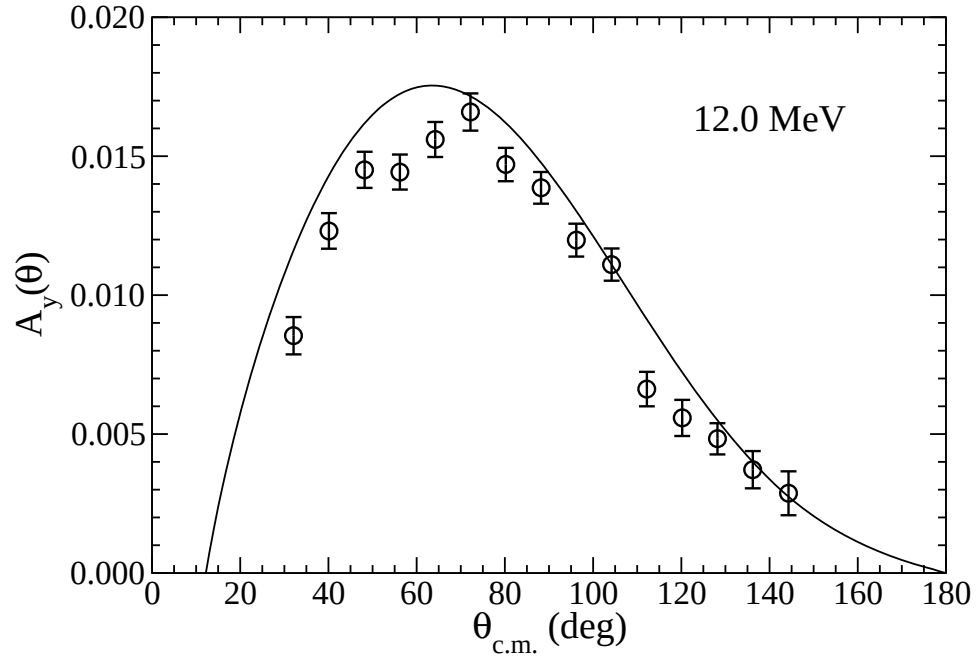


Figure 4.2: The  $n$ - $p$   $A_y(\theta)$  data at  $E_n=12.0$  MeV of [Bra08]. The solid curve is the Nijmegen PSA prediction.

gles larger than  $80^\circ$  c.m. However, for the forward angular region the new corrections provide a smoother angular dependence of  $A_y(\theta)$  than obtained with the original PDE corrections. The solid curve shown in Fig. 1 is the Nijmegen PSA prediction. In agreement with our previous findings at 12 MeV [Bra08] shown in Fig. 4.2, the Nijmegen PSA prediction overestimates the  $n$ - $p$   $A_y(\theta)$ , especially at forward angles. The same statement is true for all high-precision NN potential models. This observation may well be one of the reasons for the well-known three-nucleon analyzing power puzzle [Wit94].

[Bra98] R. Braun, Ph.D. thesis, Duke University, 1998.

[Bra08] R. Braun *et al.*, Phys. Lett. B, **660**, 161

(2008).

[Gal72] W. Galati *et al.*, Phys. Rev., **5**, 1508 (1972).

[Hol88] D. Holslin *et al.*, Phys. Rev. Lett., **61**, 1561 (1988).

[Hol89] D. Holslin *et al.*, Nucl. Instrum. Methods A, **274**, 207 (1989).

[Rop05] C. Roper *et al.*, Phys. Rev. C, **72**, 024605 (2005).

[Wei10] G. Weisel *et al.*, Phys. Rev. C, **82**, 027001 (2010).

[Wit94] H. Witała *et al.*, Phys. Rev. C, **49**, R14 (1994).

## 4.3 The A=3 Systems

### 4.3.1 Cross-Section Measurement of $^2\text{H}(n,np)n$ at 16 and 19 MeV in Symmetric Constant-Relative-Energy Configurations

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Cross-section measurements of neutron-deuteron ( $nd$ ) breakup were made at incident neutron energies of 16 and 19 MeV. The scattered proton was detected in coincidence with one of the neutrons. The energies of the scattered particles were determined via time-of-flight. Neutron beam flux normalization is obtained from  $nd$  elastic scattering performed concurrently with the main experiment. Our current measurements are of two special cases of the symmetric constant-relative-energy (SCRE) configuration: the space-star (SST) and the coplanar star. We have completed analysis of the 16 MeV data, which confirms the space-star anomaly established by previous measurements. Analysis of the 19 MeV data is in progress.

The space-star anomaly is a discrepancy between theoretical predictions and experimental measurements for the  $nd$ -breakup differential cross sections. The data are systematically higher than theory at all energies where measurements have been taken. This anomaly has been established by eight previous measurements taken at neutron beam energies of 10.3, 13.0, 16.0, and 25.0 MeV. Three of these experiments were performed in Germany at Bochum [Ste89] and Erlangen [Str89, Geb93], one at the China Institute of Atomic Energy [Zho01], and four at TUNL [Set96, Cro01, Mac04]. Figure 4.3 shows all the SST cross-section measurements, including the current experiment, compared with theoretical predictions based on the Bonn-B potential [Glo96]. All previous measurements were taken with essentially the same experimental setup, the common features being: (1) the scatterer was a deuterated scintillator, (2) two neutrons were detected in coincidence, (3) the target-beam integrated luminosity was determined through  $nd$  elastic scattering by detection of the scattered neutron. To determine if there could be a common experimental error in previous measurements, our experiment utilizes a technique similar to the one developed by Huhn *et al.* [Huh00] to measure the  $nn$  scattering length. The primary distinctions between our technique and previous SST measurements are: (1) the deuterated target was a thin foil, (2) a neutron was detected

in coincidence with the scattered proton, and (3) the integrated target-beam luminosity was determined by  $nd$  elastic scattering via detection of the scattered deuteron.

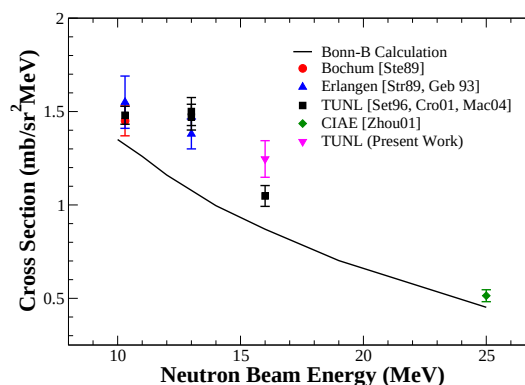


Figure 4.3: (Color online) World data for the  $nd$  breakup cross section in the SST configuration. The curve is a three-nucleon calculation based on the Bonn-B potential.

The experimental setup was surveyed and disassembled last year. Updates of various parameters given in last year's progress report [Cou09] are given below. It has been determined that the neutron beam energy spread was  $\pm 280$  keV for the 19 MeV beam and  $\pm 340$  keV for the 16 MeV beam rather than the  $\pm 300$  MeV spread reported for both last year. The space- and coplanar-star neutron detectors have flight paths from the

CD<sub>2</sub> target foil of 70 cm and 100 cm, respectively as opposed to 50 cm and 70 cm reported previously. Finally, the CH<sub>2</sub> target used in the recoil-proton telescope was not properly aligned with the CD<sub>2</sub> target used in the main experiment. Thus we were not able to use  $np$  scattering to determine the integrated beam flux as we originally intended. Instead, we used  $nd$  scattering off of the CD<sub>2</sub> target foil.

Determining the integrated beam-target luminosity from  $nd$  scattering presented some major difficulties. The deuterons that scattered from our CD<sub>2</sub> foil lost significant energy as they left the target foil and then had to traverse the  $\Delta E$  detector before being detected in the thick plastic scintillator in the charged-particle arm. More than 30% of the scattered deuterons were stopped either in the target or in the  $\Delta E$  detector. Also, even though there was more than 5 MeV separating the “prompt” neutrons in the beam, produced via  $^2\text{H}(d,n)^3\text{He}$ , from the “source breakup” neutrons, produced mainly by  $^2\text{H}(d,n)dp$ , there was significant contamination in our elastic deuteron spectrum from this process. We dealt with these difficulties by creating an  $nd$  elastic Monte-Carlo simulation that modeled scattered deuteron losses as well as the influence of source-breakup neutrons on the elastic spectrum. We then took the high-energy region of the scattered deuteron spectrum, where the source breakup influence was minimal, and used it in conjunction with the Monte-Carlo simulation to determine the total number of deuterons elastically scattered by the prompt portion of our neutron beam. Using this method, the integrated beam-target luminosity was determined to  $\pm 4\%$  for the 16 MeV data.

The results of the 16 MeV data analysis are shown in Fig. 4.4. The data points represent the number of counts measured in 1 MeV bins along the neutron energy axis after applying an accidental background subtraction and adjusting for  $nd$  breakup events arising from incident source-breakup neutrons. The error bars represent only the statistical uncertainty, which was  $\pm 5\%$  at the SST point of 4.5 MeV. The theoretical curve was produced by averaging calculated point-geometry cross sections over the finite geometry of our experiment. These smeared cross sections were used in conjunction with neutron-detector efficiencies, solid angles, and the  $nd$  elastic normalization to predict the number of counts expected as a function of detected-neutron energy. The theoretical band shows the  $\pm 5.5\%$  systematic uncertainty of our experiment. Our measurements confirm the space-star anomaly at 16 MeV, with about 35% more counts than predicted by theory. Preliminary analysis of the 19 MeV data suggests

the anomaly is present at that energy as well.

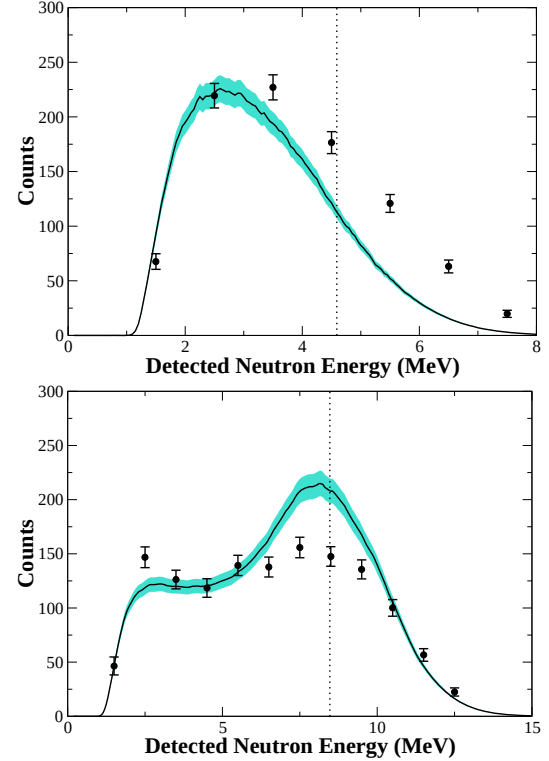


**Figure 4.4:** (Color Online) Results of the 16 MeV measurements. The top(bottom) graph is the space(coplanar)-star. The points show the data, the curves give the predicted results, and the vertical dotted lines indicate the energy of the SCRE condition.

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- [Cou09] A. Couture *et al.*, TUNL Progress Report, **XLVIII**, 56 (2009).
  - [Cro01] A. Crowell, Ph.D Dissertation, (2001).
  - [Geb93] K. Gebhardt *et al.*, Nuc. Phys., **A561**, 232 (1993).
  - [Glo96] W. Glöckle *et al.*, Phys. Rep., **274**, 107 (1996).
  - [Huh00] V. Huhn *et al.*, Phys. Rev. C, **63**, 014003 (2000).
  - [Mac04] R. Macri, Ph.D Dissertation, (2004).
  - [Set96] H. Setze *et al.*, Phys. Lett., **B388**, 229 (1996).
  - [Ste89] M. Stephan *et al.*, Phys. Rev. C, **39**, 2133 (1989).
  - [Str89] J. Strate *et al.*, Nucl. Phys., **A501**, 51 (1989).
  - [Zho01] Z. Zhou *et al.*, Nucl. Phys., **A684**, 545c (2001).

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### 4.3.2 Monte-Carlo Simulation of the Neutron-Deuteron Breakup Cross-Section Measurements at 16.0 and 19.0 MeV

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**We have upgraded the Monte-Carlo simulation code for the neutron-deuteron ( $nd$ ) breakup experiment at 16.0 and 19.0 MeV in order to determine the  ${}^2\text{H}(n,np)n$  cross sections from the data. We describe below the major improvements in the simulation code over last year's version. The code has been integrated into the data analysis and interpretation for the 16 MeV data.**

Neutron-deuteron breakup (NDBU) cross-section data at incident neutron energies of 16.0 and 19.0 MeV were measured at TUNL [Cou09]. The data were obtained using the coplanar-star and space-star configurations to study the space-star anomaly in  $nd$  breakup. In this experiment, a neutron beam is incident on a deuterium target ( $\text{CD}_2$  foil). We detect one of the neutrons from the breakup event in a neutron detector in coincidence with the scattered proton detected in the charged-particle arm using  $\Delta E$  and  $E$  detectors. The  $\Delta E$  detector consists of a thin plastic scintillator with thin aluminum covers. The charged particles from the target lose energy in the target foil and in the cover foils of the  $\Delta E$  detector. Energies of the detected particles are calculated from TOF measurements. A more detailed description of this experiment and data analysis can be found in Sect. 4.3.1.

A Monte-Carlo (MC) simulation program serves as a tool to obtain *predicted* quantities which can be compared with data. We report below an update from last year's MC simulation code for this experiment [Taj09].

To compare our measured cross section with theory, a point-geometry calculation [Glo96] is averaged over the energy spread of the beam and over the finite geometry of the detectors and target. The theoretical  $nd$  cross-section libraries at 16 and 19 MeV for this experiment have been recreated using the CD-Bonn potential and updated kinematics parameters. The  $S$  value is one of the important quantities in our analysis and represents the arc-length of a locus for a given set of beam energy and scattering angles, where  $S = 0$  corresponds to the point on the neutron energy axis. In the previous MC code, the interpolation process to calculate  $S$  and cross-section

values from the database was not complete because the final interpolation along the  $S$  curve was not done. We modified the algorithm to include the interpolation along the  $S$  curve using a projection method, and we verified that the current interpolation process correctly reproduces the  $S$  and cross section plots. In addition, we employed a better algorithm to calculate the estimated energy loss of charged particles in the foils by taking into account the effective foil thickness, which depends on the scattering angle of a charged particle. The energy of a proton detected in the  $E$  detector differs by several percent in the worst case compared to that from the calculation assuming a single foil thickness.

Our neutron beam basically consists of the mono-energetic *prompt* neutrons (produced in the gas cell via the  ${}^2\text{H}(d,n){}^3\text{He}$  reaction) and *source breakup* neutrons (produced mainly via  ${}^2\text{H}(d,n)dp$ ). The latter has much lower beam energy than the former but can still cause NDBU to happen. To study any contamination from this process, we extended the NDBU cross-section library to include energies ranging from 5.0 to 19.0 MeV (8.0 to 19.0 MeV) for the coplanar-star (space-star) configuration, and we included the low-energy neutrons in the simulation. In addition, incident neutron energies were sampled in the code according to the probability distribution of the *measured* beam energy. The simulation for the 16 MeV case showed that the majority of the scattered protons generated from the incident source breakup neutrons are not detected in the  $E$  detector, because they do not have sufficient energy to penetrate the foils. However, for the 19 MeV case, we found that the contamination from this process is more significant. Figure 4.5 shows the distribution of simulated NDBU events

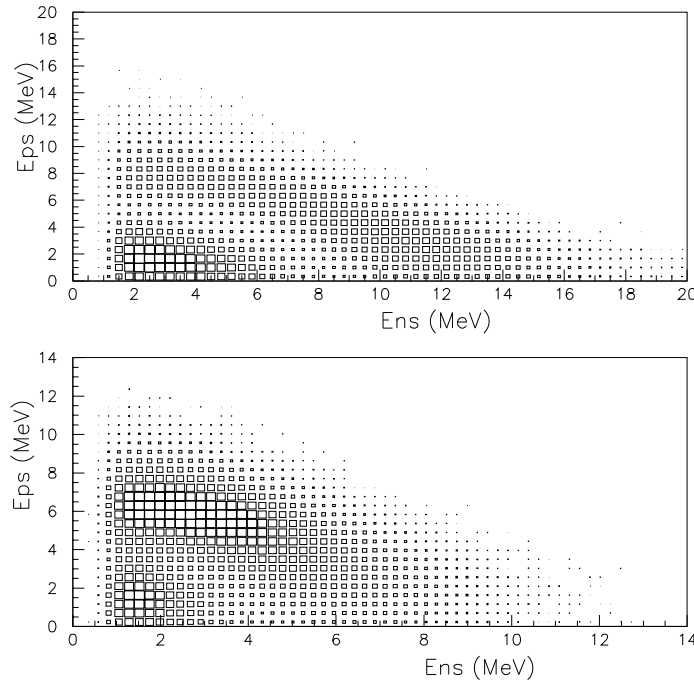


**Figure 4.5:** Distribution of simulated NDBU events. Energy of the detected neutron (proton) is on the  $x$  ( $y$ ) axis. The top (bottom) plot is made with the coplanar-star (space-star) configuration. See text for details.

for the 19 MeV case. Events from the source breakup neutrons are clustered in the low-energy region (near the origin) as shown in the plots, while the other cluster, which appears as a big locus band, represents events from the 19 MeV prompt neutrons with a beam energy spread of  $\pm 0.28$  MeV. To select the neutrons of interest, a 2-dimensional gate is set around the locus band region, and we applied the same gate to the data to extract yields. We also set the gate around the source breakup cluster in order to estimate the background yields.

In addition to the MC simulation program for generating NDBU events, we made an *nd* elastic version of the MC program in which only the deuterons are detected. We found that the large contamination from the source breakup neutrons is also seen in the deuteron TOF spectrum. However, in order to minimize such a contamination,

the TOF spectrum of high-energy deuterons was compared with data and the normalization factor for the simulation yields were obtained.

The simulation code has been applied to complete the 16 MeV data analysis as reported in Sect. 4.3.1. The predicted yields were calculated using this MC simulation based on theoretical models of nucleon-nucleon interactions and the experimental configuration. The predicted yields were then directly compared to the data in order to study the space-star anomaly.

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- [Cou09] A. Couture *et al.*, TUNL Progress Report, **XLVIII**, 56 (2009).
  - [Glo96] W. Glöckle *et al.*, Phys. Rep., **274**, 107 (1996).
  - [Taj09] S. Tajima and D. M. Markoff, TUNL Progress Report, **XLVIII**, 58 (2009).

## 4.4 Reaction Dynamics of Light Nuclei

### 4.4.1 Study of the $^{11}\text{B}(p,\alpha)$ Reaction Below $E_p = 3.8$ MeV

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**We have measured the angular distributions and total cross section for the  $^{11}\text{B}(p,\alpha)$  reaction over an incident energy range of 1.4 MeV to 3.8 MeV in 100-keV steps. Eight silicon surface-barrier detectors were used at angles from  $\theta_{lab} = 30^\circ$  to  $160^\circ$ . Sample results are reported.**

Detailed knowledge of the angular and energy distribution of the outgoing  $\alpha$  particles is important to model an aneutronic fusion reactor using the  $^{11}\text{B}(p,\alpha)$  reaction. The state-of-the-art model of the reaction assumes a sequential process, the so-called “two-step model,” leading to one high-energy  $\alpha$  particle and a nearly flat continuum of energies for the two secondary  $\alpha$  particles resulting from the breakup of the remaining  $^8\text{Be}^*$  nucleus [Bec87]. We have extensively studied the  $^{11}\text{B}(p,\alpha)$  reaction in several previous experiments [Fra07, Fra08b, Fra08a, Sta09, Seo09, Fra09] at energies between 0.15 and 2.7 MeV. Our results indicated that the two-step model is not appropriate at the very important 0.675 MeV resonance [Sta09].

New measurements of the  $^{11}\text{B}(p,\alpha)$  reaction in the proton energy range from 1.4 MeV to 3.8 MeV in 100-keV steps were made to expand the data set through the known resonances at 2.64 and 3.5 MeV. Our previous studies showed that the two-step model works well at the 2.64 MeV resonance.

Protons were incident on a thin  $^{11}\text{B}$  target and the outgoing  $\alpha$  particles were detected by silicon surface-barrier detectors positioned at eight angles:  $30^\circ$ ,  $45^\circ$ ,  $60^\circ$ , and  $75^\circ$  of beam left and  $90^\circ$ ,  $115^\circ$ ,  $135^\circ$ , and  $160^\circ$  of beam right. The outgoing particles from the reaction were collimated by  $1.5\text{mm} \times 9.2\text{ mm}$  collimators in front of each detector.

The  $\alpha$ -particle counts were normalized by the integrated beam luminosity, target thickness, and solid angle  $\Delta\Omega$ . The measured distributions were then boosted from the laboratory frame to the center-of-mass frame. Finally the data in the overlapping energy region (1.4 MeV to 2.7 MeV) between the current measurement and the previ-

ous measurement were used to scale the current distributions to those measured in 2007.

Figure 4.6 shows the distribution of  $\text{Counts}/(L \Delta\Omega)$  vs.  $E_\alpha^{\text{CM}}$  and  $E_p$ . Here  $L$  is the integrated luminosity, or the number of target nuclei multiplied by the number of incident protons. The quantity  $\text{Counts}/(L \Delta\Omega)$  is analogous to the cross section but makes no assumption about the expected number of  $\alpha$  particles produced in a given reaction. The figure includes the new data from 1.4 MeV to 3.8 MeV as well as the previous data from 0.5 to 2.7 MeV [Fra07, Fra08b] and from 0.15 to 0.4 MeV [Seo09]. Figure 4.7 is the plot of the same distribution of  $\text{Counts}/(L \Delta\Omega)$  vs.  $E_\alpha^{\text{CM}}$  and  $E_p$  as Fig. 4.6 but with a rescaled  $z$ -axis to emphasize the structures seen at higher proton energies, to show the cross section variation more clearly.

- 
- [Bec87] H. Becker, C. Rolfs, and H. Trautvetter, *Z. Phys.*, **A327**, 341 (1987).
  - [Fra07] R. France *et al.*, TUNL Progress Report, **XLVI**, 72 (2007).
  - [Fra08a] R. France *et al.*, TUNL Progress Report, **XLVII**, 68 (2008).
  - [Fra08b] R. France *et al.*, TUNL Progress Report, **XLVII**, 66 (2008).
  - [Fra09] R. France *et al.*, TUNL Progress Report, **XLVIII**, 64 (2009).
  - [Seo09] P.-N. Seo *et al.*, TUNL Progress Report, **XLVIII**, 68 (2009).
  - [Sta09] S. Stave *et al.*, TUNL Progress Report, **XLVIII**, 66 (2009).

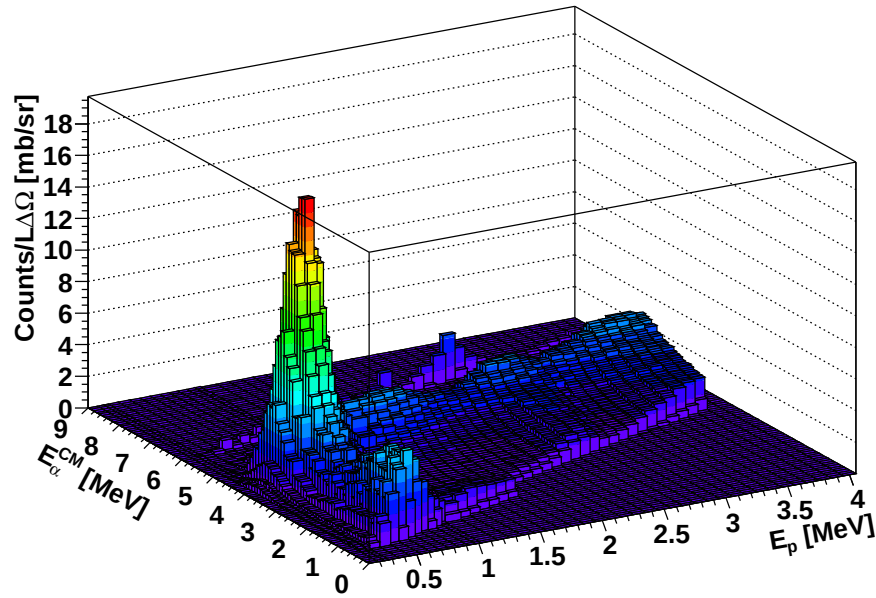


Figure 4.6: (Color online) Distribution of  $\text{Counts}/(L\Delta\Omega)$  vs.  $E_\alpha^{\text{CM}}$  and  $E_p$  in the proton energy range from 0.150 MeV to 3.8 MeV for the beam right  $90^\circ$  detector.

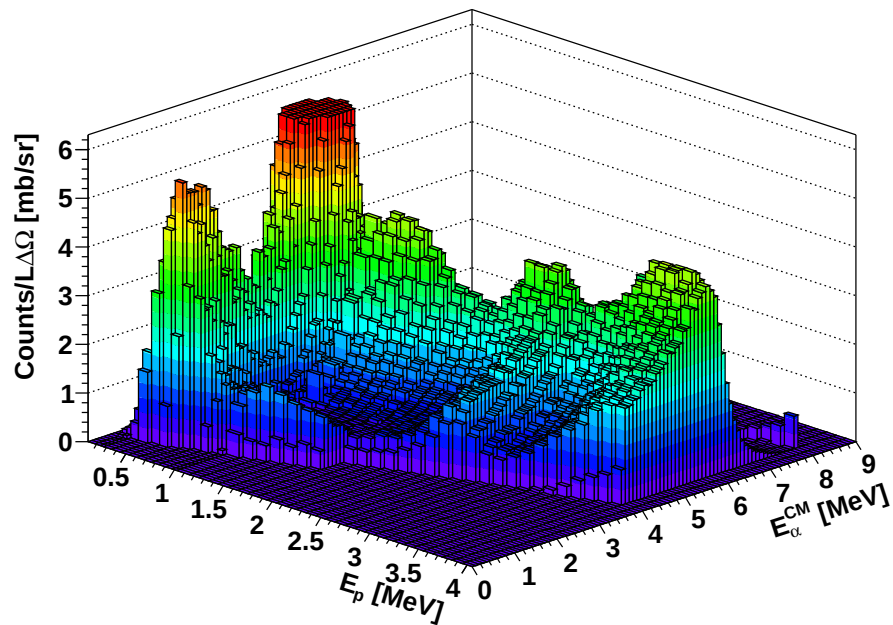


Figure 4.7: (Color online) Plot of the same distribution as in Fig. 4.6 but with a rescaled  $z$ -axis to emphasize the structures seen at higher proton energies

#### 4.4.2 The Study of the $^{11}\text{B}(\alpha,p)$ Reaction with an $\alpha$ -Particle Energy from 4.0 MeV and 7.0 MeV

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**We measured angular distributions for the emission of protons from the  $^{11}\text{B}(\alpha,p)^{14}\text{C}$  reaction at  $\alpha$  particle energies from 4.0 to 7.0 MeV. Eight silicon detectors were used at eight angles from  $\theta_{\text{lab}} = 45^\circ$  to  $160^\circ$ . Measured angular distributions were fitted with Legendre polynomials to fourth order, and total cross sections were obtained. The uncertainty of the measured total cross sections is less than 5%. The present result is compared with previous data.**

As a part of our ongoing study of the  $^{11}\text{B}(p,\alpha)$  reaction for aneutronic reactor design, we measured cross sections and angular distributions for the  $^{11}\text{B}(\alpha,p)^{14}\text{C}$  reaction at  $\alpha$ -particle energies from 4.0 to 7.0 MeV in 100-keV steps, except for 4.1 and 4.2 MeV. In a  $^{11}\text{B}$ -fueled fusion reactor,  $\alpha$  particles are produced mostly by the  $^{11}\text{B}(p,\alpha)$  reaction, and the possible production of large quantities of the long-lived isotope  $^{14}\text{C}$  by the secondary reaction  $^{11}\text{B}(\alpha,p)^{14}\text{C}$  can become an important problem [Day76]. This reaction may occur when the  $\alpha$  particles produced by the  $^{11}\text{B}(p,\alpha)$  reaction slow down within the hot, dense plasma. To estimate the  $^{14}\text{C}$  production rate in a  $(^{11}\text{B}+p)$ -fueled fusion reactor, cross sections for the  $^{11}\text{B}(\alpha,p)^{14}\text{C}$  reaction are required. Because the Q-value of this reaction is 0.784 MeV and the  $^{14}\text{C}$  first excited state lies at 6.093 MeV, only the  $(\alpha,p_0)$  reaction is energetically open for the current energy range. Only a few groups [Man63, Bon97, Gio96, Hou78] have previously measured angular distributions and total cross sections for the outgoing protons; however, their data show significant discrepancies. We compare our results with the previous measurements.

This measurement was performed using the same experimental setup as the elastic scattering experiment [Fra09]  $^{11}\text{B}(\alpha,\alpha)$ , except that thin aluminum foils were placed in front of each silicon detector to stop elastically scattering  $\alpha$  particles while allowing the passage of outgoing protons. Details of the experiment are described, and a typical proton spectrum is shown in [Fra09]. Counts in the proton peaks were normalized using the total charge on the target, target thickness, and the solid angle. Measured angular dis-

tributions in the center-of-mass system were plotted, and a three dimensional view of the angular distributions for the full range of incident  $\alpha$ -particle energies is shown in Fig. 4.8. The angular distributions show a strong dependence on  $E_\alpha$ .

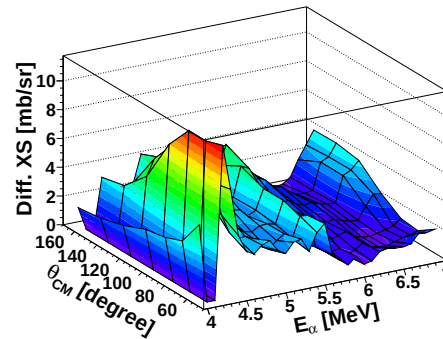


**Figure 4.8:** (Color online) Differential cross section as a function of angle and incident  $\alpha$ -particle energy

The resulting angular distributions were fitted with Legendre polynomials through the fourth order. Examples of this fit are shown in Fig. 4.9. The angular distribution at the 4.3-MeV resonance shows a large fore-aft asymmetry. The variation of the reduced Legendre polynomial coefficients (i.e., divided by the zeroth-order coefficient) with  $\alpha$ -particle energy is shown in Fig. 4.10. The error bars in the figure are smaller than the data points and include a statistical error of less than 3.2%.

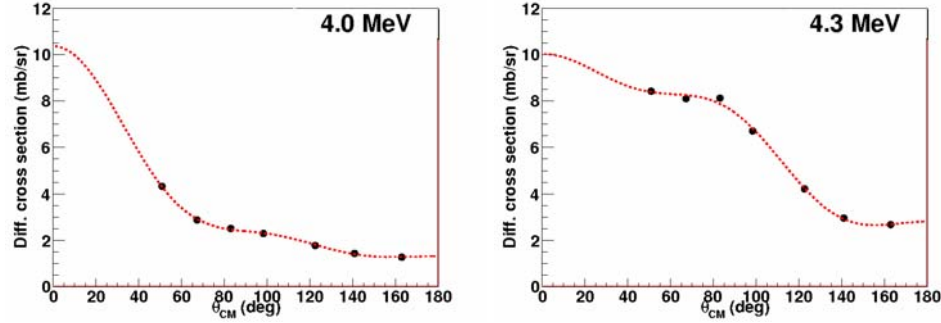


Figure 4.9: (Color online) Angular distributions in the CM system from the  $^{11}\text{B}(\alpha,p)^{14}\text{C}$  reaction at 4.0 and 4.3 MeV. The curves show a fourth order Legendre polynomial fit to the data.

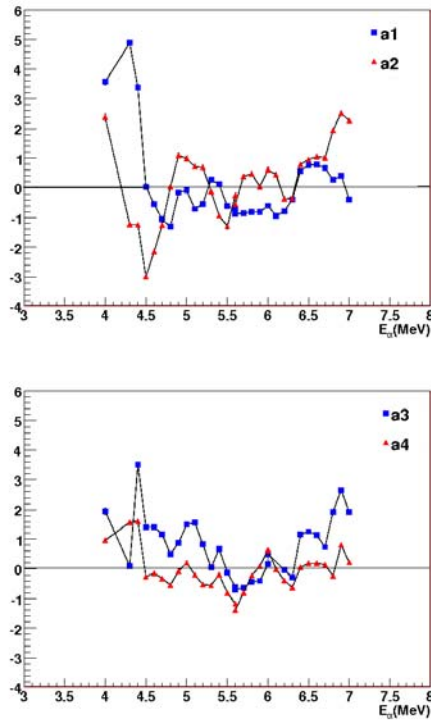


Figure 4.10: (Color online) Reduced coefficients from the Legendre polynomial fits to the proton angular distributions. The lines through the data are only to guide the eye.

The total cross section was extracted from the zeroth-order coefficient of the fit. The resulting excitation function and its uncertainty are shown in Fig. 4.11 along with other available data. The total cross section changes strongly with  $E_\alpha$ , indicating that the reaction is proceeding through the compound nucleus  $^{15}\text{N}$ . The non-vanishing odd-order coefficients indicate the presence of interference between levels of opposite parity in the compound nucleus. Results of [Bon97] and [Hou78] differ by about a factor of five at 4.3 MeV. Our data are closer to Bonetti's cross sections [Bon97], and the shape of the over-

all cross section is in excellent agreement with theirs. After normalization, the excitation function of [Man63] in the 4.3-MeV resonance region is also plotted and is in good agreement with the present data.

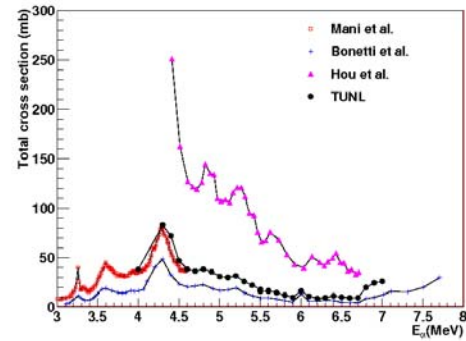


Figure 4.11: (Color online) Measured total cross sections as a function of incident  $\alpha$ -particle energy are compared with previous data

- 
- [Bon97] R. Bonetti, A. Guglielmetti, and G. Poli, *Appl. Radiat. Isot.*, **48**, 873 (1997).
  - [Day76] R. Dayras, Z. Switkowski, and T.A.Tombrello, *Nucl. Phys.*, **261**, 365 (1976).
  - [Fra09] R. France *et al.*, TUNL Progress Report, **XLVIII**, 64 (2009).
  - [Gio96] G. Giorginis *et al.*, *Nucl. Instrum. Methods*, **B118**, 224 (1996).
  - [Hou78] W.-S. Hou *et al.*, *Nucl. Sci. Eng.*, **66**, 188 (1978).
  - [Man63] G. Mani, P.D.Forsyth, and R. Perry, *Nucl. Phys.*, **44**, 625 (1963).

#### 4.4.3 $^{11}\text{B}(\alpha,\alpha)$ Elastic Cross-Section Measurements

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**Measurements of the  $^{11}\text{B}(\alpha,\alpha)$  elastic scattering reaction were performed at energies from  $E_\alpha = 2.0$  to  $8.0$  MeV. The experimental method is described, and results are shown.**

$^{11}\text{B}(\alpha,\alpha)$  scattering data were collected at TUNL using an incident  $\alpha$ -particle beam with energies ranging from 2.0 to 8.0 MeV. With an average of approximately 10 nA of beam on target, we observed scattered  $\alpha$ -particles using eight silicon surface-barrier detectors. The detector thickness was sufficient to stop  $\alpha$ -particles at all relevant energies. Detectors set at laboratory angles of 45, 60, 75 and 90 degrees were situated on the bottom plate of the vacuum chamber, and detectors at angles of 90, 115, 135 and 160 degrees were attached to the top plate.

Three targets were employed for this experiment: gold, carbon and boron. The gold foil target is  $105 \mu\text{g}/\text{cm}^2$ , and data collected were used for calibration in comparison to calculated Rutherford scattering data. The carbon target was  $20 \mu\text{g}/\text{cm}^2$ , and data collected were used to measure the  $^{12}\text{C}$  cross section at each angle and energy. The boron target was  $76 \mu\text{g}/\text{cm}^2$  of boron sandwiched between 20 and  $46 \frac{\mu\text{g}}{\text{cm}^2}$  of titanium. For each energy step throughout the 1.5 to 8.0 MeV region, data for each target was collected to ensure a calibration value for each data point. Energy calibration of the detector spectra was established using the Rutherford data from the Au target. A two-point fit between a low energy and a high energy run was sufficient to establish a linear relationship. This linear fit was used for all data collected using a specific spectroscopy-amplifier setting or gain setting.

Three different gain settings were used throughout the energy range to ensure that the expected  $\alpha$ -scattering peak location was visible in each detector. A linear fit was created for each of the eight detectors at each of the three gain settings and was used to calibrate each detector spectrum. The corrected detector spectra were then managed as a collection of histograms for the remainder of the analysis process. The energy-calibrated boron-target spectra contain cross section contributions from sev-

eral different nuclei. Easily identifiable are peaks from boron, carbon, oxygen and titanium. While the oxygen and titanium peaks are well separated from the boron peak, the carbon peak begins to merge with the boron peak at low energies and forward angles.

At high energies (7-8 MeV) these peaks are separated enough in energy to estimate the thickness of the carbon layer in the boron target by measuring the carbon peak and comparing that to the carbon yield from the known  $20 \mu\text{g}/\text{cm}^2$  carbon target. This provides an estimate of  $5 \mu\text{g}/\text{cm}^2$  for the carbon layer in the boron target. This allows a bin-by-bin subtraction of the histograms, ensuring no over subtraction when removing the carbon contribution. The remaining peak is summed to provide the boron cross sections at each angle and energy.

A transfer from the laboratory reference frame to the center-of-mass reference frame was preformed using the computer code RKIN. The  $^{11}\text{B}$  center-of-mass  $\alpha,\alpha$  scattering cross section measurements are summarized at seven different energies between 2.0 and 8.0 MeV. Above 5 MeV the boron cross section is only near Rutherford at the forward angles, while the back angles remain well above the Rutherford value. As the alpha energy decreases, the cross section at all angles approaches the Rutherford values. When the alpha energy is decreased to 3.0 MeV and below, virtually all angles are within 10-20% of the Rutherford value.

Representative results are shown in Figs. 4.12-4.18 at  $E_\alpha=2.0, 3.0, 4.0, 5.0, 6.0, 7.0$ , and 8.0 MeV. An investigation into our estimates of the systematic errors pertinent to the absolute cross-section scale allows reporting to within an  $\approx 5\%$  error. Additionally, a phase-shift analysis is being developed for the extension of this data set to intermediate unmeasured angles and energies. It is described in Sect. 4.4.4.

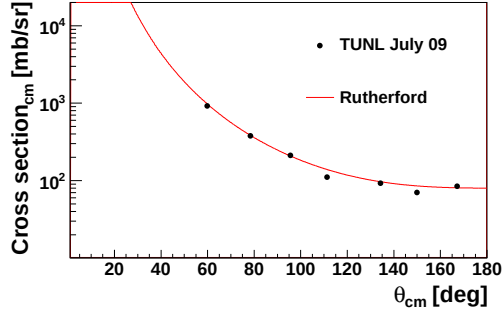


Figure 4.12: (Color online)  $^{11}\text{B}(\alpha, \alpha)$  center-of-mass scattering cross section for  $E_\alpha = 2.0$  MeV.

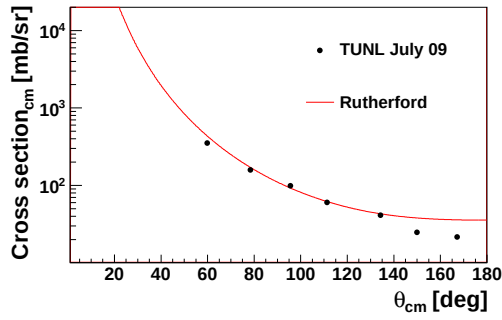


Figure 4.13: (Color online) Same as Fig. 4.12 for  $E_\alpha = 3.0$  MeV.

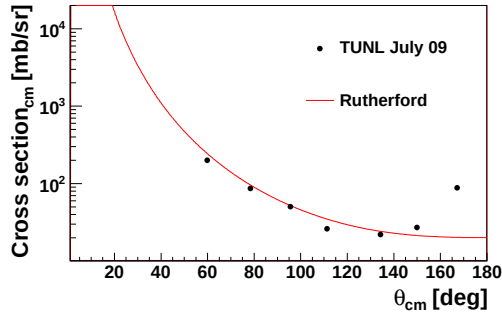


Figure 4.14: (Color online) Same as Fig. 4.12 for  $E_\alpha = 4.0$  MeV.

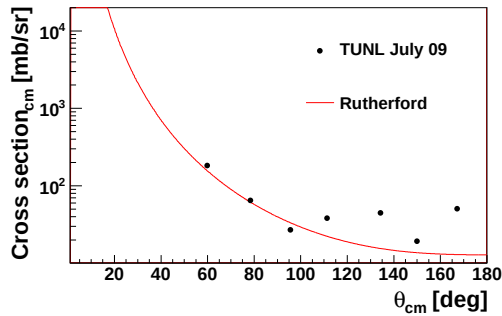


Figure 4.15: (Color online) Same as Fig. 4.12 for  $E_\alpha = 5.0$  MeV.

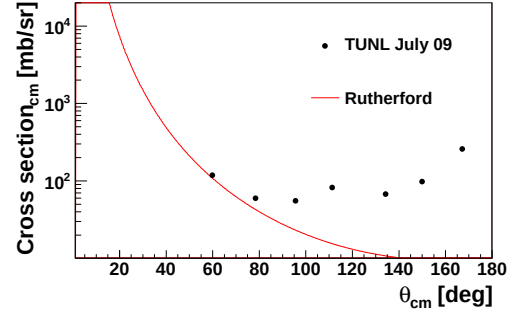


Figure 4.16: (Color online) Same as Fig. 4.12 for  $E_\alpha = 6.0$  MeV.

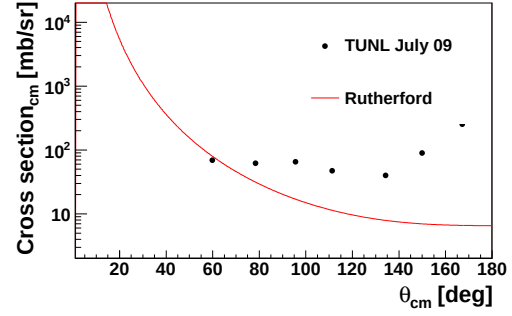


Figure 4.17: (Color online) Same as Fig. 4.12 for  $E_\alpha = 7.0$  MeV.

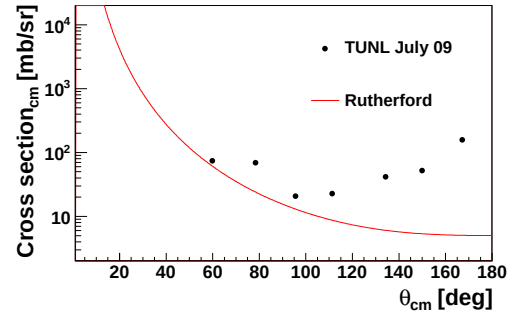


Figure 4.18: (Color online) Same as Fig. 4.12 for  $E_\alpha = 8.0$  MeV.

#### 4.4.4 Phase-Shift Analysis of $^{11}\text{B}(\alpha,\alpha)^{11}\text{B}$ from 2.0 to 5.4 MeV

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The  $^{11}\text{B}(\alpha,\alpha)^{11}\text{B}$  elastic-scattering cross section has been measured as a part of a study of the  $^{11}\text{B}(p,\alpha)\alpha\alpha$  reaction and its use as a power source in an aneutronic fusion reactor. A phase-shift analysis has been performed to allow interpolation of the scattering data.

As a part of the consideration of using the  $^{11}\text{B}(p,\alpha)\alpha\alpha$  reaction in an aneutronic fusion reactor, it is necessary to know the properties of other reactions that may occur within the reactor. The elastic scattering of alpha particles from  $^{11}\text{B}$  has been measured at TUNL at laboratory scattering angles of  $45^\circ$ ,  $60^\circ$ ,  $75^\circ$ ,  $90^\circ$ ,  $115^\circ$ ,  $135^\circ$ , and  $160^\circ$ . The experimental details and results have been reported in Sect. 4.4.3.

An exact phase-shift analysis of the elastic scattering data would be complicated by the  $3/2$

spin of  $^{11}\text{B}$ , and would require data at a much larger number of scattering angles at each energy because of the number of partial waves that would have to be included. Physically, the spin of the nucleus is not likely to have much effect on the scattering, so a simpler formalism was used to fit the data set. The phase-shift formalism for spin-0 particles scattering from a spin-0 target was used to fit the data. The formalism is given below.

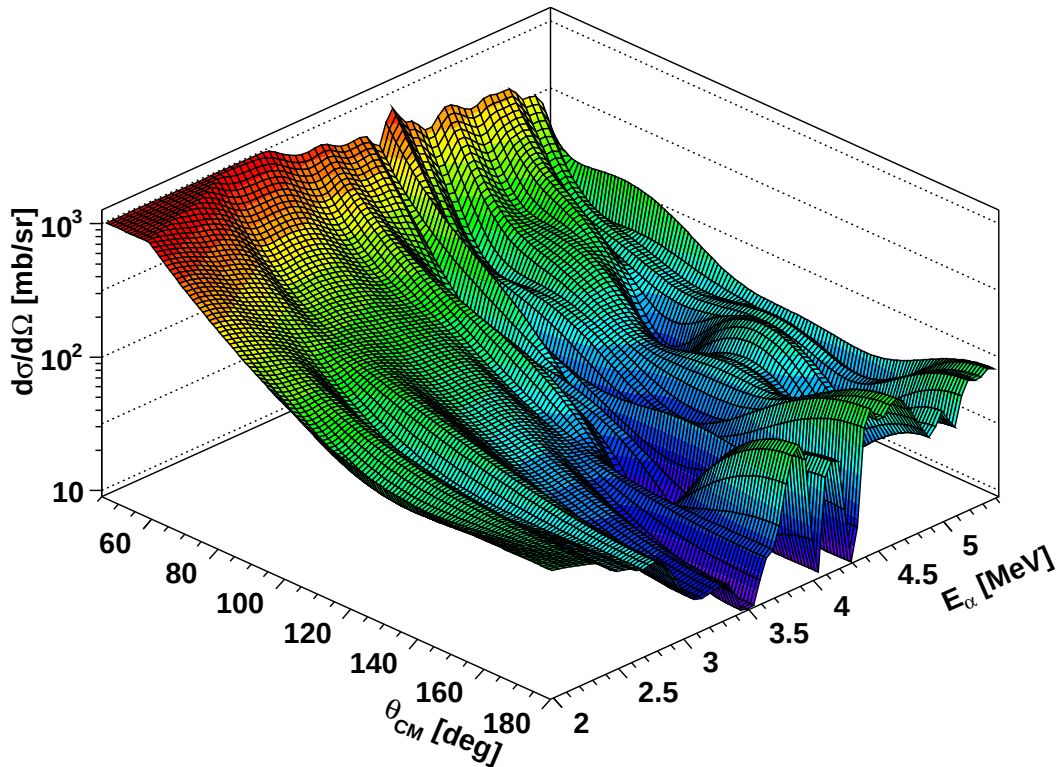


Figure 4.19: (Color online) The differential cross section evaluated using the fitted phase shifts for the  $^{11}\text{B}(\alpha,\alpha)$  reaction for incident  $\alpha$  energies between 2 and 5.4 MeV as a function of the outgoing  $\alpha$ -particle polar angle in the center-of-mass frame.

The differential cross section can be written in terms of two complex scattering amplitudes,  $F_C$  and  $F_N$ :

$$\frac{d\sigma}{d\Omega}(\theta) = \frac{1}{k^2} |F_C + F_N|^2 \quad (4.1)$$

where the wave number  $k = 0.2187 \times 10^{13} \mu \sqrt{\frac{E}{m_1}}$  cm for  $E$  in MeV and  $m_1$  in amu. The quantity  $\mu$  is the reduced mass  $\mu = \frac{m_1 m_2}{m_1 + m_2}$ . The terms  $m_1$  and  $m_2$  are the incident and target particle masses respectively. The Coulomb scattering amplitude  $F_C$  is written in terms of the center-of-mass scattering angle  $\theta$  and the quantity  $\eta$  as:

$$F_C = -\frac{1}{2}\eta \left( \frac{1}{\sin^2 \frac{\theta}{2}} \right) e^{i\eta \ln \left( \frac{1}{\sin^2 \frac{\theta}{2}} \right)}, \quad (4.2)$$

where  $\eta = \frac{Z_1 Z_2}{h\nu} = 0.1575 Z_1 Z_2 \sqrt{\frac{m_1}{E}}$  and  $E$  is in MeV. The terms  $Z_1$  and  $Z_2$  are the incident and target particle atomic numbers, respectively. The nuclear scattering amplitude  $F_N$  is:

$$F_N = -\frac{i}{2} \sum_{l=0}^{l_{\max}} e^{i\alpha_l} (2l+1)(S_l - 1) P_l(\cos \theta) \quad (4.3)$$

where the Coulomb phase shift is given by  $\alpha_0 = 0$ ,  $\alpha_l = \alpha_{l-1} + 2 \tan^{-1} \left( \frac{\eta}{l} \right)$ , and  $S_l = \gamma_l e^{2i\delta_l}$ . The parameters that have to be determined to reproduce the experimental cross-section data are  $\delta_l$ , the real part of the phase shift, and  $\gamma_l$ , the damping parameter that represents the imaginary part of the phase shift for each  $l$ -value included in the fit. The real part of the phase shift is usually expressed in degrees or radians. The damping pa-

rameter represents absorption of the corresponding partial wave; it is dimensionless and varies between 1.0 (meaning no absorption) and 0 (meaning total absorption).

No attempt has been made to interpret the analysis in terms of the reaction mechanism. The results provide a way to parameterize the entire data set and allow interpolation over energies within the range of the data and to interpolate and extrapolate to any scattering angle.

In this analysis, partial waves for angular-momentum quantum numbers 0 through 3 were included, meaning four complex phase shifts were adjusted. Since each phase shift is a complex number, two parameters were adjusted for each phase shift giving a maximum of 8 parameters. At the lower energies the higher order phase shifts were not needed so that fewer parameters had to be determined. The fitting was done with a Fortran code that used the Marquart method for parameter determination.

Angular distribution data at energies from 2.0 MeV to 5.4 MeV were used. The angular distribution at each energy was fitted. Tables of phase shifts and damping parameters can then be used to calculate cross sections at any energy between 2.0 and 5.4 MeV by interpolating the table of fitted parameters and using the parameters to calculate the corresponding cross section. The cross sections can also be calculated at any angle. Figure 4.19 shows the calculated cross section as a function of angle and energy over the range from 2.0 to 5.4 MeV. Over 80% of the fitted differential cross-section values are within 20% of the experimental input data.



# The Many-Nucleon Problem

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Chapter 5

- Preequilibrium Nuclear Reactions and Random Matrix Theory
- Neutron-Induced Reactions

## 5.1 Preequilibrium Nuclear Reactions and Random Matrix Theory

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### 5.1.1 Random Matrices and Chaos in Nuclear Physics

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The last comprehensive review of random-matrix theory (RMT) in nuclear physics was given by Brody *et al.* over 25 years ago. A two-part review on this topic has been prepared for the Reviews of Modern Physics. The first part (on spectra) has recently been published; the second part (on reactions) has been accepted for publication. One important application of RMT is the evaluation of the completeness of neutron resonance data. We have prepared a report for the International Atomic Energy Agency that describes a missing-level analysis using measures that characterize the spacings rather than the more conventional widths.

The last comprehensive review concerning the application of random-matrix theory (RMT) to nuclear physics was by Brody *et al.* in 1981 [Bro81]. In response to a request from Reviews of Modern Physics, we have prepared a two-part series of reviews. The first, entitled *Random Matrices and Chaos in Nuclear Physics: Nuclear Structure* [Wei09], was published in 2009 and the second part, *Random Matrices and Chaos in Nuclear Physics: Nuclear Reactions* [Mit], has been accepted for publication.

Random matrices were introduced into nuclear physics by Wigner in the late 1950s. This step was preceded and probably motivated by Bohr's insight that nuclei are systems of great complexity. Bohr's idea that the nucleus is a complex, strongly interacting system is most clearly demonstrated in the compound nucleus (CN) model. Wigner first applied random-matrix ideas to the spacings of neutron resonances. The random-matrix approach characterizes spectra by their fluctuation properties. The distribution of spacings of nearest neighbors is the most common measure. To implement this approach one needs a statistical theory of spectra, and random matrices provide this tool. One considers an ensemble of Hamiltonians (in matrix form). The ensemble is defined in terms of the probability distribution for the matrix elements, thus the name random matrices. The ensemble is chosen such that the Hamiltonians incorporate generic features. The spectral distribution functions are calculated as averages over the ensemble and are compared with the actual fluctuation properties

of nuclear spectra. Since nuclei are invariant under time reversal, the nuclear Hamiltonian can be chosen to be real and symmetric.

In part I of the series, following a brief definition of the Gaussian orthogonal ensemble (GOE) and an interpretation of the results for the ensemble (average level density, universality, information content, etc.), we (HAW and GEM) consider the standard GOE fluctuation measures (Porter-Thomas distribution, nearest-neighbor-spacing distribution, Dyson-Mehta statistic, etc.). We then provide a comparison of the experimental results with the predictions of RMT. We focus on neutron and proton resonances, low-lying levels, high-spin states, low-lying modes of excitation, and eigenvector distributions. We then consider both the models and the data for isospin symmetry violation and for tests of time-reversal invariance. Most of the rest of the review is devoted to the issue of chaos in nuclear models. In addition to consideration of the shell model and the collective model in various forms, we also consider random-matrix models that were inspired by nuclear structure concepts. The evidence strongly supports the view that chaos is a generic property of nuclei.

In part II, we (GEM, AR, and HAW) first consider early work in nuclear reactions, such as the Hauser-Feshbach formula. Later work extended this formula to direct reactions. Another major development was Ericson's prediction of statistical fluctuations in nuclear cross sections. Attempts were made to connect the statistical models of CN scattering with RMT. Following

the development of the theory of chaotic motion, CN scattering was recognized as a paradigmatic case of quantum chaotic scattering. After a summary of some basic facts and concepts of nuclear-reaction theory, we present the central ideas and models that were developed before the connection to RMT was established (Hauser-Feshbach formula, Weisskopf estimate, Ericson fluctuations, etc.). In order to avoid repeating the arguments later in a different form, we present them in modern terminology. Tests of the theory are reviewed, as are applications in nuclear physics, with special attention given to violation of symmetries (isospin, parity) and to time-reversal invariance.

A classic problem in applied nuclear physics is the evaluation of data quality. A key example involves the determination of nuclear level densities from neutron resonances. This information is crucial for such areas as shielding calculations and advanced-fuel-cycle issues. The key question is whether some levels are missing, and if so, how many. The standard approach is to assume that RMT applies to the level statistics of neutron resonances and to use the Porter-Thomas width distribution in order to estimate the number of missing levels. Unfortunately, the width distribution is strongly affected by the presence of non-statistical effects, which can severely distort the distributions and lead to incorrect values for the missing level correction and thus for the level density. The spacing distributions are not affected by non-statistical effects. Since widths and spacings are independent in RMT (the eigenvalues and eigenfunctions factor in the probabil-

ity distribution), missing-level analysis using the spacings provides an independent check of the same data set. In principle any of the measures that are used to evaluate spacing data can be utilized. We (GEM and JFS) have used the nearest-neighbor-spacing, the  $\Delta_3$  statistic, the thermodynamic energy, and the linear correlation of adjacent spacings in order to evaluate neutron resonance data.

Our initial efforts have been for targets with spin zero. This work is summarized in a report for the Nuclear Data section of the International Atomic Energy Agency [Mit09]. The specific focus is on the results for key actinides. The general effort is to provide best practice procedures. Analysis codes for the five measures that we use are available under the RIPL (Reference Input Parameters Libraries) framework. Our present efforts are to extend these analysis methods to targets with non-zero spin.

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- [Bro81] T. A. Brody *et al.*, Rev. Mod. Phys., **53**, 385 (1981).
  - [Mit] G. E. Mitchell, A. Richter, and H. A. Weidenmüller, to be published in Rev. Mod. Phys.
  - [Mit09] G. E. Mitchell and J. J. F. Shriners, *Missing Level Corrections Using Neutron Spacings*, Technical Report INDC(NDS)-0561, International Atomic Energy Agency, Vienna, 2009.
  - [Wei09] H. A. Weidenmüller and G. E. Mitchell, Rev. Mod. Phys., **81**, 539 (2009).

### 5.1.2 Preequilibrium Reaction Phenomenology

C. KALBACH WALKER, *TUNL*

**Work has continued on a phenomenological model for light-projectile breakup reactions. Previously reported systematics for the angular distributions and the absolute breakup cross sections have been revised, and the revised model is yielding good agreement with experiment for  $d$  and  $^3\text{He}$  breakup. Comparisons for  $\alpha$ -particle breakup are continuing.**

For light-particle ( $A \leq 4$ ) induced reactions at incident energies of 14 to 200 MeV, the semi-classical exciton model of preequilibrium nuclear reactions provides a simple way to describe the continuum energy and angular distributions of the light particles emitted during energy equilibration. The TUNL code system PRECO is based on the exciton model and has been used (either alone or in Hauser-Feshbach codes) in applied projects and in basic research. Model development uses simple physical concepts and relies on available data to direct choices between alternative model formulations and to provide values for key model parameters.

An important strength of PRECO is its ability to treat reactions with complex particles in the entrance channel and/or exit channel, but for loosely bound projectiles— $d$ ,  $t$  and  $^3\text{He}$ —and for  $\alpha$  particles at incident energies above about 50 MeV, the lack of a model for projectile breakup makes the description incomplete. Yet deuteron-induced reactions are of increased importance. The International Atomic Energy Agency has initiated a Coordinated Research Project (CRP) to upgrade the Fusion Energy Nuclear Data Library to version FENDL-3. An important addition will be “data” (mostly model-generated) for deuteron-induced reactions. Therefore a phenomenological projectile-breakup model has been developed as part of the FENDL-3 CRP. Once validated, the model will be included in the next release of PRECO.

Projectile breakup is here defined as the emission of a projectile fragment with a fairly narrow energy distribution peaked at an emission energy corresponding to the projectile velocity. The inclusion of data for  $d$ ,  $^3\text{He}$  and  $\alpha$ -particle projectiles in the database for this work leads to a more robust and global model than one developed for a single projectile type.

Early work [Kal08] concentrated on the centroid energies and shapes of the breakup peaks.

Then the angular distribution systematics and the variation of the breakup cross section with target, incident energy, and breakup channel were described [Kal09]. This year, early comparisons between model calculations and experimental data indicated that the angular distribution systematics needed revision.

The angular distributions for projectile breakup typically follow an exponential falloff with  $a_{\text{bu}}\theta_{\text{lab}}$ , where  $\theta_{\text{lab}}$  is the emission angle in the laboratory system and  $a_{\text{bu}}$  is the angular-distribution slope parameter for projectile breakup. When the detected fragment is one mass unit lighter than the projectile, the slope parameter was previously described as increasing linearly with the energy of the breakup peak. For all lighter fragments, it was given the value  $5.87 \text{ rad}^{-1}$ . The new description shown in Fig. 5.1 is more complicated but also more accurate.

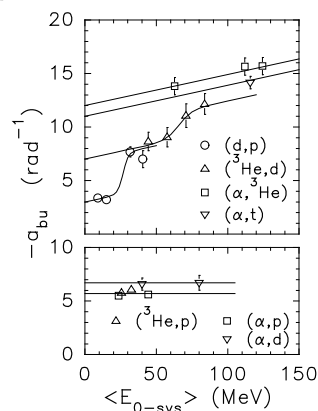


**Figure 5.1: Empirical values for the breakup-angular-distribution slope parameter  $a_{\text{bu}}$  as a function of the average peak energy. The lines show the systematics.**

For relatively large values of  $C_a/E_{\text{inc}}$  (the ratio of the entrance-channel Coulomb barrier to the incident energy), this behavior is modified by a forward-angle dip in the experimental breakup

cross section. The dip is described as due to penetration through an angular barrier. With the change in the systematics of  $a_{bu}$ , the systematics for this barrier also had to be revised. The forward-angle dip is best characterized for  $(d,p)$  breakup at 15 MeV. The experimental angular distributions for other breakup systems do not include small enough angles to show the dip, but the angular barrier plays a role in determining the relative breakup yields for a range of targets with a fixed breakup channel, incident energy, and measurement angle, thus providing further guidance for the systematics.

The changes in the angular distribution systematics resulted in revised estimates of the angle-integrated cross sections, so the normalization systematics of the overall breakup cross sections as a function of breakup channel and incident energy were revised. The target dependence of the breakup cross section was unchanged.

The small computer code used to calculate the breakup cross section using the current model was modified to include all of these changes, and a comprehensive comparison of model calculations with measured double-differential cross sections is being carried out. Good agreement is found for  $(d,p)$  breakup at 15 and 56 MeV, as seen in Figs. 5.2 and 5.3. Similar results have been obtained for  $(^3\text{He},d)$  breakup at 70, 90, 110, and 130 MeV (see Fig. 5.4) and for  $(^3\text{He},p)$  at 70 and 90 MeV.

A more complete description of the model and additional data comparisons are given in a report to the second Research Coordination Meeting of the FENDL-3 project [Kal10].

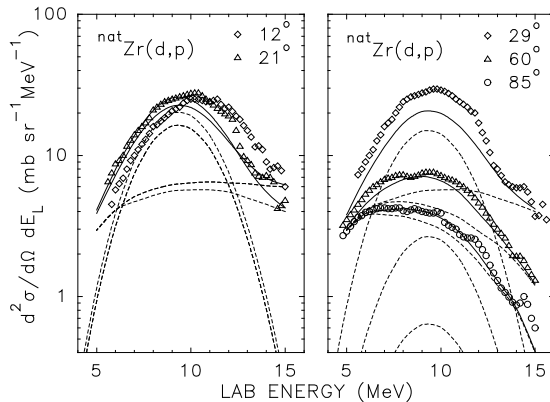


**Figure 5.2:** Comparison of experimental and calculated breakup peaks for  $\text{Zr}(d,p)$  at 14.8 MeV. The points show the data from Ref. [Ham61], the Gaussian-shaped dashed curves show the calculated breakup peaks, the other dashed curves show a reasonable estimate of the underlying continuum cross section at each angle, and the solid curves show the total estimated spectra.

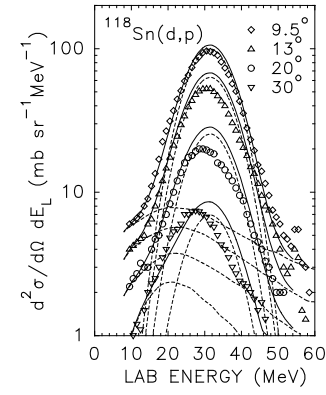


**Figure 5.3:** Comparison of experimental and calculated breakup peaks for  $^{118}\text{Sn}(d,p)$  at 56 MeV. The points and curves have the same significance as in Fig. 5.2, except that the data are from Ref. [Mat80].

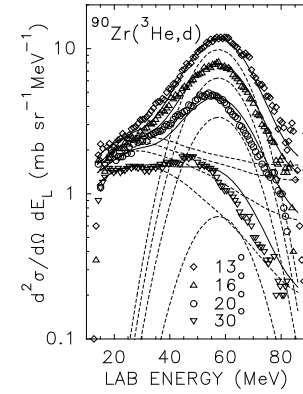


**Figure 5.4:** Comparison of experimental and calculated breakup peaks for  $^{90}\text{Zr}(^3\text{He},d)$  at 90 MeV. The points and curves have the same significance as in Fig. 5.2, except that the data are from Ref. [Mat78].

[Ham61] E. W. Hamburger, B. L. Cohen, and R. E. Price, Phys. Rev., **121**, 1143 (1961).

[Kal08] C. Kalbach Walker, TUNL Progress Report, **XLVII**, 78 (2008).

[Kal09] C. Kalbach Walker, TUNL Progress Report, **XLVIII**, 74 (2009).

[Kal10] C. Kalbach Walker, Report to the 2nd meeting of the FENDL-3 CRP, Vienna, Austria, March 2010, posted at [www.nds.iaea.org/fendl3/vardocs.html](http://www.nds.iaea.org/fendl3/vardocs.html), 2010.

[Mat78] N. Matsuoka *et al.*, Nucl. Phys., **A311**, 173 (1978).

[Mat80] N. Matsuoka *et al.*, Nucl. Phys., **A345**, 1 (1980).

## 5.2 Neutron-Induced Reactions

### 5.2.1 Energy Dependence of the Fission-Product Yields in Fast and Thermal Neutron-Induced Reactions

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The goal of this experimental activity is to gain insight into the possible neutron-energy dependence of fission-product yields by measuring their  $\gamma$ -ray yield ratios. The long-standing experimental problem is whether the yield of specific fission products, such as  $^{140}\text{Ba}$  and  $^{147}\text{Nd}$ , and their ratio varies as a function of incident neutron energy. The existing literature indicates that the high-yield fission product  $^{140}\text{Ba}$  does not have any energy dependence. We performed high-precision fission-product-yield measurements on  $^{238}\text{U}$  using monoenergetic 14.5 MeV neutrons. The results will be compared to theoretical analyses to provide a more fundamental understanding of the fission process.

One of the primary interests of the stockpile stewardship program is to gain knowledge of the energy dependence of fission product yields in certain mass regions as a function of incident neutron energy. The primary interest is  $^{239}\text{Pu}$  with thermal neutrons and fast neutrons from  $E_n = 1$  to 16 MeV.

ated for 24 h at an average neutron flux of  $7 \times 10^6$  n/( $\text{cm}^2$ ). The uranium target was sandwiched between thin gold and aluminum foils, which served as flux monitors. Following the irradiation, the foils were counted using the GENIE Multipoint II high-resolution  $\gamma$ -ray spectrometer system. No radiochemical separation procedure was applied to the irradiated target.

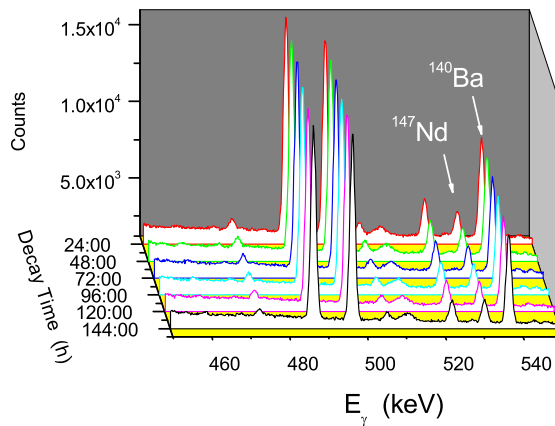


Figure 5.5: (Color online) Partial  $\gamma$ -ray spectra of  $^{238}\text{U}$  after irradiation with  $E_n = 14.5$  MeV neutrons.

The first proof-of-principle experiment has been performed at TUNL to demonstrate the feasibility of the  $^{147}\text{Nd}/^{140}\text{Ba}$  ratio technique. An 1100 mg/ $\text{cm}^2$   $^{238}\text{U}$  target was irradiated with 14.5 MeV neutrons produced via the  $^2\text{H}(d,n)^3\text{He}$  reaction. The depleted  $^{238}\text{U}$  target was irradi-

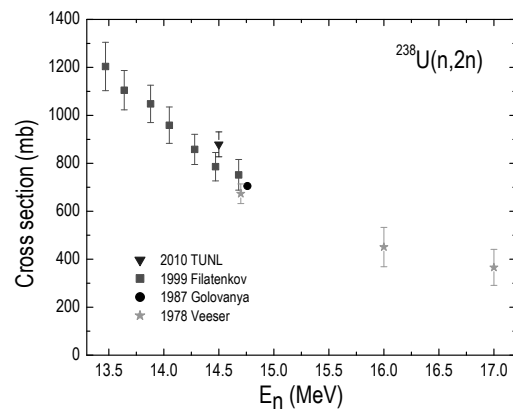


Figure 5.6: Cross section data for the  $^{238}\text{U}(n,2n)$  reaction in the energy region around  $E_n = 14$  MeV.

The intensities of the characteristic  $\gamma$  rays from the decay of the 12.75 d  $^{140}\text{Ba}$  ( $E_\gamma = 537$  keV) and 10.98 d  $^{147}\text{Nd}$  ( $E_\gamma = 531$  keV) isotopes were measured continuously during the following three months. A portion of the  $\gamma$ -ray spectra recorded in the first week after irradiation is shown in Fig. 5.5. It should be noted that at

short times, the  $^{147}\text{Nd}$  peak at  $E_\gamma = 531$  keV interferes with the strong 530 keV transition from the decay of the 20.8 h  $^{133}\text{I}$  isotope. Due to the large difference in the half lives, the  $^{133}\text{I}$  decays away, leaving a pure  $^{147}\text{Nd}$   $\gamma$ -ray peak after a few days. The ratio of the yield of the  $^{140}\text{Ba}$  fission fragment to that of  $^{147}\text{Nd}$  as obtained from the present measurement is equal to  $2.222 \pm 0.037$ . This ratio agrees with the data value for the  $^{239}\text{Pu}(n,f)$  reaction at  $E_n = 14$  MeV.

Besides the fission product yield measurements, the cross section of the  $^{238}\text{U}(n,2n)^{237}\text{U}$  reaction was determined by measuring the emission rate of the 208.0 keV  $\gamma$ -rays from the  $^{237}\text{U}$  decay. The residual  $^{237}\text{U}$  nucleus has very a long half-life ( $T_{1/2} = 6.75$  d) and hence the activation method is a very convenient technique to obtain certain reaction cross sections [Ton08]. One drawback of the activation measurements in this particular case is the large attenuation corrections which need to be applied for the 208.0 keV  $\gamma$  ray exiting the thick  $^{238}\text{U}$  sample.

The result from the present  $^{238}\text{U}(n,2n)$  cross-section measurement and the existing literature data [Fil99, Gol87, Ves78] around 14 MeV neutron energy are shown in Fig. 5.6. As can be seen, the present result and previous measurements are

in good agreement.

Our future plans include analyzing the energy dependent yields of various fission product isotopes to investigate whether this ratio changes with increasing neutron energy and whether it is similar for different fissile actinides.

This work was supported by the National Nuclear Security Administration under the Stewardship Science Academic Alliances Program through Department of Energy grant DE-FG52-09NA29465.

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- [Fil99] A. A. Filatenkov *et al.*, *Systematic Measurement of Activation Cross Sections at Neutron Energies from 13.4 to 14.9 MeV*, Technical Report RI 252, Khlopin Radium Institute, Leningrad, 1999.
  - [Gol87] V. Y. Golovnya *et al.*, In *First Int. Conf. on Neutron Physics, Kiev*, volume 3, p. 281, 1987.
  - [Ton08] A. Tonchev *et al.*, *Phys. Rev. C*, **77**, 054610 (2008).
  - [Ves78] L. R. Veaser *et al.*, In *International Conference on Neutron Physics and Nuclear Data, Harwell*, p. 1054, 1978.

### 5.2.2 Test Measurements of the $^{235}\text{U}(n, 2n\gamma)^{234}\text{U}$ Reaction with PPAC-Based Fission Chamber

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**Future measurements of neutron-induced reactions on minor actinides at TUNL's shielded-neutron-source area require an efficient detector setup in combination with a low background. First measurements with a PPAC-based fission chamber were carried out to determine the level of background. Results of these measurements are presented.**

Measurements of neutron-induced reactions on  $^{235}\text{U}$  and  $^{238}\text{U}$  were carried out with monoenergetic neutron beams at TUNL with target masses of about 1.5 g [Hut09]. The natural radioactivity of the uranium targets together with the beam-related background make measurements of  $\gamma$ -ray transitions from low-lying states of the product nuclei very difficult. A novel approach to overcoming this background problem was proposed by the experimental nuclear physics group at LLNL. An experiment with a parallel-plate-avalanche-counter (PPAC)-based fission chamber, shown in Fig. 5.7, would have the advantages that (i) a thin target with a mass of 20 mg used in the PPAC would provide 75 times less natural radioactivity than the 1.5 g target used in the past, and (ii) the thinner target will not stop the fission fragments, which will then give a signal in the PPAC and can be used as a veto for the HPGe detectors to further reduce the background. Note that the induced fission in  $^{235}\text{U}$  from 10 MeV neutrons has a cross section of 1.7 barn. Furthermore, measurement of the  $\gamma$ -rays from the  $^{235}\text{U}(n, 2n\gamma)$  reaction can benefit from the reduced background of the  $4^+ \rightarrow 2^+$  transition in  $^{234}\text{U}$  at 99.9 keV which collects most of the  $\gamma$  cascades.

A scan of the neutron beam distribution at TUNL's shielded-neutron-source area was performed prior to the measurement with the PPAC. A liquid scintillator detector with a diameter of 5 cm was placed downstream to measure the flux of the neutron beam. Another small plastic scintillator detector with an area of  $0.32 \times 2.54 \text{ cm}^2$  was mounted on a remotely controlled stand positioned at the location where the PPAC chamber was to be installed. We deduced the diameter of the beam to be 4 cm at half intensity. This mea-

surement was used for precision alignment of the PPAC chamber.

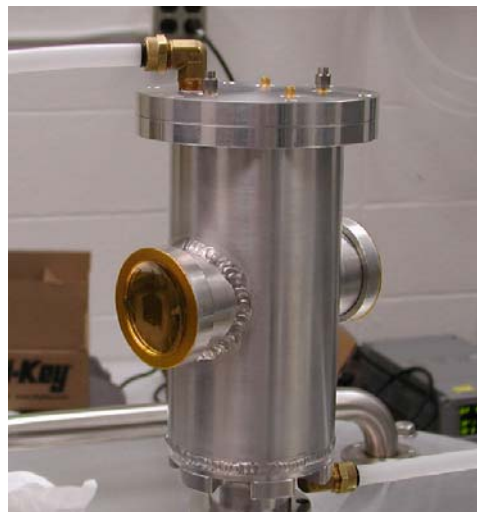


**Figure 5.7:** (Color online) A photograph of the PPAC-based fission chamber, showing the Al chamber, the Kapton windows for the neutron beam and the tubing of the gas-handling system.

We carried out a test measurement with the PPAC chamber containing two  $^{235}\text{U}$  foils, each with a mass of 10 mg, at  $E_n = 10 \text{ MeV}$ . Two aluminized Mylar foils on either sides of the  $^{235}\text{U}$  foil collected the charge produced by the fission fragments in isobutane gas. Two thin Kapton foils on the entrance and exit windows were used in order to reduce the scattering of the neutron beam off the windows. Two 40% HPGe planar detectors, positioned on either side of the PPAC chamber and  $90^\circ$  relative to the beam, registered the  $\gamma$ -rays from the neutron-induced reaction in  $^{235}\text{U}$ . The detectors were equipped with BGO escape-suppression shields. Passive

shielding consisting of two 20 cm thick tungsten walls installed at the upstream side of each detector was built. A copper ring with a length of 22 cm was positioned at the end of the collimator to serve as a post-collimator and reduce the beam halo. We installed an evacuated aluminum pipe with thin Kapton windows upstream from the collimator and the PPAC chamber in order to reduce the scattering of neutrons in air. In previous measurements with an iron target, we determined that the vacuum pipe reduced the time spread of the neutron beam. The results from this measurement are shown in Fig. 5.8. The whole setup was placed in a housing made of paraffin blocks in order to reduce the accidental background from neutrons scattered in the experimental hall. Tests with the paraffin  $2\pi$  half-housing revealed a 10% reduction of the accidental background, as shown in Fig. 5.8.

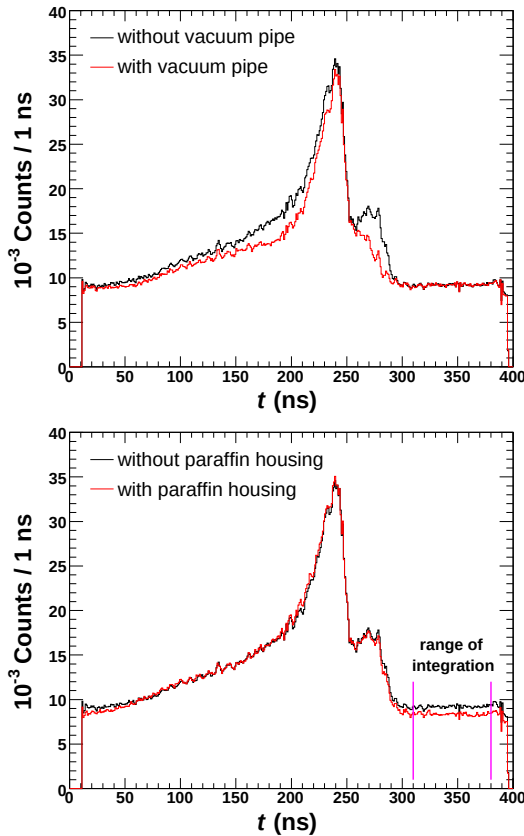


Figure 5.8: (Color online) Measurements with an iron target with and without a vacuum pipe (top panel) and with and without a paraffin housing (bottom panel) covering  $2\pi$  of the Ge detectors.

We carried out measurements with the described setup, without the  $^{235}\text{U}$  foils, without the PPAC chamber and without the neutron beam. These measurements helped us to decompose the background contributions from the aluminum chamber, the accidental background and the natural activity of the  $^{235}\text{U}$  foils in the measurement with the PPAC chamber. The results of this decompositions are shown in Fig. 5.9 in the energy range where the  $6^+ \rightarrow 4^+$  transitions in  $^{234}\text{U}$  at 152.7 keV is expected.

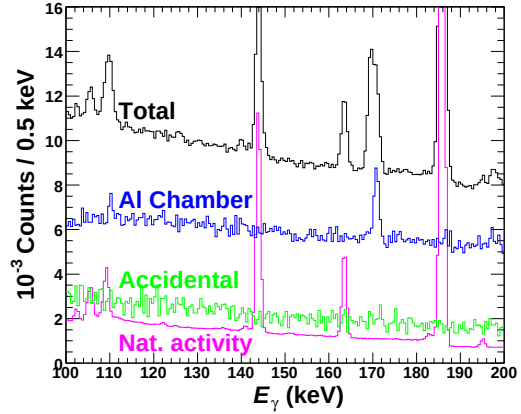


Figure 5.9: (Color online) Decomposition of the background in the  $\gamma$ -ray spectrum from the measurement with the PPAC-based fission chamber. The curves show the total background and the contributions of the scattered neutrons from the Al chamber, the accidental background and the background due to the natural activity of the  $^{235}\text{U}$  target.

A redesign of the aluminum chamber or reduction of the diameter of the neutron beam should be performed, because scattering of the beam in the chamber makes the greatest contribution to the background. Such a reduction in a future experiment will allow us to measure the efficiency of the PPAC and to deduce the detection sensitivity for the transitions at 99.9 keV in  $^{234}\text{U}$ .

This work was supported by the National Nuclear Security Agency under the US Department of Energy grant DE-FG52-09NA29465.

[Hut09] A. Hutcheson *et al.*, Phys. Rev. C, **80**, 014603 (2009).

### 5.2.3 Measurement of the $^{187}\text{Re}(n,2n\gamma)^{186m}\text{Re}$ Destruction Cross Section

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We are continuing a program to measure cross sections for  $^{187}\text{Re}(n,2n\gamma)$  reactions with particular interest in confirming a transition that has tentatively been identified as a doorway transition feeding  $^{186m}\text{Re}$  at  $E_x = 149(7)$  keV. The cross sections are being measured using pulsed, nearly mono-energetic neutron beams and an array of planar HPGe  $\gamma$ -ray detectors. At present, the reaction cross sections for the  $^{187}\text{Re}(n,2n\gamma)$  reaction are poorly known, so measuring the cross sections can have positive implications, for example, on the physics of reactors, where Re can be produced. Furthermore, refining the cross section measurements may reduce uncertainties in the Re/Os cosmochronometer.

The level structure of  $^{186}\text{Re}$  includes a long-lived isomeric state identified at  $E_x = 149(7)$  keV with a half-life of  $2 \times 10^5$  y. At present, no  $\gamma$ -ray transitions have been identified that feed into the isomer [Bag03]. A recent conference proceeding reporting on a  $^{186}\text{W}(d,2n)$  experiment has suggested that the isomer is fed from an  $E_x = 324$  keV level that decays sequentially via  $E_\gamma = 144.2$  and 30 keV transitions [Kon06], but these observations have not been confirmed. In addition to uncertainties in the feeding of the isomeric state, the situation for the  $^{187}\text{Re}(n,2n)^{186,186m}\text{Re}$  cross sections is also open for great improvement, since the current data on the cross sections are much lower than the cross sections given in the recent ENDF evaluations.

In general, studies of rhenium nuclei cover a range of topics including medical physics [Sze09], reactor physics [Yam94] and nuclear astrophysics [Mos10]. The latter two areas of study may be influenced by improved cross section measurements for the  $^{187}\text{Re}(n,2n)$  reactions. For example, the  $^{187}\text{Re}$  isotope is produced as a fission fragment in reactors, where it acts as a neutron multiplier via  $(n,2n)$  reactions. Its effect as a catalyst speeding up chain reactions needs to be considered to ensure optimal running conditions inside the reactor.

Improvement in the  $^{187}\text{Re}(n,2n)^{186,186m}\text{Re}$  cross sections may also benefit the Re/Os cosmochronometer. The chronometer evaluation, which depends on the composition of  $^{187}\text{Os}$  (produced by the  $s$ -process) and  $^{187}\text{Re}$  (produced by the  $r$ -process) in a meteorite, can be interpreted to deduce the age of the speci-

men. While the  $(n,\gamma)$  and  $(\gamma,n)$  reactions are of primary importance for the chronometer, the  $^{187}\text{Re}(n,2n)^{186,186m}\text{Re}$  reactions also act to destroy cosmogenic  $^{187}\text{Re}$ , and improvements in the cross sections may provide improvements in the chronometer's accuracy.

In previous years, we have reported on two measurements. In 2007 we attempted to measure prompt  $\gamma$  rays emitted during an in-beam measurement aimed at observing the transition feeding the isomer, and in 2008 we attempted an activation experiment intended to measure the cross sections by standard activation and off-line counting techniques. Feasible improvements have been implemented in the prompt  $(n,xn\gamma)$  measurements reported here. On the other hand, the extremely long half-life of  $^{186}\text{Re}$  and the high background from the  $t_{1/2} = 6$  month isomer produced in the  $^{185}\text{Re}(n,2n)^{184m}\text{Re}$  reaction essentially rule out the activation technique as a feasible approach for measuring the cross sections with  $^{nat}\text{Re}$  samples.

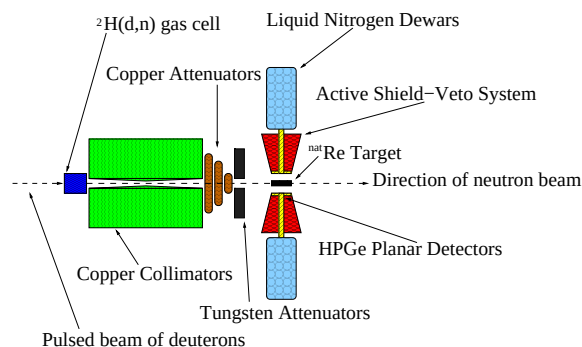


Figure 5.10: Diagram of experimental apparatus used in May 2010.

In May 2010,  $^{187}\text{Re}(n, xn\gamma)$  reaction data were taken using a 5 cm by 5 cm, 0.1 mm thick  $^{nat}\text{Re}$  target. A thin Fe foil matching the size of the Re target was included in the target package and will be used for neutron beam flux normalization. The target was placed between two HPGe planar detectors surrounded by passive shielding in the Shielded Source Area at TUNL (see Fig. 5.10). The target was bombarded by a pulsed, quasi-monoenergetic beam of 12 MeV neutrons, and a neutron detector was placed at zero degrees with respect to the beam to act as a neutron-beam-flux monitor. The beam flux on the target was approximately  $10^4$  neutrons/(cm<sup>2</sup>s). Data from this measurement are presented here, though a subsequent measurement incorporated two planar HPGe detectors and an HPGe clover detector.

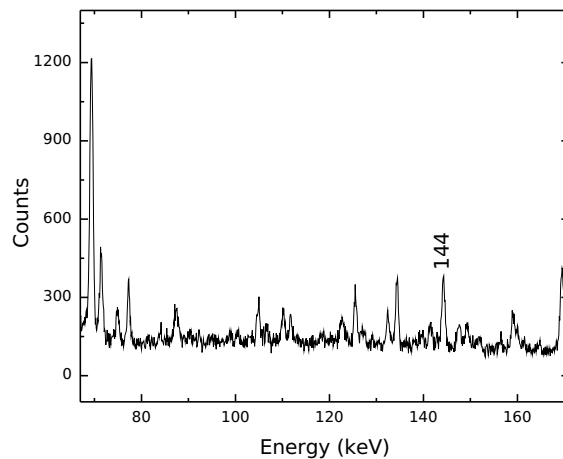


Figure 5.11: Spectrum illustrating observed  $\gamma$ -ray transitions near the 144 keV region.

The present  $\gamma$ -ray spectra are selected by gating on the prompt neutron time-of-flight peak. The so-called time-of-flight spectra show a flat background with peaks corresponding to events produced by  $^2\text{H}(d,n)^3\text{He}$  prompt neutrons and  $^2\text{H}(d,np)\text{D}$  breakup neutrons. Software gates on the “beam-on” and “beam-off” parts of the TOF spectrum are used to generate the associated spectra, and the final spectrum shown in Fig. 5.11 is obtained by subtracting the beam-off background spectrum from the beam-on spectrum. Numerous transitions in the Re isotopes

are visible, including the suggested 144 keV transition.

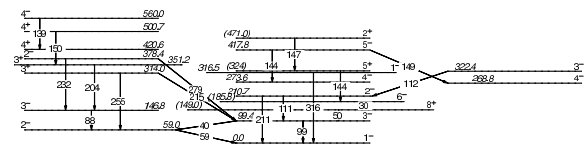


Figure 5.12: Level diagram showing presently observed  $^{186}\text{Re}$   $\gamma$ -ray transitions from  $^{185}\text{Re}(n, n'\gamma)^{186}\text{Re}$  reactions.

A simple analysis of the transitions populated in the  $^{187}\text{Re}(n, 2n\gamma)$  reaction is illustrated in the decay scheme shown in Fig. 5.12. Unfortunately, the measured yields do not permit a coincidence analysis. A survey of the transitions shows ambiguity in the placement of the 144 keV  $\gamma$ -ray. Future analysis of these data requires efficiency corrections in order to obtain the differential cross sections for the observed transitions and a determination of the total cross sections. An analysis of the sequential-decay transitions may shed light on which levels are involved in producing the 144 keV transition yield. A further extension of this analysis must involve, for example, a Hauser-Feshbach analysis to determine the total  $(n, 2n)$  cross section. A second approach in the analysis centers on the 17.3 ns half-life of the  $E_x = 324$  keV level. Evaluation of the 144 keV emission-time characteristic may be the most convincing evidence to confirm the doorway state transition and to evaluate the  $^{187}\text{Re}(n, 2n)^{186m}\text{Re}$  cross section.

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- [Bag03] C. Baglin, Nucl. Data Sheets, **99**, 1 (2003).
- [Kon06] F. Kondev *et al.*, In *Int. Symp. on Nuclear Astrophysics, Nuclei in the Cosmos - IX*, p. 41, CERN, Geneva, Switzerland, 2006.
- [Mos10] M. Mosconi *et al.*, Phys. Rev. C, **82**, 1 (2010).
- [Sze09] F. Szelecsényi *et al.*, J. Radioanal. Nucl. Chem., **282**, 261 (2009).
- [Yam94] N. Yamamuro, Nucl. Sci. Eng., **118**, 249 (1994).

## 5.2.4 Neutron-Induced Reaction Cross-Section Measurements on GaAs

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Neutron-induced reaction cross sections on GaAs have been measured at ten different energies from 7.5 to 15 MeV. Monoenergetic neutron beams were produced via the  ${}^2\text{H}(d,n){}^3\text{He}$  reaction at the TUNL 10 MV tandem accelerator facility. The induced activity in the irradiated samples was measured using HPGe detectors in a low-background counting area. The present data can serve as a test for statistical model calculations over a wide range of neutron energies and for a number of different reaction channels.

Cross section measurements of fast-neutron-induced reactions on GaAs are important for the characterization of this widely used semiconductor in high radiation environments. Such studies can have significant applications in the area of homeland security through nuclear forensics and the Stockpile Stewardship program. From a basic research perspective, these measurements are useful for testing statistical model codes and refining their parameter sets. Some of the measurements on GaAs were previously reported [Rau09]. Here we record the complete set of measurements carried out over the last year.

Neutron activation of GaAs foils was carried out at the 10 MV FN Tandem Accelerator in TUNL at ten different neutrons energies:  $E_n = 7.5(2)$ ,  $8.0(1)$ ,  $8.5(2)$ ,  $9.5(1)$ ,  $10.2(1)$ ,  $11.0(1)$ ,  $11.5(1)$ ,  $12.5(1)$ ,  $13.25(10)$ ,  $14.0(1)$ ,  $14.5(1)$ , and  $15.0(1)$  MeV, where the numbers in parentheses represent the energy spread of the incident beam. The monoenergetic neutron beam was produced via the  ${}^2\text{H}(d,n){}^3\text{He}$  reaction, known for its high neutron yield in the energy regime of the measurements. The deuterium gas was contained in a 3 cm long cylindrical cell at a pressure of around 2 atm and was sealed from the beamline vacuum by a thin Havar foil. The GaAs samples, 99.9% pure and cut into dimensions  $1\text{ cm} \times 1\text{ cm}$ , were mounted normal to the incident beam and 2.6 cm downstream from the exit end of the gas cell. Natural Al and Au foils with the same dimensions were irradiated together with the GaAs samples in order to estimate the incident neutron flux.

The neutron flux was  $\sim 10^7\text{ s}^{-1}$  and remained constant throughout the run. Following the irradiations, the samples were measured in a low-background counting area using HPGe detectors.

The  $\gamma$ -ray spectra acquired from the offline measurements of the activated samples were analyzed to identify the reaction products and estimate the respective  $\gamma$ -ray-transition peak areas in order to calculate the corresponding reaction cross sections. Table 5.1 lists the different reaction channels studied in the present measurements along with the half-life of the product and the  $\gamma$ -ray-transition energy used to identify and calculate the respective cross sections.

The cross sections for the reactions of interest from the present work are plotted in Figure 1 as a function of the incident neutron energy  $E_n = 7.5$ –15 MeV. Statistical model calculations using the TALYS [Kon08] code were carried out for these reactions, and the results are plotted along with the experimental numbers. The theoretical excitation functions are found to be in good agreement with the experimental cross sections for most of the reactions. Similar calculations with the EMPIRE [Her07] and GNASH [You92] codes are currently in progress, and the preliminary results for some of the reactions have been shown in the plot. The existing measurements for the different reactions and the latest cross-section-data evaluations have also been plotted.

This work is supported by the National Nuclear Security Agency under Grant No. DE-FG52-06NA-26155.

Table 5.1: Neutron induced reactions on GaAs and the monitor foils measured in the present work.

| Reaction Channel                         | Product Half-life | Q-value (keV) | Gamma Energy (keV) | Intensity (%) |
|------------------------------------------|-------------------|---------------|--------------------|---------------|
| <b>GaAs Reactions</b>                    |                   |               |                    |               |
| $^{69}\text{Ga}(n,2n)^{68}\text{Ga}$     | 67.71 m           | -10312.95     | 1077.34            | 3.22          |
| $^{69}\text{Ga}(n,p)^{69m}\text{Zn}$     | 13.76 h           | -127.44       | 438.634            | 94.77         |
| $^{71}\text{Ga}(n,p)^{71m}\text{Zn}$     | 3.96 h            | -2031.0       | 386.28             | 0.93          |
| $^{75}\text{As}(n,2n)^{74}\text{As}$     | 17.77 d           | -10243.76     | 634.78             | 15.4          |
| $^{75}\text{As}(n,p)^{75}\text{Ge}$      | 82.78 m           | -393.63       | 264.6              | 11.4          |
| <b>Monitor Reactions</b>                 |                   |               |                    |               |
| $^{197}\text{Au}(n,2n)^{196}\text{Au}$   | 6.1669 d          | -8072.39      | 355.73             | 87            |
| $^{27}\text{Al}(n,\alpha)^{24}\text{Na}$ | 14.997 h          | -3132.14      | 1368.626           | 99.9936       |

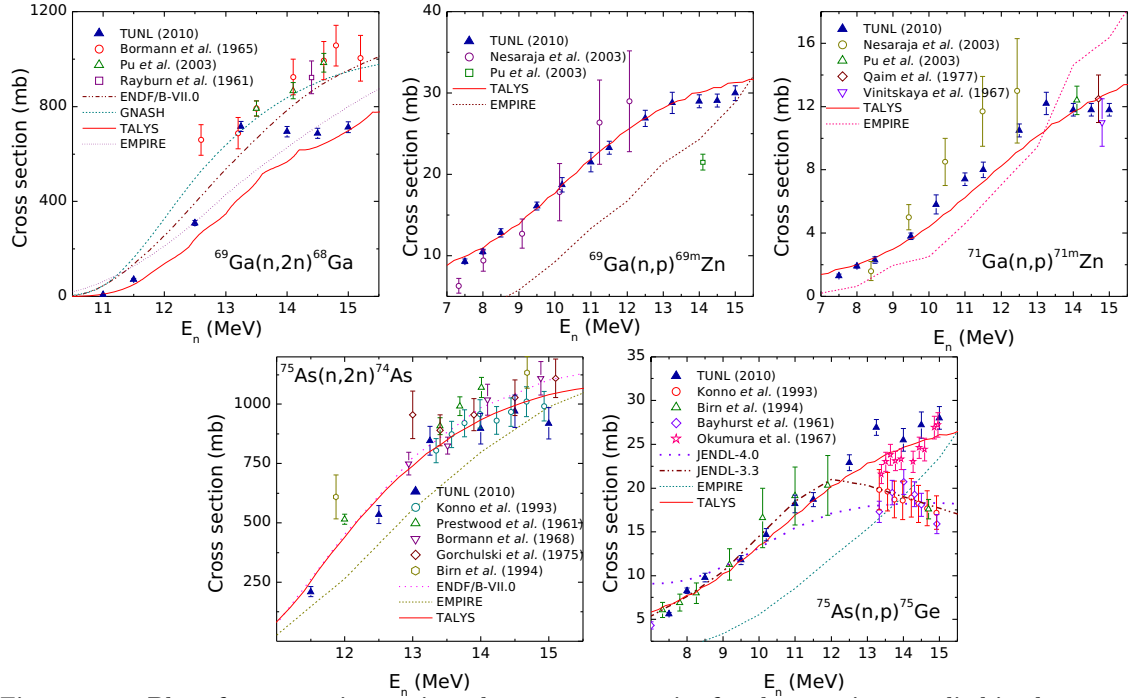


Figure 5.13: Plot of cross section against the neutron energies for the reactions studied in the present measurements. Each plot also includes the theoretical calculations using the statistical model codes, the latest evaluations and the available literature data.

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- [Her07] M. Herman *et al.*, Nucl. Data Sheets, **108**, 2655 (2007).
- [Kon08] A. J. Koning, S. Hilaire, and M. C. Dujvestijin, In *Proceedings of the International Conference on Nuclear Data for Science and Technology*, p. 211, 2008.
- [Rau09] R. Raut *et al.*, TUNL Progress Report, **XLVIII**, 109 (2009).
- [You92] P. Young, E. Arthur, and M. Chadwick, *Comprehensive Nuclear Model Calculations, Introduction to the Theory and Use of the GNASH Code*, Technical Report LA-12343-MS, Los Alamos National Laboratory, 1992.

### 5.2.5 Neutron Capture Experiments

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**The neutron capture reaction is very important for a wide variety of pure and applied physics. Our measurements utilize the DANCE array (at LANSCE/Lujan)—a highly efficient calorimeter consisting of 160 BaF<sub>2</sub> detectors. The high degree of segmentation can be used to perform neutron resonance spectroscopy. The study of the statistical  $\gamma$ -ray cascade from different resonances and for different multiplicities provides unique opportunities to test models of the photon strength function.**

The neutron capture reaction is important for a variety of pure and applied physics, ranging from stewardship science (radiochemical applications) to astrophysics to advanced fuel cycle issues. We are performing neutron capture experiments with the Detector for Advanced Neutron Capture Experiments (DANCE) at the Manuel Lujan Center at Los Alamos National Laboratory. DANCE is an array of barium fluoride crystals (162 segments with 160 crystals). The high efficiency of DANCE (this is a calorimeter that identifies capture by the  $\gamma$ -ray total energy) makes possible the study of very small samples, including radioactive samples. The high degree of segmentation makes possible the separation of the statistical  $\gamma$ -ray cascade for different multiplicities. One limitation of this calorimeter system involves setting the energy gate on the total  $\gamma$ -ray energy. In order to accumulate sufficient statistics, the range of this gate is typically one MeV.

We first focused on the photon strength function (PSF) in <sup>95</sup>Mo. We tested various models by simulating the statistical cascade with the program DICEBOX. The DANCE data provide information on the  $\gamma$ -ray spectra for many different multiplicities. We label these as multi-step-cascade (MSC) measurements. Another measurement is the two-step-cascade (TSC) measurement, which is essentially a multiplicity-two measurement. The MSC measurements provide information on many multiplicities but with poor resolution, while the TSC measurements have excellent resolution but are limited (by definition) to only one multiplicity. To examine further the issue of how well the statistical model

works in this mass region, we also performed a TSC measurement on <sup>95</sup>Mo at the Rez Institute. This measurement complements and extends the DANCE results, so we were able to study the TSC to 11 different final states. We determined a rather standard set of values for the level density and the PSFs that fit all of the TSC data very well.

We then adopted the parameter set that provided this excellent agreement and applied it in the simulation of our DANCE data with the statistical model code DICEBOX. The result was very good agreement. Thus, there is strong evidence that the extreme statistical model works very well in this mass region. These DANCE results have been published [She09].

Measurement of the neutron capture reaction has now been performed on <sup>152,154,155,156,157,158,160</sup>Gd. We are in the process of analyzing all of these data. The gadolinium isotopes are very important both for practical reasons and for pure physics. For example, measurement of the scissors-mode resonance for all of the gadolinium isotopes should clarify the dependence of this excitation mode on mass and deformation. Our initial focus was on <sup>155</sup>Gd and <sup>157</sup>Gd, because these isotopes have very large cross sections and important applications. Analysis of these two nuclides formed the basis of the dissertations of A. Chyzh (<sup>157</sup>Gd) and B. Baramsai (<sup>155</sup>Gd). The scissors mode resonance is required in order to obtain even a qualitative fit to the DANCE  $\gamma$ -ray spectra. The location and width of the resonance seem in reasonable agreement with other data, but the strength appears somewhat low. Analysis of the complete set of

isotopes is needed before reaching any definitive conclusions.

Another interesting aspect of these data is the neutron spectroscopy. At DANCE we have measured neutron capture on  $^{94,95,97}\text{Mo}$ . The analysis of the recently measured  $^{97}\text{Mo}$  data is in progress, and additional measurements are scheduled for the summer of 2010. For  $s$ -wave resonances on  $^{95}\text{Mo}$  (ground state  $J^\pi = 5/2^+$ ), the compound-state  $s$ -wave resonances have  $J = 2$  or 3. The ground state of  $^{96}\text{Mo}$  has  $J = 0$ . If the decay is statistical, one expects, on average, a higher multiplicity for the  $J = 3$  states. In addition, the energy spectra for resonances with different spin are different, especially for the multiplicities  $M = 2$  and 3. The combination of the average multiplicity and the  $M = 2$  and 3 spectra leads to a very clear signature. There is excellent agreement with previous information on  $^{96}\text{Mo}$ .

In the study on  $^{95}\text{Mo}$ , determining the average multiplicity was sufficient to determine the  $J$ -values for the  $s$ -wave resonances. For the odd mass gadolinium targets, the average multiplicity is not sufficient to determine  $J$ . For  $^{155}\text{Gd}$ , the average multiplicities appear to separate into two groups, but there are many ambiguities. A variety of methods have been developed that enable the determination of the spin  $J$ . One method is described in the thesis of B. Baramsai [Bar10]. If there were no experimental errors or Porter-Thomas (PT) fluctuations, then the values of the multiplicity distributions for the two  $s$ -wave spins ( $J = 1$  and 2) would be points in a multiplicity hyperspace. The errors and PT fluctuations lead to two clusters rather than two points. Determining which of the two clusters a given resonance belongs to (and with what probability) is a problem in pattern-recognition theory. We have applied pattern-recognition methods to determining the spins of the  $s$ -wave resonances in

the compound system  $^{156}\text{Gd}$ . The  $s$ -wave level density agrees well with previously established values. The separate level densities for  $J = 1$  and 2 obey the expected  $(2J + 1)$  dependence extremely well.

In principle one can apply this analysis method to more complicated cases, such as combined  $s$  and  $p$  sequences. For targets with spin, this leads to two  $s$ -wave and four  $p$ -wave states. In the Mo isotopes there are a significant number of  $p$ -wave resonances, and the spins of the resonances are of astrophysical interest. One critical issue is the determination of the parity of the resonance. After separation by parity, the pattern-recognition analysis method works reasonably well, even for the  $p$ -wave resonances. For spin-zero targets, where there are only one  $s$ -wave and two  $p$ -wave possibilities, this analysis method work well even without the parity separation.

The DANCE array can be used to determine the cross section, even in unfavorable cases where the scattering cross section is many times greater than the capture cross section. This is case for  $^{89}\text{Y}$ , which is used as a radiochemical detector. The capture cross section for  $^{89}\text{Y}$  has been measured with significantly reduced errors. Much of the reduction in the cross-section errors involved the use of nuclides with similar ratios of scattering-to-capture cross sections in order to better determine the backgrounds. The details are covered in the thesis of A. Chyzh [Chy09].

Much of this research is supported by an academic alliances grant from the National Nuclear Security Agency.

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[Bar10] B. Baramsai, Ph.D. thesis, NCSU, 2010.

[Chy09] A. Chyzh, Ph.D. thesis, NCSU, 2009.

[She09] S. A. Sheets *et al.*, Phys. Rev. C, **79**, 024301 (2009).



# Photonuclear Reactions at $\text{HI}\gamma\text{S}$

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Chapter 6

- Nuclear Astrophysics
- $\gamma$ - $^3\text{He}$  Interaction
- $\gamma$ - $^4\text{He}$  Interaction
- Study of Many-Body Systems

## 6.1 Nuclear Astrophysics

### 6.1.1 Measurements of the angular distributions of the $^{12}\text{C}(\gamma, 3\alpha)$ reaction at $E_\gamma \approx 9.8$ MeV with the O-TPC detector.

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**We have used the optical readout time projection chamber (O-TPC) detector to study the  $^{12}\text{C}(\gamma, 3\alpha)$  reaction at  $E_\gamma = 9.363, 9.556$  and  $9.771$  MeV in search for the elusive  $2_2^+$  state of  $^{12}\text{C}$ . We developed a method to separate  $^{12}\text{C}$  and  $^{16}\text{O}$  dissociation events emanating from the  $\text{CO}_2$  target. Pure E2 angular distributions were measured at all energies.**

Carbon is formed during stellar helium burning in the triple-alpha process, the  $^8\text{Be}(\alpha, \gamma)^{12}\text{C}$  reaction, that is mostly governed by the contribution of the  $0^+$  Hoyle state at 7.654 MeV. At high temperatures ( $T > 3$  GK) higher lying states in  $^{12}\text{C}$  may contribute. Indeed a broad ( $\Gamma = 560$  keV,  $\Gamma_\gamma = 0.2$  eV)  $2^+$  state at 9.11 MeV in  $^{12}\text{C}$  was included in the NACRE compilation [Ang99] following a theoretical prediction [Des87] for the  $2^+$  member of the rotational band built on top of the  $0^+$  Hoyle state at 7.654 MeV. It increases the production of carbon at temperatures in excess of 1 GK by up to a factor of 15. A larger production of  $^{12}\text{C}$  at high temperatures increases the neutron density as required for an r-process, due to the competition between the  $^8\text{Be}(\alpha, \gamma)$  reaction and the  $^8\text{Be}(n, \gamma)$  reaction [Del71, Pru05]. A  $2^+$  member of the rotational band built on top of the Hoyle state is not predicted in the conjectured alpha condensate [Fun09] which predicts a spherical Hoyle state. Evidence for a broad  $2^+$  state was found in a  $^{12}\text{C}(\alpha, \alpha')$  experiment [Ito04] and at 9.6 MeV in a  $^{12}\text{C}(p, p')$  measurement [Fre09] but such a state was not observed in the beta-decay of  $^{12}\text{B}$  and  $^{12}\text{N}$  [Hyl09].

We used our Optical-Readout Time Projection Chamber (O-TPC) [Gai10] operating with  $\text{CO}_2$  gas and gamma beams extracted from the HI $\gamma$ S facility [Wel09] to search for such a  $2^+$  state via the identification of triple alpha events from the  $^{12}\text{C}(\gamma, 3\alpha)$  reaction. We have studied this reaction at  $E = 9.363, 9.556$  and  $9.771$  MeV. One major draw back for using  $\text{CO}_2$  gas is that the difference of Q-values for the dissociation of  $^{16}\text{O}$  and  $^{12}\text{C}$  (112 keV) is considerably smaller than the beam width and comparable to the detector resolution of approximately 80 keV [Gai10].

In addition the larger quenching factor for the low energy  $^{12}\text{C}$  projectiles leads to a smaller grid charge-signal from the dissociation of  $^{16}\text{O}$  with an energy very similar to that of the dissociation of  $^{12}\text{C}$ . Hence the total energy deposited in the O-TPC detector (grid charge signal) cannot be used to separate (and thus identify)  $^{12}\text{C}$  and  $^{16}\text{O}$  dissociation events.

The energy shared by the two body  $\alpha + A_2$  decay differs for  $^{16}\text{O}$  and  $^{12}\text{C}$  events. We define the ratio:  $R = \frac{E(\alpha)}{E(A_2)}$ . This ratio is 3 for  $^{16}\text{O}$  events and 2 for  $^{12}\text{C}$  events. Due to the attenuation factor of the outgoing  $^{12}\text{C}$  the measured ratio R for  $^{16}\text{O}$  events is in fact closer to 4. Thus the ratio R can be used to distinguish and identify  $^{12}\text{C}$  events. This ratio R can be measured by measuring the ratio of the emitted light as well as the ratio of the track lengths measured in time. In addition a similar measurement can be performed using the pixel content of the CCD camera as long as the CCD camera provides clean signals; a goal that has not yet been achieved with our current camera but is anticipated with the new camera we purchased. Thus the ratio R can be measured four times. A multiplication of the measured R values yields a separation which is approximately a factor of 2 better since the fluctuations increase by only approximately the square root of 4. We also fit each event with a line shape calculated for an  $\alpha + ^{12}\text{C}$  event, yielding good  $\chi^2$  for  $^{16}\text{O}$  events and bad  $\chi^2$  for  $^{12}\text{C}$  events.

In Fig. 1 we show the so obtained surface plot of event identification using the "effective  $\chi^2$ " and the multiplication of the ratio R as obtained from the PMT signal only; the ratio of the integrated light (I) times the track length (L). In

Fig. 2 we show the same surface plot for events that were clearly identified as  $^{12}C$  events by observing kinks in the PMT signal or in the CCD image. In both Figs. 1 and 2 we show data bins including at least two events. The separation of  $^{12}C$  events using the above discussed method is estimated to yield an uncertainty which is smaller than 10%.

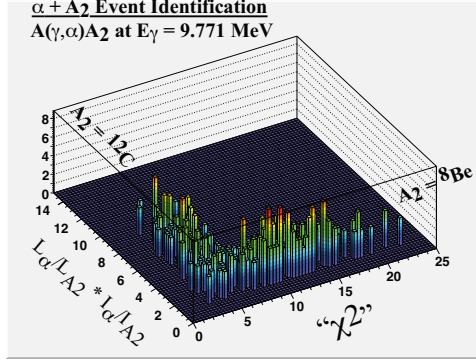


Figure 6.1: Event identification surface plot (1 count suppressed) for all events as discussed in the text.

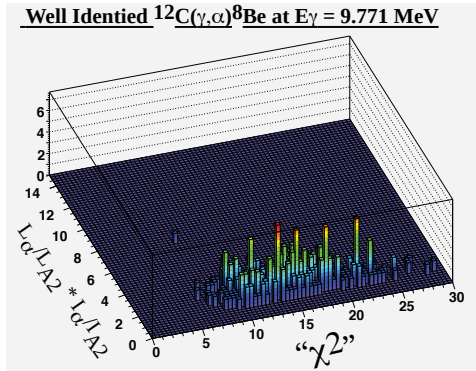


Figure 6.2: Event identification surface plot (1 count suppressed) for well identified  $^{12}C$  dissociation events as discussed in the text.

The in plane angle ( $\alpha$ ) measured by the track registered in the CCD image and the out-of-plane angle ( $\beta$ ) measured by the Time projection signal of the PMT allow us to deduce for each event the scattering angle ( $\theta$ ) and the azimuthal angle ( $\phi$ ) of the polar coordinate system used in scattering theory:  $\cos\theta = \cos\beta \times \cos\alpha$  and  $\tan\phi = \frac{\tan\beta}{\sin\alpha}$ . The so obtained angular distribution is

shown in Fig. 3 together with that predicted for a pure  $0^+ \rightarrow 2^+$  E2 transition. For these data we used only in plane ( $\beta < 20^\circ$ ) data for which the scattering angle ( $\theta$ ) is determined with high accuracy.

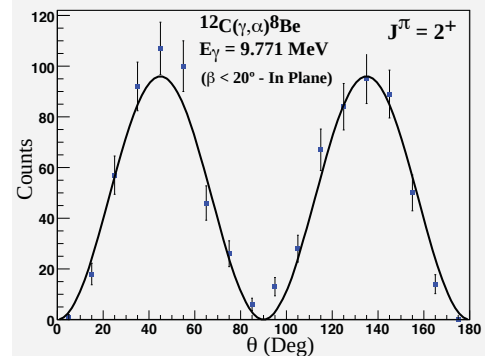


Figure 6.3: Measured angular distribution for in plane ( $\beta < 20^\circ$ )  $^{12}C(\gamma, 3\alpha)$  events compared to the prediction for a pure  $0^+ \rightarrow 2^+$  E2 transition.

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- [Ang99] C. Angulo *et al.*, Nucl. Phys. A, **656**, 3 (1999).
  - [Del71] M. Delano and A. Cameron, Astr Space Sci., **10**, 203 (1971).
  - [Des87] P. Descouvemont and D. Baye, Phys. Rev. C, **36**, 54 (1987).
  - [Fre09] M. Freer *et al.*, Phys. Rev. C, **80**, 041303(R) (2009).
  - [Fun09] Y. Funaki *et al.*, Phys. Rev. C, **80**, 64326 (2009).
  - [Gai10] M. Gai *et al.*, submitted to JINST, 2010.
  - [Hyl09] S. Hyldegaard *et al.*, Phys. Lett. B, **678**, 459 (2009).
  - [Ito04] M. Itoh *et al.*, Nucl. Phys. A, **738**, 268 (2004).
  - [Pru05] J. Pruet *et al.*, Astr. Jour., **623**, 325 (2005).
  - [Wel09] H. R. Weller *et al.*, Prog. Part. Nucl. Phys., **62**, 257 (2009).

### 6.1.2 Photoneutron Measurements of Astrophysically Important States in $^{26}\text{Mg}$

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**The photoneutron cross section of  $^{26}\text{Mg}$  near the neutron-separation energy, which is of interest for s-process nucleosynthesis, was studied at the High Intensity Gamma-Ray Source of the Triangle Universities Nuclear Laboratory. A nearly mono-energetic and linearly polarized  $\gamma$ -ray beam was used to scan the excitation energy range from 10.8 to 12.05 MeV as a preparatory run for a high resolution time of flight measurement.**

The s-process is a mechanism for the formation of many of the heavy isotopes up to lead. The s-process proceeds by neutron capture onto stable light isotopes who subsequently  $\beta$ -decay, but a mechanism for neutron production must be available. In stellar environments,  $^{22}\text{Ne}$  can be produced by the reaction chain  $^{14}\text{N}(\alpha, \gamma)^{18}\text{F}(\beta^+)^{18}\text{O}(\alpha, \gamma)^{22}\text{Ne}$  where  $^{14}\text{N}$  is one of the main products of the CNO cycle. It has been suggested [Ibe75] that a main source of neutrons for the s-process is the  $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$  reaction rate. Therefore, knowledge of the level parameters of  $^{26}\text{Mg}$  in the critical energy range from  $10.9 \text{ MeV} < E_x < 11.5 \text{ MeV}$ , are essential. Photoexcitation at the High Intensity Gamma-Ray Source (HI $\gamma$ S) provides an alternative approach to the direct reaction method which is made hampered by high coulomb penetrability.

A recent successful experiment, also performed at HI $\gamma$ S [Lon09], has prompted further investigation. While the last experiment focused on photon scattering on  $^{26}\text{Mg}$ , the aim of the current experiment is to investigate levels by  $^{26}\text{Mg}(\gamma, n)$ . The main goal is to investigate key resonances near the neutron-separation energy by the time-of-flight (TOF) method. The experiment has been divided into two parts: a preliminary background and count rate measurement run, and the TOF measurement. The background run has been completed with encouraging results prompting the continuation of the second part of the experiment later this year. The following summarizes the results obtained so far.

The experimental setup consisted of an enriched  $^{26}\text{MgO}$  target placed at the center of a  $4\pi$   $^3\text{He}$  neutron counter [Spr93] which was positioned symmetrically along the beam axis. One

of the main goals of this part of the experiment was to measure and then minimize background. To test the beam induced background several initial runs were performed at 10.8 MeV, well below the  $^{26}\text{Mg}$  neutron-separation energy at 11.1 MeV. Background was tested in five stages: a blank run, target holder only, aluminum scatterer, a natural  $\text{MgO}$  sample, and the enriched target. For the first two tests the background was found to be 20 neutrons/s. The Al scatterer and the natural sample showed in ceases of 2 and 4 neutrons/s respectively.

The enriched target was  $^{26}\text{MgO}$  and had a total mass of 16.4185 grams and was isotopically enriched to 99.41(6)%  $^{26}\text{Mg}$  (0.41(2)%  $^{24}\text{Mg}$  and 0.18(4)%  $^{25}\text{Mg}$ ) with natural oxygen isotopic abundance. Other impurities were of the order parts per million. Of main concern was  $^{25}\text{Mg}$ ,  $^{17}\text{O}$ ,  $^{18}\text{O}$  which have neutron-separation energies of 7.3, 4.1, and 8.0 MeV respectively. Cross sections for all isotopes had been measured in the energy range of interest previously and are of the same order (mbarns) as the  $^{26}\text{Mg}$ . Since the amount these isotopes is small compared to the  $^{26}\text{Mg}$ , minimal background contribution were expected. The total count rate was found to be about 30 neutrons/s at 10.8 MeV.

The main source of background was found to be the beam induced background most likely from lead near the beam pipe. The lead  $(\gamma, n)$  cross section is very high at these energies ( $\sim 200$  mb). In fact, the small lead plug used for beam alignment was observed to produced count rates of  $\sim 50$  neutrons/s when it was placed in front and then behind the detector. An effort was made to decrease the beam induced neutron background by shielding the front of the detec-

tor with cadmium sheets and Lithium and Boron loaded polyethylene blocks. Final analysis finds the neutron background at 24 neutrons/s after all shielding was in place.

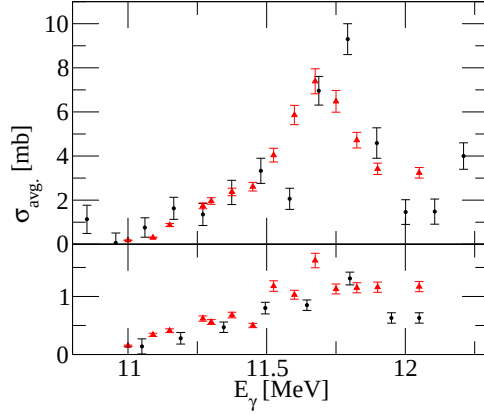


**Figure 6.4:** (Color online) Integrated cross sections of  $^{26}\text{Mg}(\gamma, n)$  and  $^{nat}\text{Mg}(\gamma, n)$  (Preliminary). The upper plot shows the  $^{26}\text{Mg}(\gamma, n)$  while the bottom plot shows the  $^{nat}\text{Mg}(\gamma, n)$  cross section. The data shown in red triangles are our recent measurements while those in black circles are those from Ref. [Ful71].

The  $^{26}\text{Mg}(\gamma, n)$  and  $^{nat}\text{Mg}(\gamma, n)$  cross sec-

tions were measured at 14 energies between 10.8 and 12.2 MeV as shown in Fig. 6.4. Count rates varied from  $\sim 100$  neutrons/s near the neutron-separation energy up to  $\sim 1000$  neutrons/s on top of the large resonance at  $E_\gamma = 11.7$  MeV. The average cross section was found to be in good agreement with that of Ref. [Ful71] and smaller uncertainties were obtained. The excitation curve was mapped up to 12.05 MeV in order to scan the first resolvable resonance at  $E_\gamma = 11.7$  MeV. Area analysis ( $g_\gamma \Gamma_{\gamma_0} \Gamma_n / \Gamma = 32(2)$  eV) of this peak finds it to be in excellent agreement with that of Ref. [Bag71].

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[Bag71] R. J. Baglan, C. D. Bowman, and B. L. Berman, Phys. Rev. C, **3**, 672 (1971).

[Ful71] S. C. Fultz *et al.*, Phys. Rev. C, **4**, 149 (1971).

[Ibe75] I. Iben, Jr., Astrophys. J., **196**, 525 (1975).

[Lon09] R. Longland *et al.*, Phys. Rev. C, **80**, 055803 (2009).

[Spr93] J. Sprinkle *et al.*, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, la-12496-ms edition, 1993.

### 6.1.3 A New Astrophysical Reaction Rate for $\alpha + \alpha + n$

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A new astrophysical reaction rate for the three-body  $\langle\alpha\alpha n\rangle$  reaction has been calculated using new, high-precision  ${}^9\text{Be}(\gamma, n)$  cross section data. This rate is important for modeling nucleosynthesis in neutrino-driven winds from core-collapse Type II supernovae ( $\nu\text{wSII}$ ). Reaction network codes rely on accurate cross-section data to produce meaningful universal-nuclear-abundance predictions. The production of heavy  $r$ -process nuclei under realistic  $\nu\text{wSII}$  conditions is extremely sensitive to the  $\langle\alpha\alpha n\rangle$  rate. For temperatures relevant to the  $r$ -process at this astrophysical site, the present calculated rate is 24 to 30% larger than rates currently in use. The effects of this new rate in reaction network codes are discussed.

The  ${}^4\text{He}(\alpha n, \gamma){}^9\text{Be}$  reaction and the triple- $\alpha$  reaction are the two 3-body reactions known to have significant astrophysical relevance for their ability to bridge the mass stability gaps at  $A = 5$  and  $A = 8$ . The  ${}^4\text{He}(\alpha n, \gamma){}^9\text{Be}$  reaction has predominance over the  $3\alpha$  reaction in high-temperature, high-neutron-flux, and short-time-scale environments such as the neutrino-wind from core-collapsed Type II supernovae. The formalism for interpreting 3-body astrophysical reaction rates described by Angulo *et al.* [Ang99] was adopted, and is described in brief below.

Calculation of the astrophysical reaction rate for  $\langle\alpha\alpha n\rangle$  is performed in two steps. First two  $\alpha$ -particles with center-of-mass (COM) energy  $E$  interact to form a metastable  ${}^8\text{Be}$  nucleus ( $\tau \sim 10^{-16}$  s). A neutron and a  ${}^8\text{Be}$  with COM energy  $E'$  subsequently interact, forming stable  ${}^9\text{Be}$ . For a given temperature,  $\alpha$ -particles and neutrons will have a Maxwell-Boltzman distribution of energies. To calculate the rate of production of  ${}^9\text{Be}$ , a double integral of the form

$$N_A^2 \langle\sigma v\rangle^{\alpha\alpha n} = N_A \left( \frac{8\pi\hbar}{\mu_{\alpha\alpha}^2} \right) \left( \frac{\mu_{\alpha\alpha}}{2\pi k_b T} \right)^{3/2} \times \int_0^\infty \frac{\sigma_{\alpha\alpha}(E)}{\Gamma_\alpha({}^8\text{Be}, E)} \exp(-E/k_b T) \times N_A \langle\sigma v\rangle^{n {}^8\text{Be}} E dE \quad (6.1)$$

with

$$N_A \langle\sigma v\rangle^{n {}^8\text{Be}} = N_A \left( \frac{8\pi\hbar}{\mu_{n {}^8\text{Be}}^2} \right) \left( \frac{\mu_{n {}^8\text{Be}}}{2\pi k_b T} \right)^{3/2} \times \int_0^\infty \sigma_{n {}^8\text{Be}}(E'; E) \exp(-E'/k_b T) E' dE'. \quad (6.2)$$

was used, where  $\mu_{\alpha\alpha}$  and  $\mu_{n {}^8\text{Be}}$  are reduced masses, and  $E$  and  $E'$  are the formation energies of the  $\alpha + \alpha$  and  $n + {}^8\text{Be}$  systems respectively.

The  $\alpha + \alpha \rightarrow {}^8\text{Be}$  cross section used in the outer integral over  $E$  of Eq. 6.1, has been measured to high precision [Wus92]. High-quality absolute total cross section data for the  ${}^9\text{Be}(\gamma, n)$  reaction with an overall uncertainty of  $\pm 5\%$  were obtained at TUNL's HI $\gamma$ S facility [Arn09]. Breit-Wigner parameters for  $\Gamma_n$  and  $\Gamma_\gamma$  were deduced by fitting the cross-section data, and the results are shown in Table 6.1.

Table 6.1: Resonance parameters from the present work.

| $J^\pi$ | $E_R(\text{MeV})$ | $\Gamma_\gamma(\text{eV})$ | $\Gamma_n(\text{keV})$ |
|---------|-------------------|----------------------------|------------------------|
| $1/2^+$ | $1.739 \pm 0.002$ | $0.730 \pm 0.013$          | $221.4 \pm 6.7$        |
| $5/2^-$ | $2.431 \pm 0.006$ | $0.097 \pm 0.026$          | —                      |
| $1/2^-$ | $2.854 \pm 0.019$ | $1.752 \pm 0.163$          | $480 \pm 25$           |
| $5/2^+$ | $3.024 \pm 0.001$ | $0.789 \pm 0.054$          | $271.0 \pm 2.3$        |

The total cross section is then the sum of four Breit-Wigner resonances. The reciprocity theorem relates the  ${}^9\text{Be}(\gamma, n){}^8\text{Be}$  cross section to the  ${}^8\text{Be}(n, \gamma){}^9\text{Be}$  cross section yielding

$$\sigma_{n\,{}^8\text{Be}}(E'; E) = \sum_{j=\frac{1}{2}, \frac{3}{2}} \frac{1}{2} (2j+1) \frac{\pi \hbar^2}{2\mu_{n\,{}^8\text{Be}} E'} \times \frac{\Gamma_n({}^9\text{Be}^j, E') \Gamma_\gamma({}^9\text{Be}^j, E' + E)}{(E_\gamma - E_R^j)^2 + \frac{1}{4} \Gamma_n({}^9\text{Be}^j, E')^2}. \quad (6.3)$$

This neutron capture cross section goes directly into the inner integral over  $E'$  of Eq. 6.2.

The present cross section yields a reaction rate that is  $\sim 30\%$  higher than the rate used by NACRE [Ang99] and  $\sim 24\%$  higher than the rate of Sumiyoshi *et al.* [Sum02], as shown in Fig. 6.5. These two rates have been widely used in reaction network codes over the last several years and have typically replaced the rate of Caughlan and Fowler [Cau88], which does not include off-resonance contributions.

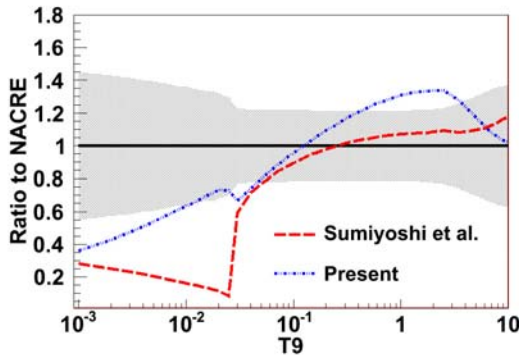


Figure 6.5: (Color Online) Plots of the present rate and of Ref. [Sum02] relative to the rate of NACRE. An error band for the NACRE rate is shown.

The relative increase of the present rate is expected to effect the results from reaction network codes. For the same realistic  $\nu\text{wSII}$  conditions, the present rate will over-produce seed nuclei and light  $r$ -process nuclei ( $60 < A < 120$ ) and under-produce heavy  $r$ -process nuclei ( $A > 130$ ) relative to production under the rates currently in use. The reason for these relative differences in abundance is the sensitivity of  $r$ -process nucleosynthesis to the ratio of the densities of seed nuclei and neutrons. Under realistic  $\nu\text{wSII}$  conditions, production of seed nuclei, light  $r$ -process nuclei,

and heavy  $r$ -process nuclei are in competition for neutrons. The produced abundance of seed nuclei determines the number of neutrons available for production of light and heavy  $r$ -process elements. If seed nuclei are produced such that the abundance of neutrons is sufficiently diminished, then heavy  $r$ -process nuclei may not be produced at all. As an example of the extreme sensitivity, a scenario exists where a 2.5% change in the neutron-excess parameter causes a truncation of the  $r$ -process at  $A \sim 130$  [Sur10].

Recently, a new cross-section and reaction rate calculation was extracted from  ${}^9\text{Be}(e, e')$  data across the  $1/2^+$  threshold resonance of  ${}^9\text{Be}$  [Bur10]. The rate of Burda *et al.* is reported to be 10 to 60% *smaller* than the NACRE rate, in contrast to the present rate, which is as much as 30% *larger*. The authors of Ref. [Bur10] point out that the intriguing disagreement with previous  $(\gamma, n)$  data may point to a violation of Siegert's theorem, regarding the manner in which the  $(\gamma, n)$  cross section is extracted from  $(e, e')$  data. The present cross section provides a new benchmark for identifying the nature of the apparent violation, and the new rate will give improved constraints on the space of realistic parameters at the  $\nu\text{wSII}$  site. Hopefully it will also lead to better understanding of the role of Type II supernovae in  $r$ -process nucleosynthesis.

This work was supported, in part, by U.S. Department of Energy Grants No. DE-FG02-97ER41033 and DE-FG02-97ER41041.

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- [Ang99] C. Angulo *et al.*, Nucl. Phys., **A656**, 3 (1999).
  - [Arn09] C. W. Arnold *et al.*, TUNL Progress Report, **XLVIII**, 100 (2009).
  - [Bur10] O. Burda *et al.*, Phys. Rev. C, **82**, 015808 (2010).
  - [Cau88] G. R. Caughlan and W. A. Fowler, At. Data Nucl. Data Tables, **40**, 283 (1988).
  - [Sum02] K. Sumiyoshi *et al.*, Nucl. Phys., **A709**, 476 (2002).
  - [Sur10] R. Surman and G. McLaughlin, private communication, 2010.
  - [Wus92] S. Wustenbecker *et al.*, Z. Phys. A, **344**, 205 (1992).

## 6.2 $\gamma$ - $^3\text{He}$ Interaction

### 6.2.1 Measurements of the Absolute Cross Section of the Three-Body Photodisintegration of $^3\text{He}$ Between $E_\gamma = 11.4$ MeV and 14.7 MeV at HI $\gamma$ S

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Measurements of the absolute differential cross sections of the  $^3\text{He}(\gamma, n)pp$  reaction have been completed at four  $\gamma$ -ray energies. The measurements were made at the incident  $\gamma$ -ray energies of 11.4, 12.8, 13.5, and 14.7 MeV. It has been found that the shape of the outgoing neutron energy distributions at a given scattering angle at 12.8, 13.5, and 14.7 MeV agrees with current theoretical predictions [Del09]. The shape of the neutron energy distribution at  $E_\gamma = 11.4$  MeV was found to agree with both a phase-space-only shape and the shape predicted by theory.

Two experiments were conducted at the HI $\gamma$ S facility to provide the data for this study. One experiment (denoted as experiment A) focused on the collection of the data at 11.4 MeV, and the other experiment (denoted as experiment B) acquired data at 12.8, 13.5 and 14.7 MeV. Both experiments utilized a pulsed beam of  $\gamma$  rays collimated to a diameter of 25 mm. The neutrons resulting from the photon-induced three-body breakup of  $^3\text{He}$  were detected using the TUNL Bicron liquid-scintillator detectors [Gon09]. In experiment A, the target was a 39.8 cm long GE180 aluminosilicate glass cylinder filled with  $\approx 12$  atm of  $^3\text{He}$  gas. This polarized- $^3\text{He}$  target was developed by the Medium Energy Physics group at Duke University [Kra07]. The target used in experiment B was a 400 mL cylindrical aluminum bottle filled with 168 atm of  $^3\text{He}$  gas.

A simultaneous measurement of  $d(\gamma, n)p$  was made to monitor the  $\gamma$ -ray beam intensity and to provide an absolute normalization for the  $^3\text{He}$ -breakup reaction. This experimental setup consisted of two TUNL Bicron liquid-scintillator detectors placed at  $90^\circ$  and a 47.4 mm long cylindrical heavy-water target. The deuterium photodisintegration reaction has been measured to better than  $\pm 3\%$  in the energy range of the current experiments [Jau96].

The analysis of the data from both experi-

ments has been completed, and the results of the analysis are presented in the Ph.D. dissertation of Perdue [Per10]. Selected results from the analysis are shown in Fig. 6.6. The experimental data are compared with the results of two GEANT4 simulations. In each of the figures, the solid black curve is the result of a simulation using a theoretical cross section [Del09] as input. This cross section includes the contribution of the Coulomb interaction of the protons in the final state [Del05]. The theory predicts a peak in the neutron energy distribution at around 85% of the maximum neutron energy  $E_n^{\text{max}}$  allowed by energy and momentum conservation. The dashed curve is the simulated result when a phase-space input cross section is used. Since phase space does not provide an absolute scale, the simulation results were normalized to the total cross section predicted by Deltuva, Fonseca, and Sauer [Del09].

All the data shown are absolute cross sections and agree well with the magnitude of the predicted cross section. The data at  $E_\gamma = 11.4$  MeV are described well by both the phase space shape and the theoretical shape. However, the high neutron energy threshold only allowed a small portion of the neutron energy distribution to be measured. The data at the higher  $\gamma$ -ray energies show the peaking near 85% of  $E_n^{\text{max}}$ , which is in agreement with the theoretical calculations.

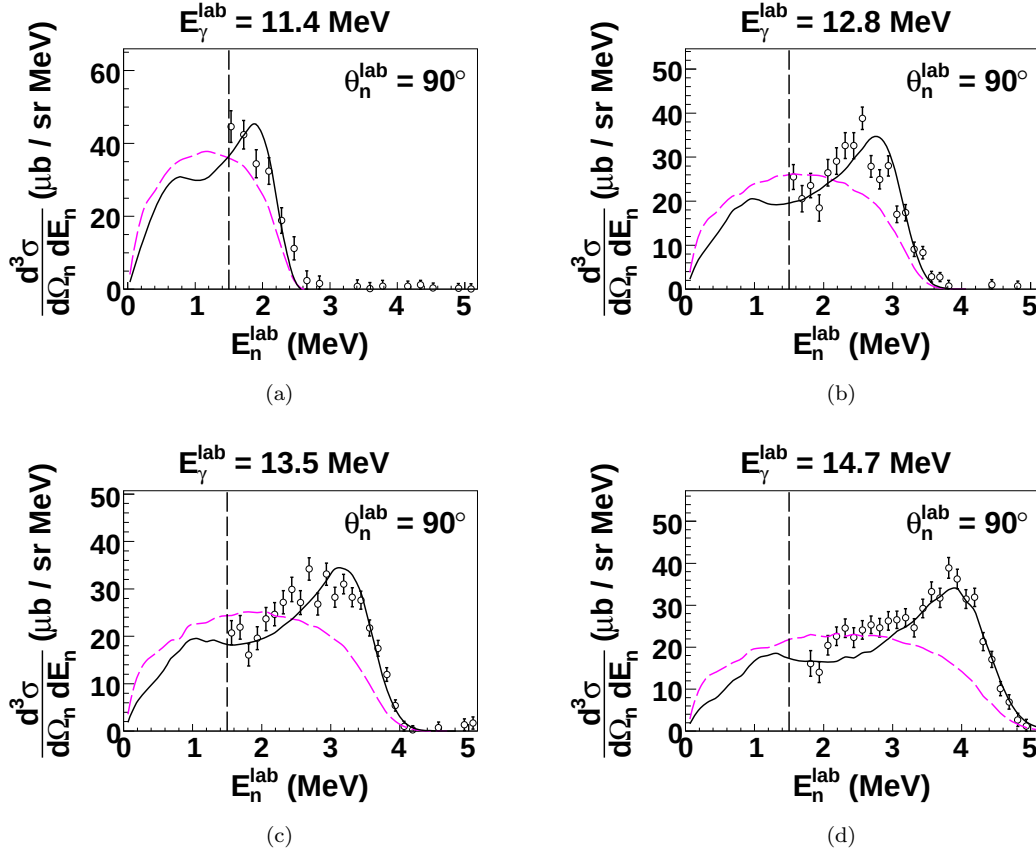


Figure 6.6: (Color online) Neutron energy spectra at  $E_\gamma = 11.4, 12.8, 13.5,$  and  $14.7$  MeV for a detector at  $\theta_n^{\text{lab}} = 90^\circ$ . Experimental data are plotted against two sets of simulated results, one using a normalized phase-space cross section (dashed line) and the other using a theoretical cross section [Del09] (solid line) as the input to the simulation. The neutron energy threshold is indicated by the vertical line. The error bars represent the statistical uncertainties associated with the data points.

- |                                                                                                  |                                                                                     |
|--------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|
| [Del05] A. Deltuva, A. C. Fonseca, and P. U. Sauer, Phys. Rev. C, <b>72</b> , 054004 (2005).     | [Jau96] W. Jaus and W. S. Woolcock, Nucl. Phys., <b>A608</b> , 399 (1996).          |
| [Del09] A. Deltuva, Private Communication, 2005, 2006, 2007, 2009.                               | [Kra07] K. Kramer <i>et al.</i> , Nucl. Instrum. Methods, <b>A582</b> , 318 (2007). |
| [Gon09] D. E. González Trotter <i>et al.</i> , Nucl. Instrum. Methods, <b>A599</b> , 234 (2009). | [Per10] B. A. Perdue, Ph.D. thesis, Duke University, 2010.                          |

## 6.2.2 Three-Body Photodisintegration of $^3\text{He}$ : Comparison of Neutron Backgrounds from Different Glasses

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TUNL

**Experiment E-03-09 on three-body photodisintegration of  $^3\text{He}$  with double polarizations using a circularly polarized photon beam,  $^3\text{He}(\vec{\gamma}, n)(pp)$ , was approved for 180 hours of beam time at HI $\gamma$ S. One major concern is the neutron background from the front and back windows of the target chamber of the hyper-polarized  $^3\text{He}$  target. An in-beam test took place in April 2010 at the HI $\gamma$ S facility. We present preliminary results from the test at an incident photon energy of 11.4 MeV using different glasses.**

A one-day in-beam test was carried out at the HI $\gamma$ S facility in April 2010 on three-body photodisintegration of  $^3\text{He}$  by detecting neutrons. Eight liquid-organic-scintillator detectors filled with BC-501A [Cro01] fluid from Bicron Corporation were placed at  $30^\circ$ ,  $50^\circ$ ,  $90^\circ$ ,  $130^\circ$ , and  $160^\circ$  at a distance of 1 m from the center of the aluminum frame recently constructed by the TUNL capture group. The detectors at  $50^\circ$ ,  $90^\circ$ , and  $130^\circ$  were doubled. All the detectors were configured by the TUNL capture group with lower discrimination thresholds in the MPD-4 module [Rub07], allowing the detectors to run with  $\sim 98\%$  live-time.

A vertical, multi-layer, motor-controlled support was placed at the center of the frame and was used to place different targets in the  $\gamma$ -ray beam. The targets were: (1) a liquid  $\text{D}_2\text{O}$  target; (2) a Corning-1720-glass [Dan81] reference cell with  $\sim 100$  torr of  $\text{N}_2$ ; (3) a thin aluminum rod for calibration purposes; (4) a GE180-glass [Tho78] reference cell with  $\sim 100$  torr of  $\text{N}_2$ ; (5) empty; (6) a Corning-1720-glass Rb-only cell named PABLUM filled with  $9.1 \pm 0.2$  amg of  $^3\text{He}$ . PABLUM contains  $\sim 100$  torr of  $\text{N}_2$  (at room temperature) as a buffer gas. Targets (2) and (4) were 40 cm long, 20 mm in diameter and  $\sim 250$   $\mu\text{m}$  thick at the front and back windows. At the end of the test, target (4) was replaced by a pyrex-glass [Chy89] reference cell 40 cm long, 30 mm in diameter and with a uniform wall thickness of 1 mm, filled with  $\sim 97.5$  torr of  $\text{N}_2$ .

A vacuum pipe constructed by the TUNL capture group was placed upstream in the  $\gamma$ -ray vault to minimize beam scattering from air. The energy of the photon beam was 11.4 MeV, and the photon flux was  $\sim 7.0 \times 10^7$   $\text{s}^{-1}$ . The beam was monitored by a five-paddle system located af-

ter the 12-mm beam collimator. The five-paddle system gives consistent results for the estimation of the incident number of photons on each target.

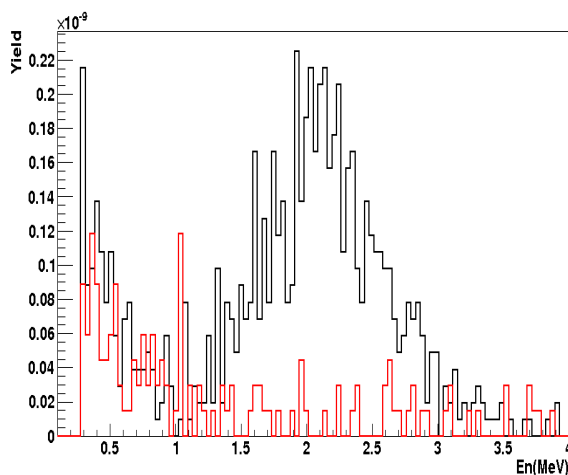


**Figure 6.7: (Color online) Comparison between neutron energy spectra from the Corning-1720-glass  $^3\text{He}$  PABLUM cell (black line with peak around 2.2 MeV) and the Corning-1720-glass  $\text{N}_2$  reference cell (red line without this peak) for the left  $50^\circ$  detector.**

Figure 6.7 shows a comparison between the neutron energy spectra from the PABLUM and Corning-1720-glass  $\text{N}_2$  reference cells after pulse-shape-discrimination (PSD) and pulse-height (PH) cuts. The spectra were measured in the left  $50^\circ$  detector. The PH cut is set to be higher than 0.2  $\text{MeV}_{ee}$  for all the detectors. The PSD cut varies between detectors. The Corning-1720-glass  $\text{N}_2$  reference cell is used to estimate the neutron background due to the Corning 1720 glass and the  $\text{N}_2$  inside the  $^3\text{He}$  cell. The signal-to-noise ratio is defined as the neutron yield of

the  $^3\text{He}$  cell corrected by the Corning-1720-glass  $\text{N}_2$  reference-cell yield divided by the Corning-1720-glass  $\text{N}_2$  reference cell yield.

After the time-of-flight/energy cut, which is from 1.1 to 2.6 MeV, the signal-to-noise ratio varies from  $\sim 3:1$  for the  $30^\circ$  detector to  $\sim 10:1$  for the left  $90^\circ$  detector. Two detectors—those at right  $90^\circ$  and  $130^\circ$ —present higher levels of electronic noise. In those detectors the signal-to-noise ratio is  $\sim 3:1$ . The low neutron background contribution from Corning 1720 glass was observed in online analysis during the experiment, and an extended beam position scan on both the GE180-glass and Corning-1720-glass  $\text{N}_2$  reference cells then followed.

Figure 6.8 shows the ratio of the normalized neutron yields at different laboratory angles under the aforementioned cuts for the Corning-1720-glass and GE180-glass  $\text{N}_2$  reference cells, corrected by the mean yield of the empty-target runs for each detector. The position of the center of the beam was 0.51 cm above the center of the cell in both runs. Due to its barium content, the GE180-glass  $\text{N}_2$  reference cell gives a much higher neutron background than the Corning-1720-glass  $\text{N}_2$  reference cell.

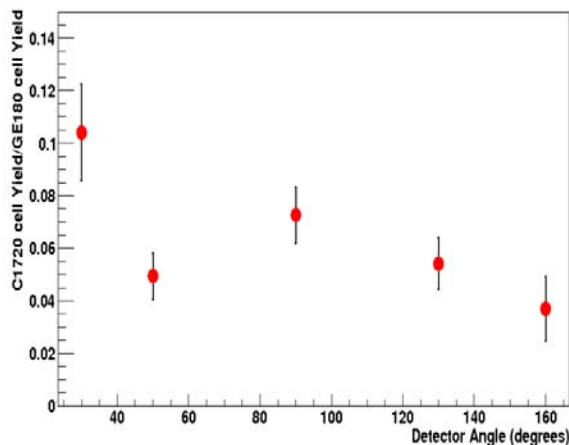


**Figure 6.8:** (Color online) The data points, shown with their statistical uncertainties, give the ratio between the corrected neutron yields from the Corning-1720-glass and GE180-glass  $\text{N}_2$  reference cells.

In addition, an in-beam test was carried out at HI $\gamma$ S in May 2009 [YeQ10]. The energy of the photon beam was 11.4 MeV, and the photon flux was  $\sim 1.5 \times 10^7 \text{ s}^{-1}$ , monitored by a three-

paddle system right after the 22 mm collimator. One goal of the test was to estimate the neutron background of the GE180- and pyrex-glass  $\text{N}_2$  reference cells. All the neutron events were selected from the raw data after the multiplicity cut, PSD cut, PH cut, and time-of-flight cut. They had energies ranging from 1 to 2.5 MeV. The GE180-glass  $\text{N}_2$  reference cell was found to give a higher neutron background than the pyrex-glass  $\text{N}_2$  reference cell.

Although preliminary studies from the April 2010 test run indicate that neutron backgrounds from the pyrex- and Corning-1720-glass  $\text{N}_2$  reference cells are comparable, Corning 1720 glass has a much lower contribution to the wall relaxation of  $^3\text{He}$  [Wag04] and a much slower  $^3\text{He}$  leakage rate [Smi98, Deu08] than pyrex glass.

Thus, Corning 1720 glass is considered to be a serious candidate for the construction of hyper-polarized targets of  $^3\text{He}$  for future double-polarized two-body or three-body photodisintegration experiments. New Corning-1720-glass cells are currently being made and will soon be tested.

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- [Chy89] K. Chyung *et al.*, *Providing Reinforced Alkaline Earth Aluminosilicate Glasses*, U.S.Pat. No. 4,846,866, 1989.
  - [Cro01] A. Crowell, Ph.D. thesis, Duke University, 2001.
  - [Dan81] P. Danielson *et al.*, *Glass for sealing to Molybdenum Metal*, U.S.Pat. No.4,255,198, 1981.
  - [Deu08] A. Deur, *Estimate of the  $^3\text{He}$  leakage from a sol-gel coated cell*, Technical report, University of Virginia, 2008.
  - [Rub07] A. Ruben *et al.*, In *IEEE Nuclear Science Symposium Conference Record*, pp. 681–684. IEEE, 2007.
  - [Smi98] T. Smith, Ph.D. thesis, University of Massachusetts, Amherst, 1998.
  - [Tho78] G. Thomas, *High Temperature Glass Composition*, U.S.Pat. No. 4,105,826, 1978.
  - [Wag04] G. Wang, Ph.D. thesis, Caltech, 2004.
  - [YeQ10] Q. Ye *et al.*, *Eur. Phys. J. A*, **44**, 55 (2010).

### 6.2.3 Two-Body Photodisintegration of $^3\text{He}$ between 7 and 16 MeV

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We extended our previously reported data set for the two-body photodisintegration cross section of  $^3\text{He}$  from 8.8 MeV down to 7.0 MeV and from 12.8 MeV up to 16.0 MeV, doubling the number of data points in this important giant dipole resonance energy region of the  $^3\text{He}(\gamma, p)^2\text{H}$  reaction. Our extended data set puts on more solid ground our earlier conclusion that our data differ significantly from the majority of the previous data, including the recent data of Naito *et al.* obtained with a mono-energetic photon beam and a time-projection chamber. However, our present data are in good agreement with recent theoretical calculations up to about 10 MeV, but differ at higher energies.

New data were obtained for the cross section of the reaction  $^3\text{He}(\gamma, p)^2\text{H}$  at 7.0, 8.0, 12.0, 14.0, 15.0 and 16.0 MeV. Details of the experimental setup and measuring technique are given in previous TUNL Progress Reports [Est04, Est05, Tor08, Tor09]. Therefore, here we present only our results for the photodisintegration cross section of  $^3\text{He}$  between 7.0 and 16.0 MeV.

Figure 6.9 compares our still preliminary data to previous experimental data taken during the past half century and calculations by the Lisbon [Del07] and Krakow [Wit04] groups. The data represented by solid symbols were obtained with bremsstrahlung beams, except for our data and the two recent data points by Naito *et al.* [Nai06] (red dots), which were measured with a mono-energetic photon beam (produced via Compton backscattering of an external laser from electrons in a storage ring). The open symbols are from  $p$ - $d$  capture experiments using the principle of detailed balance. The crosses show data obtained with incident electrons using the long wavelength approximation. Our data are in agreement with the very old bremsstrahlung data of Fetisov *et al.* [Fet65] obtained with a bubble chamber, and with the old  $p$ - $d$  capture data of Belt *et al.* [Bel70]. They differ significantly from all other bremsstrahlung and  $p$ - $d$  capture data. They are also in disagreement with the trend of the data of Naito *et al.* [Nai06] measured with a mono-energetic photon beam, and using a time-projection chamber as target and detector. The black curve is the result of a calculation by the Krakow group using the NN potential Av18 plus the UR-IX three-nucleon force (3NF) and full treatment of meson-exchange currents (MECs). The Coulomb interaction is not

included in this calculation. The other three curves are recent calculations from the Lisbon group. Here, the blue curve is based on the NN potential CD-Bonn, while 3NF effects are included via Delta excitations. MECs are included, but the Coulomb interaction is neglected. The green curve gives the result with the Coulomb interaction included, but without Delta degrees of freedom. Finally, the red curve represents the full calculation, *i.e.*, CD-Bonn + Delta & MECs and with the Coulomb interaction included. The difference between the blue and red curves is a measure of the importance of Coulombs effects, while the difference between the green and red curves shows the magnitude of 3NF effects.

- [Bel70] B. D. Belt *et al.*, Phys. Rev. Lett., **24**, 1120 (1970).
- [Del07] A. Deltuva, 2007, Private Communication.
- [Est04] J. Esterline *et al.*, TUNL Progress Report, **XLIII**, 110 (2004).
- [Est05] J. Esterline *et al.*, TUNL Progress Report, **XLIV**, 168 (2005).
- [Fet65] V. Fetisov, A. Gorbunov, and A. Varfolomeev, Nucl. Phys., **71**, 305 (1965).
- [Nai06] S. Naito *et al.*, Phys. Rev. C, **73**, 034003 (2006).
- [Tor08] W. Tornow *et al.*, TUNL Progress Report, **XLVII**, 100 (2008).
- [Tor09] W. Tornow *et al.*, TUNL Progress Report, **XLVIII**, 84 (2009).

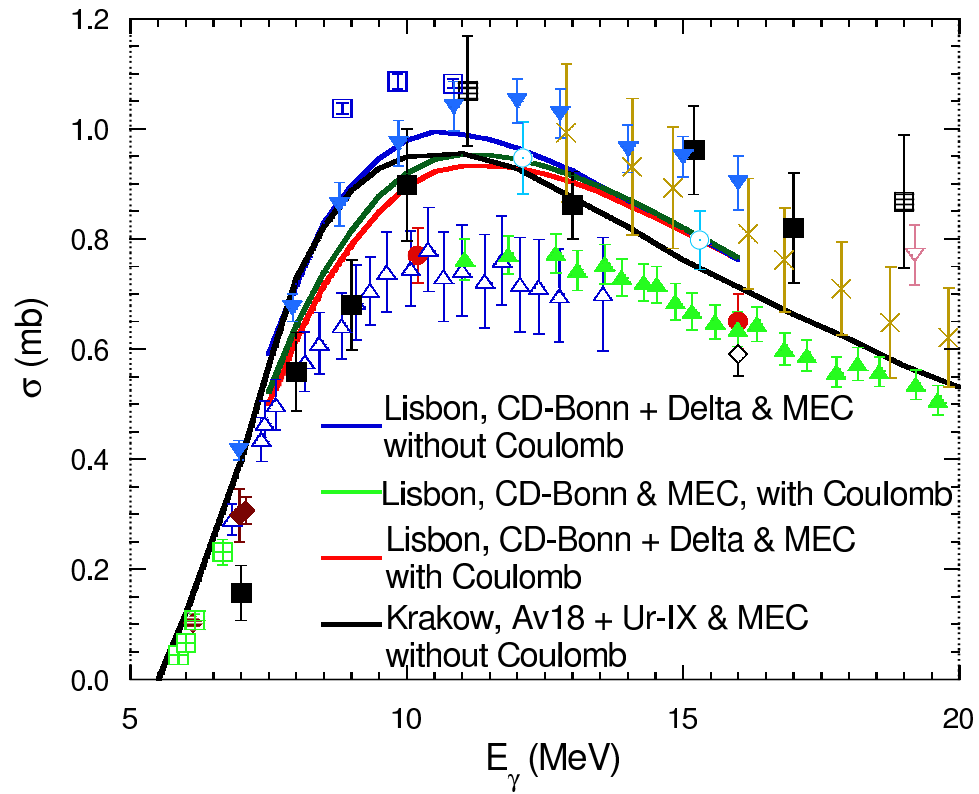


Figure 6.9: (Color online) Comparison of present data (inverted blue triangles) for the reaction  ${}^3\text{He}(\gamma, p){}^2\text{H}$  to previous experimental data and theoretical calculations. See text for details.

[Wit04] H. Witała *et al.*, TUNL Progress Report, **XLIII**, 112 (2004).

## 6.3 $\gamma$ - $^4\text{He}$ Interaction

### 6.3.1 The Photodisintegration Reaction $^4\text{He}(\gamma, p)^3\text{H}$ below 30 MeV

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The two-body photodisintegration cross section of  $^4\text{He}$  into a proton and triton was measured between 22 and 30 MeV in 0.5 MeV energy steps. High-pressure  $^4\text{He}$ -Xe gas scintillators of various  $^4\text{He}$ /Xe ratios served as targets and detectors. Pure Xe gas scintillators were used for background measurements. A NaI detector was employed for the determination of the incident photon flux. Our data are in fairly good agreement with recent theoretical calculations of the Trento group, but differ significantly from the majority of the previous data, including the recent data of Shima *et al.*

For many reasons the  $^4\text{He}$  nucleus is often considered as the link between the classical few-body systems, *i.e.*, deuteron, triton and  $^3\text{He}$ , and more complex nuclei. For example, one expects three-nucleon force (3NF) effects to be more important in the four-nucleon (4N) system than in the three-nucleon (3N) system. On the other hand, the theoretical treatment of the photodisintegration of  $^4\text{He}$  is not as advanced as that of  $^3\text{He}$  and  $^3\text{H}$ . Only recently it became possible to calculate the photoabsorption cross section of  $^4\text{He}$  [Qua04] with a realistic nucleon-nucleon potential model (Av18) and a 3NF (Urbana IX) using the Lorentz integral transform method of the Trento group [Efr00]. The calculations reproduce the strong giant dipole resonance peak, but they provide only a 6% reduction in the cross section in this energy regime once the 3NF is turned on. This is a surprising result, because the same calculations yield a 35% enhancement of the total photoabsorption cross section at pion threshold.

As can be seen from Fig. 6.10, the experimental situation for the total cross section of the reaction  $^4\text{He}(\gamma, p)^3\text{H}$  is very unsatisfactory. In the energy region between 20 and  $E_\gamma=35$  MeV the available experimental data are scattered considerably, and provide hardly any guidance for different theoretical approaches. Especially, the recent data of Shima *et al.* (red dots in Fig. 6.10) obtained with a quasi-monoenergetic photon beam and a time-projection chamber are about a factor of two lower than the predictions of the Trento group at about 26 MeV.

The Q-value for the reaction  $^4\text{He}(\gamma, p)^3\text{H}$  is Q=-19.81 MeV. The Q-value for the three-body

breakup of  $^4\text{He}$  is -26.07 MeV. According to Shima *et al.* [Shi05], the three-body cross section in the energy region of interest is only about 3% of the two-body cross section. In addition, events from the three-body breakup reaction are at lower pulse heights than the events of interest.

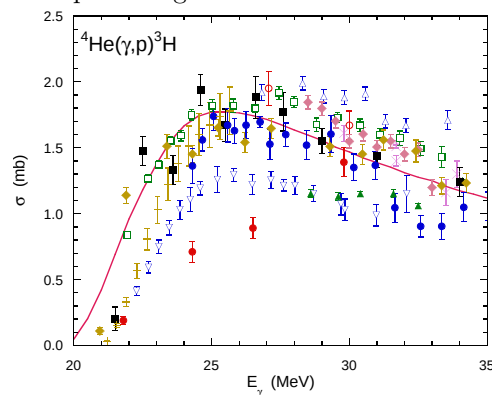


**Figure 6.10:** (Color online) Existing data for the reaction  $^4\text{He}(\gamma, p)^3\text{H}$  in comparison to a calculation of the Trento group [Qua04]. The data shown by solid symbols were obtained with bremsstrahlung or monoenergetic beams. The data indicated by open symbols were obtained from the capture reaction  $^3\text{H}(p, \gamma)^4\text{He}$  via detailed balance. The data of Shima *et al.* are given by the red dots.

We used high-pressure  $^4\text{He}$ -Xe gas scintillators with total pressure of 750 psi as target and detector. In such detectors the measured pulse height is a linear function of the deposited energy, independent of the nature of the strongly ionizing particles. For mono-energetic incident  $\gamma$

rays of 26 MeV, the protons and tritons deposit a total energy of 5.8 MeV, while the proton alone has an energy of 5.3 MeV. In pure  $^4\text{He}$  gas of 750 psi pressure, the range of those protons is about 4.6 cm, resulting in unwanted edge effects in our 5.1 cm diameter cylindrical stainless steel vessels (see Fig. 6.14 in Sect. 6.3.2) of 1 mm wall thickness. Therefore, depending on incident  $\gamma$ -ray energy, we added Xe varying between 7 and 47% admixture (and keeping the total pressure at 750 psi) to provide the necessary stopping power to reduce the proton range to less than 1 cm. Of course, the admixture of Xe increases considerably the number of electrons due to Compton scattering of the incident  $\gamma$  rays and, in addition, increases their stopping power as well. In order to account for photon induced reactions on Xe and the MgO coating on the inner surface of the scintillator vessel, runs were taken with identical and gained-matched scintillator vessels filled with Xe only.

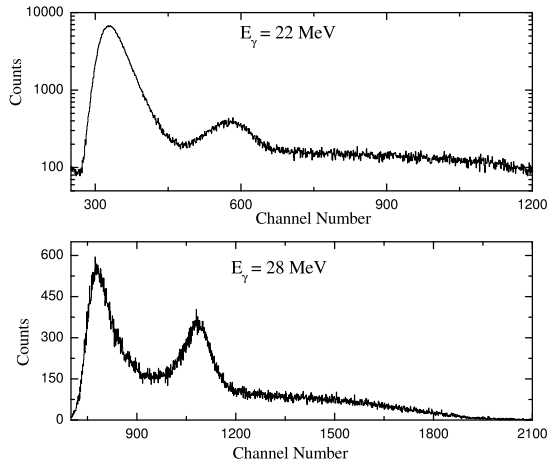


**Figure 6.11:** Typical spectra at  $E_\gamma = 22$  MeV (top panel) and  $E_\gamma = 28$  MeV (bottom panel) for  $^4\text{He}(\gamma, p)^3\text{H}$ . Note that the 22 MeV spectrum is plotted with a logarithmic scale on the y-axis.

Two 10 mm diameter and 10 cm long collimators made of lead defined the size and energy spread of the incident  $\gamma$ -ray beam. The actual  $\gamma$ -ray energy was determined using a calibrated NaI detector. It agreed within 30 keV with the energy determined from the electron energy and FEL photon wave length. The absolute  $\gamma$ -ray flux was determined in the standard way using the combination of a NaI detector and the HI $\gamma$ S scintillator paddle system. In order to eliminate pile-up events in the  $^4\text{He}$ -Xe gas scintillator, and to operate the HI $\gamma$ S scintillator paddle system used for relative flux determination in its linear counting-rate range, an 8-in. long attenuator made of copper was inserted into the  $\gamma$ -ray beam (inside of the concrete shielding wall some 50 m

from the location of the  $^4\text{He}$ -Xe gas scintillator), reducing the  $\gamma$ -ray flux on target to  $10^6$   $\gamma$ -ray/s.

Figure 6.11 shows typical spectra obtained with incident  $\gamma$ -ray energies of 22.0 MeV for a 710 psi  $^4\text{He}$ -40 psi Xe (top panel), and of 28 MeV for a 500 psi  $^4\text{He}$ -250 psi Xe (bottom panel) gas scintillator, respectively. The yield at small pulse heights is dominated by electrons. The pulses of interest due to the protons and tritons from the two-body breakup of  $^4\text{He}$  produce the enhancement seen at higher pulse heights. The background due to photon-induced reactions on Xe and the vessel wall extends to even higher pulse heights. The xenon only spectra show no enhancement in the region of interest.

Figure 6.12 presents the preliminary data (triangles with 10% error bars) for the total cross section of the reaction  $^4\text{He}(\gamma, p)^3\text{H}$  in comparison to the theoretical predictions of the Trento group (solid curve) and the recent data of Shima *et al.* (circles). Our data are in close agreement with the theoretical calculations, and therefore, in strong disagreement with the data of Shima *et al.*, which have been considered by many as the state-of-the-art data set. The statistical uncertainty of our data is 1% or below. The uncertainty in the incident  $\gamma$ -ray flux determination is about 3 to 4%. In addition, we estimate that our background subtraction procedure contributes an additional uncertainty of about 3 to 6%.

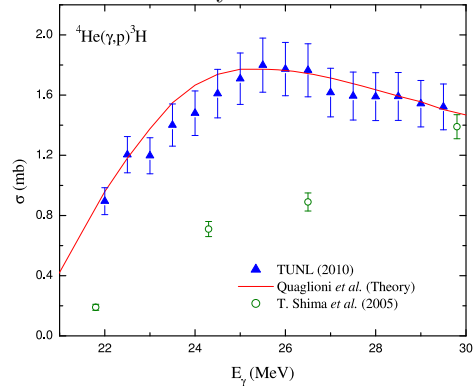


**Figure 6.12:** (Color online) Preliminary results (blue triangles) for the total cross section of the reaction  $^4\text{He}(\gamma, p)^3\text{H}$  in comparison to the prediction of the Trento group (red curve) and the recent data of Shima *et al.* (green circles with error bars).

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- [Efr00] V. Efros *et al.*, Phys. Lett. B, **484**, 223 (2000).  
 [Qua04] S. Quaglioni *et al.*, Phys. Rev. C, **69**, 044002 (2004).  
 [Shi05] T. Shima *et al.*, Phys. Rev. C, **72**, 044004 (2005).

### 6.3.2 The Photodisintegration Reaction ${}^4\text{He}(\gamma, n){}^3\text{He}$ below 30 MeV

W. TORNOW, J.H. KELLEY, R. RAUT, G. RUSEV, S.C. STAVE, A.P. TONCHEV, *TUNL*

The two-body total photodisintegration cross section of  ${}^4\text{He}$  into a neutron and helion was measured at incident photon energies between 25 and 30 MeV. High-pressure  ${}^4\text{He}$ -Xe gas scintillators of various  ${}^4\text{He}$ /Xe ratios served as targets and detectors. Pure Xe gas scintillators were used for background measurements. A NaI detector in combination with the standard HI $\gamma$ S scintillator paddle was employed for absolute photon flux determination. Data analysis is underway.

The determination of the  ${}^4\text{He}(\gamma, p){}^3\text{H}$  to  ${}^4\text{He}(\gamma, n){}^3\text{He}$  cross-section ratio has a long history. By accurately determining this ratio it appeared that Shima *et al.* [Shi05] had resolved the long-standing problem associated with claims of large charge-symmetry breaking (CSB) effects in these two reactions. Their result for the cross-section ratio agrees well with the recent calculations of the Trento group [Qua04] without introducing CSB effects beyond those already included in the Av18 nucleon-nucleon potential model. However, the individual cross sections for the two reactions  ${}^4\text{He}(\gamma, p){}^3\text{H}$  and  ${}^4\text{He}(\gamma, n){}^3\text{He}$  disagree by about a factor of two with those calculations at the peak of the giant dipole resonance region at about 26 MeV, while the disagreement at 30 MeV is only about 10%. Furthermore, the findings of Shima *et al.* for the  ${}^4\text{He}(\gamma, n){}^3\text{He}$  cross section at  $E_\gamma=24.3$  and 26.5 MeV are in disagreement with the very recent data of Nilsson *et al.* [Nil07] at  $E_\gamma=24.6$  and 26.7 MeV, although the latter data have fairly large uncertainties. While Shima *et al.* used a nearly  $4\pi$  time-projection chamber to detect the charged particles from the breakup of  ${}^4\text{He}$ , Nilsson *et al.* detected the emitted neutrons in the angular range between  $30^\circ$  and  $130^\circ$ .

As can be seen from Fig. 6.13, the experimental situation for the total cross section of the reaction  ${}^4\text{He}(\gamma, n){}^3\text{He}$  is very unsatisfactory. Overall, the picture looks pretty similar to that given in Sect. 6.3.1 for the reaction  ${}^4\text{He}(\gamma, p){}^3\text{H}$ . The curve is the theoretical prediction of the Trento group. The red dots are the data of Shima *et al.*, while the green upright triangles represent the recent data of Nilsson *et al.*

From an experimental point of view, the "target equal detector" scheme of Shima *et al.* is the ideal experimental approach, because it allows

for the simultaneous measurement of both the  ${}^4\text{He}(\gamma, p){}^3\text{H}$  and  ${}^4\text{He}(\gamma, n){}^3\text{He}$  cross sections, and in addition, it avoids the complications associated with neutron detection. We used the "target equal detector" approach described in Sect. 6.3.1 for the measurement of the  ${}^4\text{He}(\gamma, p){}^3\text{H}$  total cross section by employing a high-pressure  ${}^4\text{He}$ -Xe gas scintillator.

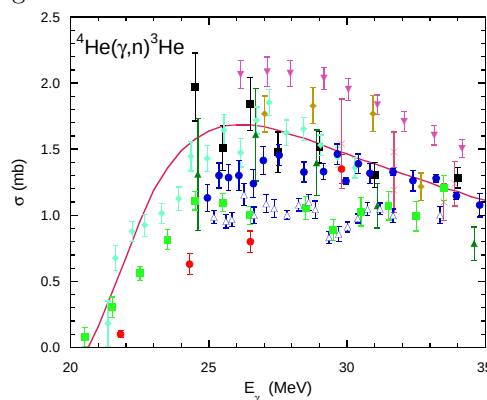


**Figure 6.13:** (Color online) Existing data for the reaction  ${}^4\text{He}(\gamma, n){}^3\text{He}$  in comparison to a calculation of the Trento group [Qua04]. The data shown by solid symbols were obtained with bremsstrahlung or monoenergetic beams. The data indicated by open symbols were obtained from the capture reaction  ${}^3\text{He}(n, \gamma){}^4\text{He}$  via detailed balance. The data of Shima *et al.* are given by the red dots.

The Q-value for the reaction  ${}^4\text{He}(\gamma, n){}^3\text{He}$  is  $Q=-20.58$  MeV. Incident  $\gamma$  rays of  $E_\gamma=26$  MeV provide helions of energies between 1.14 and 2.2 MeV, depending on the emission angle of the undetected neutrons. The pulse height produced by strongly ionizing charged particles in gas scintillators is proportional to the energy deposited and independent of the particle type. For exam-

ple, 3 MeV protons, deuterons, tritons, helions, and  $^4\text{He}$  ions all produce the same pulse height, provided they are completely stopped in the gas volume. Therefore, in principle the pulse-height interval associated with helions is clearly separated from the summed pulse height of the protons and tritons from the reaction  $^4\text{He}(\gamma, p)^3\text{H}$ , which deposit a total energy of 5.8 MeV for 26 MeV incident  $\gamma$  rays. However, in standard  $^4\text{He}$ -Xe gas scintillators the pulse heights produced by Compton scattered electrons overlap with those generated by some fraction of the low-energy helions, unless the Xe/ $^4\text{He}$  ratio is kept very low. In addition, at high incident  $\gamma$ -ray flux, the electron-generated pulses tend to pile up on top of each other, creating pulse heights beyond those expected from the maximum range available within the scintillator vessel. Therefore, a quite complicated optimization process is required if one wants to measure the  $^4\text{He}(\gamma, n)^3\text{He}$  cross section with  $^4\text{He}$ -Xe gas scintillators. The required small Xe/ $^4\text{He}$  ratio makes it impossible to measure the  $^4\text{He}(\gamma, p)^3\text{H}$  and  $^4\text{He}(\gamma, n)^3\text{He}$  cross sections simultaneously. Xe/ $^4\text{He}$  ratios well below 5% not only result in deteriorated energy resolution of the gas scintillator, but in addition, the protons from the  $^4\text{He}(\gamma, p)^3\text{H}$  reaction will range out, *i.e.*, run into the inner wall of the gas scintillator housing without depositing their full energy. As a matter of fact, at very small Xe admixtures the reaction products of the reactions  $^4\text{He}(\gamma, p)^3\text{H}$  and  $^4\text{He}(\gamma, n)^3\text{He}$  become indistinguishable, because the pulse heights produced by tritons and helions will start to overlap, due to the lack of sufficient pulse height produced by the energetic protons.

We used a high-pressure  $^4\text{He}$ -Xe gas scintillator filled with a mixture of 710 psi  $^4\text{He}$  and 40 psi Xe as target and detector. For background estimation we used an identical scintillator housing filled with 40 psi of Xe. Data were taken in 0.5 MeV energy steps between 27.0 and 28.5 MeV. Experimental details are similar to those given in Sect. 6.3.1. A pulse-height spectrum obtained with 28 MeV incident photons is shown

in the top panel of Fig. 6.14. The events due to electrons are located at the low pulse heights. The broad and symmetric enhancement located at larger pulse-heights is due to the helions of interest. The symmetric shape is due to the  $\sin^2\theta$  angular distribution of the associated, but undetected neutrons. Following this pulse-height distribution one notices the broad distribution caused by tritons and ranged out protons, which are also responsible for the "saturated" events at the very end of the pulse-height distribution.

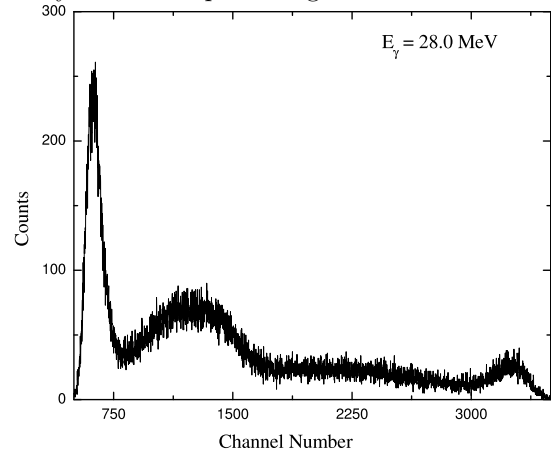


**Figure 6.14:** Pulse-height distribution obtained with a 710 psi  $^4\text{He}$  and 40 psi Xe gas scintillator and 28 MeV incident  $\gamma$  rays. See text for details.

Data analysis is currently underway. We plan to extend our  $^4\text{He}(\gamma, n)^3\text{He}$  total cross-section measurements to lower energies by using 570 psi  $^4\text{He}$ -30 psi Xe and 380 psi  $^4\text{He}$ -20 psi Xe gas scintillators.

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- [Nil07] B. Nilsson *et al.*, Phys. Rev. C, **75**, 014007 (2007).
  - [Qua04] S. Quaglion *et al.*, Phys. Rev. C, **69**, 044002 (2004).
  - [Shi05] T. Shima *et al.*, Phys. Rev. C, **72**, 044004 (2005).

## 6.4 Study of Many-Body Systems

### 6.4.1 Compton@HI $\gamma$ S on $^{209}\text{Bi}$ from $E_\gamma = 15\text{--}30\text{ MeV}$

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As part of the ongoing Compton@HI $\gamma$ S effort, data have been collected to investigate the isovector-giant-quadrupole-resonance (IVGQR) region in  $^{209}\text{Bi}$  at  $E_\gamma = 15\text{--}30\text{ MeV}$ . Linearly polarized  $\gamma$  rays were incident on a  $^{209}\text{Bi}$  target, and scattered  $\gamma$  rays were detected in the HI $\gamma$ S NaI Detector Array (HINDA). Angular distributions, both parallel and perpendicular to the plane of polarization, are used to study the sensitivity to the IVGQR parameters. Preliminary extraction of the IVGQR resonance parameters for  $^{209}\text{Bi}$  are reported.

In June 2009 the Compton@HI $\gamma$ S group performed an experiment to commission the HI $\gamma$ S NaI Detector Array (HINDA) and measure the Compton-scattering cross section from  $^{209}\text{Bi}$  in the giant resonance region [Hen09]. Although these data were of high quality, the quantity was insufficient to make an unambiguous statement regarding the parameters of the isovector giant quadrupole resonance in  $^{209}\text{Bi}$ . For this reason, in May 2010 six HINDA detectors were placed both in and out of the HI $\gamma$ S polarization plane at scattering angles of  $\theta = 55^\circ$  and  $125^\circ$ , as shown in Fig. 6.15, in order to measure the IVGQR parameters.

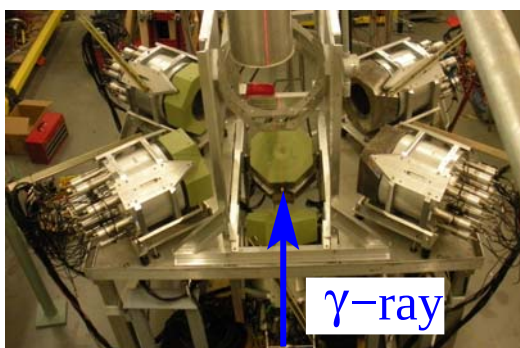


Figure 6.15: (Color online) May 2010 detector setup showing six HINDA detectors. The arrow indicates the  $\gamma$  beam direction.

During the run, a linearly polarized  $\gamma$ -ray beam was incident on an isotopically pure ( $>$

99.9%)  $^{209}\text{Bi}$  target for approximately 80 hours over the energy range  $E_\gamma = 15\text{--}30\text{ MeV}$ . During the running at 15 MeV, a  $^{12}\text{C}$  target was placed in the beam to obtain the intrinsic detector response using the mono-energetic 15.1 MeV NRF  $\gamma$  rays. A typical spectrum from this  $^{12}\text{C}$  run is shown in Fig. 6.16 along with a fit from a GEANT4 simulation.

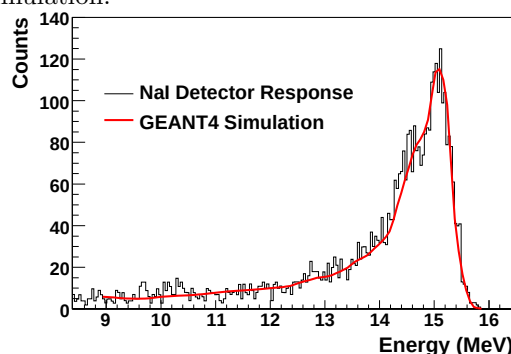


Figure 6.16: (Color online) The 15.1 MeV NRF  $\gamma$  ray in  $^{12}\text{C}$ . The red (thick) line is a fit to the data using the geant4 simulation convolved with a gaussian.

The simulation calculates the total energy deposited by mono-energetic  $\gamma$  rays, taking into account target geometry, detector geometry, energy and intensity loss of the  $\gamma$  rays through different materials, and multiple scattering effects. The simulation output is convolved with a Gaussian to account for detector resolution effects not included in the simulation. Once convolved and

fit, the simulation output can be used to predict the HINDA response to Compton-scattered  $\gamma$  rays from  $^{209}\text{Bi}$  by convolving a second Gaussian representative of the  $\gamma$ -ray beam energy width. An exponential background is added to account for atomic Compton-scattering events from  $^{209}\text{Bi}$ , which is a minimal effect at backward angles but plays a major role at forward angles where the atomic Compton scattering is large.

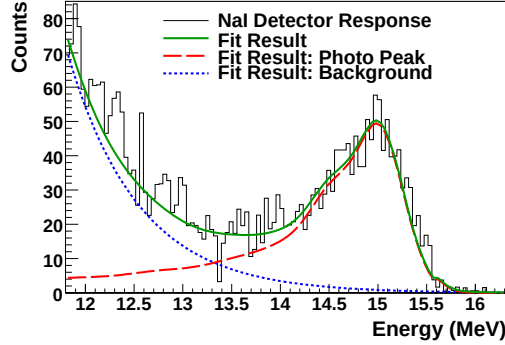


Figure 6.17: (Color online) Typical fitting result from the  $^{209}\text{Bi}$  scattering data.

Figure 6.17 shows the results of a fit to a forward angle detector at  $E_\gamma = 15$  MeV. The solid line is fitted to the spectrum, and the peak and background line shapes are extracted. The background is subtracted bin-by-bin from the data, and the counts left over are summed to give the  $\gamma$ -ray yield. This procedure is used for each detector at each energy step. Thirteen energy steps were made for  $E_\gamma = 15$ –25 MeV in 80 hours of beam on target. The in-plane detector yields are summed for each scattering angle, fore ( $\theta = 55^\circ$ ) and aft ( $\theta = 125^\circ$ ), and the ratio of perpendicular to parallel yields ( $\sigma_\perp/\sigma_\parallel$ ) is formed. Figure 6.18 shows the results of this procedure as a function of  $\gamma$ -ray energy ( $E_\gamma$ ). The solid lines correspond to a preliminary fit of a model to the fore and aft ratios, respectively. This is the first measurement confirming the phase difference between the fore and aft ratio curves and exploiting this fact to better determine the IVGQR parameters. The phase difference is due to the  $\cos(\theta)$  dependence of the interference term, which changes sign when going from a forward angle to a backward one.

The model uses a phenomenological calculation of Wright [Wri85], which starts with the photo-absorption cross sections, the charge and exchange form factors, and the nucleon polarizabilities and uses the optical theorem and dispersion relations to calculate the Compton-scattering cross section. The giant-dipole-resonance (GDR) parameters come from previ-

ous studies of Dale *et al.* [Dal88], and the form factors are from  $(e, e')$  studies done by Euteneuer *et al.* [Eut78]. The IVGQR parameters are free parameters in the fit. The preliminary parameters extracted from this analysis are  $E_{res} = 23.0 \pm 0.13$  MeV,  $\Gamma_{res} = 3.9 \pm 1.4$  MeV, and  $\sigma_{res}^{[-2]} = 0.6 \pm 0.04$  IVEWSR. Here the total energy-weighted integrated strength  $\sigma_{res}^{[-2]}$  is given in units of the isovector energy-weighted sum rule (IVEWSR) [Liu76], and the errors are purely statistical. The scale of  $\sigma_{res}^{[-2]}$  is determined from the input GDR cross section given by Dale [Dal88]. Results for these parameters in the neighboring  $^{208}\text{Pb}$  nucleus are  $E_{res} = 20.2 \pm 0.5$  MeV,  $\Gamma_{res} = 5.5 \pm 0.5$  MeV, and  $\sigma_{res}^{[-2]} = 1.4 \pm 0.3$  IVEWSR.

Much work is still needed to characterize the systematic errors, as well as the robustness of the fitting procedure. This will be done in the coming months and will result in a PhD thesis.

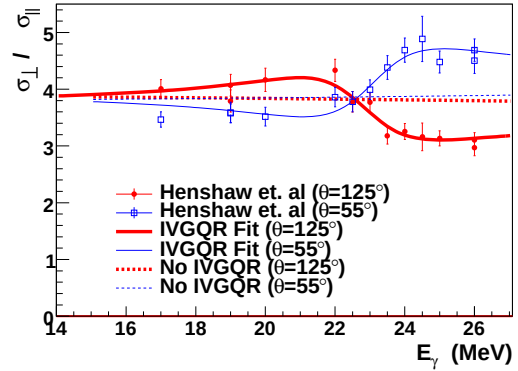


Figure 6.18: (Color online) Preliminary fit to the perpendicular-to-parallel ratios extracted from the May 2010 data. The solid curves are fits to the data using the model described in the text. The dashed lines show the ratios when no IVGQR strength is present.

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- [Dal88] D. S. Dale *et al.*, Phys. Lett., **B214**, 329 (1988).
  - [Eut78] H. Euteneuer *et al.*, Nucl. Phys., **A298**, 452 (1978).
  - [Hen09] S. S. Henshaw *et al.*, TUNL Progress Report, **XLVIII**, 94 (2009).
  - [Liu76] K. Liu and G. Brown, Nucl. Phys., **A265**, 385 (1976).
  - [Wri85] D. H. Wright *et al.*, Phys. Rev. C, **32**, 1174 (1985).

### 6.4.2 Fine and Gross Structure of the Pygmy Dipole Resonance

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**High-sensitivity studies of E1 and M1 transitions observed in the reaction  $^{138}\text{Ba}(\bar{\gamma},\gamma')$  at energies below the one-neutron separation energy have been performed using the nearly monoenergetic and 100% linearly polarized photon beams of the HI $\gamma$ S facility. The electric dipole character of the so-called “pygmy” dipole resonance was experimentally verified for excitations from 4.0 to 8.6 MeV. The fine structure of the M1 “spin-flip” mode was observed for the first time in  $N = 82$  nuclei.**

In stable and weakly bound neutron-rich nuclei, a resonance-like concentration of dipole strength has been observed at excitation energies around the neutron separation energy. This clustering of strong dipole transitions has been named the pygmy dipole resonance (PDR). It was suggested that the oscillation of a small portion of nuclear matter relative to the rest of the nucleus is responsible for the generation of enhanced dipole strength. The theoretical calculations in the framework of the quasiparticle random-phase approximation (QRPA) indicated a correlation between the observed total  $B(\text{E}1)$  strength of the PDR and the neutron-to-proton ratio  $N/Z$  [Tso08].

The existence of the PDR mode near the neutron threshold also has important astrophysical implications, while for very neutron-rich exotic nuclei, the PDR will be an important topic of study at the new generation of radioactive-ion-beam facilities. The evolution of the giant dipole resonance (GDR) strength from stable to more weakly bound nuclei with extreme neutron-to-proton ratios is an interesting and open question.

In the present work we report first on the experimental determination of the character of the PDR as a predominantly E1 mode of excitation. Furthermore, the fine structure of the dominant E1 and dispersed M1 strength distributions below the particle separation energy is determined. Finally, the dynamics of the PDR as an interplay between isoscalar and isovector excitation modes is revealed. Our experimental study focuses on the  $^{138}\text{Ba}(\bar{\gamma},\gamma')$  reaction below the neutron separation energy of about 8.6 MeV using the nearly monoenergetic and 100% linearly polarized photon beams of the HI $\gamma$ S facility.

The photon flux was measured by Compton scattering of the beam from a 1.0 mm thick copper plate. At energies above 8.1 MeV, the photon

flux was also monitored by the  $^{197}\text{Au}(\gamma,n)$  reaction.

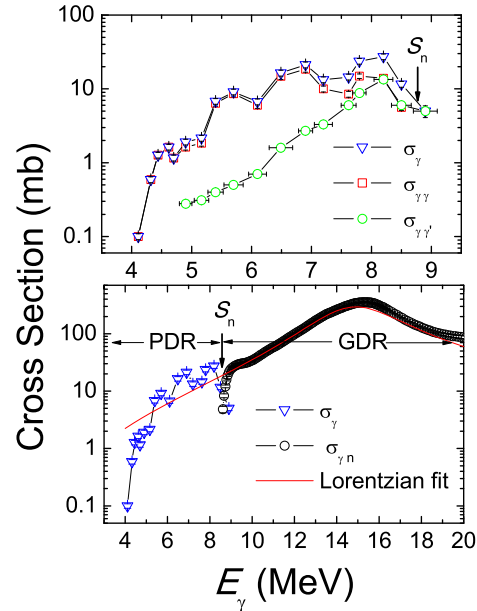


**Figure 6.19:** (Color online) Upper panel: Elastic ( $\sigma_{\gamma\gamma}$ ), inelastic ( $\sigma_{\gamma\gamma'}$ ), and total absorption cross sections ( $\sigma_\gamma$ ) in  $^{138}\text{Ba}$  below the one-neutron separation energy ( $S_n=8.6$  MeV) averaged over the beam energy spread of about 3%. Lower panel: Total absorption cross section ( $\sigma_\gamma$ ) from the present photon-scattering experiment is combined with the  $(\gamma,xn)$  data from the GDR. A Lorentzian curve is applied to the experimental photoneutron cross-section data.

The  $^{138}\text{Ba}$  target consisted of 4290.5 mg of  $\text{BaCO}_3$  powder enriched to 99.68% in  $^{138}\text{Ba}$ . It was placed into an evacuated plastic tube at the center of an array of five large-volume HPGe detectors. These detectors were arranged around

the target at  $(\theta, \phi) = (90^\circ, 90^\circ \text{ and } 270^\circ), (90^\circ, 0^\circ \text{ and } 180^\circ), \text{ and } (135^\circ, 0^\circ)$ , where  $\theta$  is the polar angle of the outgoing radiation with respect to the horizontally polarized incoming photon beam, and  $\phi$  is the azimuthal angle measured from the polarization plane.

The 100% polarized and nearly monoenergetic photon beam allows us not only to determine unambiguously the electromagnetic character of the transitions, but it also enables a closer examination of the dynamics of the decay pattern in the PDR region. The elastic ( $\sigma_{\gamma\gamma}$ ), inelastic ( $\sigma_{\gamma\gamma'}$ ), and photoabsorption ( $\sigma_\gamma = \sigma_{\gamma\gamma} + \sigma_{\gamma\gamma'}$ ) cross sections for the  $^{138}\text{Ba}(\gamma, \gamma')$  reaction below the neutron separation energy are shown in the upper panel of Fig. 1 in [Ton10]. The elastic cross section, which is due to ground-state transitions, shows resonance-like structures and dominates the nuclear dipole response up to the neutron separation energy. In contrast, the inelastic cross section, which is due to statistical decays, shows an exponential increase with excitation energy. The deduced photoabsorption cross section ( $\sigma_\gamma$ ) is shown in the lower panel of Fig. 6.19 along with experimental data for the  $^{138}\text{Ba}(\gamma, xn)$  reaction in the GDR region. As can be seen, for certain energies below the neutron separation energy  $S_n$ , the photoabsorption cross section has values larger than the extrapolation of the tail of the GDR implies.

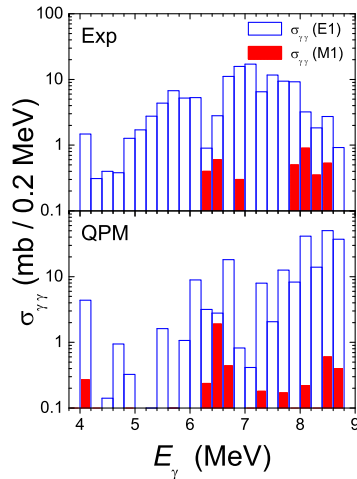


**Figure 6.20:** (Color online) Experimental (top panel) and QRPA calculations (lower panel) for E1 and M1 elastic scattering cross sections in  $^{138}\text{Ba}$  below 9.0 MeV. The cross sections are averaged over 0.2 MeV energy bins.

magnetic photoabsorption cross sections are presented in comparison to the present experimental data for the  $1^\pm$  states in  $^{138}\text{Ba}$  at  $E^* < 8.5$  MeV. The measured elastic E1 and M1 cross sections, integrated over 200 keV bins, are shown in the upper part of Fig. 6.20. At excitation energies below the particle emission threshold, the E1 transitions in  $^{138}\text{Ba}$  are distributed in a broad, resonance-like structure. The observed concentration of  $1^-$  states is characterized by the high level density which increases steeply towards the threshold. In contrast, the magnetic dipole transitions, which result from the decay of single-particle states, are much more isolated, and they are concentrated in well specified regions.

The comparison of E1 and M1 strengths over the whole energy range between 4 and 8.6 MeV shown in Fig. 6.20 leads to the conclusion that E1 transitions clearly dominate M1 transitions by intensity and amplitude. The ratio of elastic M1 and E1 cross sections is only 2.7 (0.8)%.

In conclusion, the systematic spin and parity measurements on  $^{138}\text{Ba}$  at the HI $\gamma$ S facility have unambiguously verified that the observed dipole strength from 4 MeV to the neutron separation energy is predominantly of electric dipole nature. In addition, the fine structure of the M1 “spin-flip” mode was observed for the first time in  $N = 82$  nuclei. The QRPA predictions for the character and strength of this dipole mode of excitation are confirmed by our measurements. Enhanced dipole strength above the Lorentzian extrapolation of the GDR has been directly measured for elastic and inelastic transitions below the neutron separation energy and found to be related to the dominance of electric transitions. This strength falls into two categories: elastic, originated by the skin oscillation of the excess neutrons against the proton-neutron saturated core, and inelastic, due to states coupled to more complicated configurations than  $1p\text{-}1h$  states. Combining these two strengths, they define the gross structure of the PDR resonance, which exhibits a resonance-like shape distribution with pronounced peak structure above the low-energy extrapolation of the GDR. According to the theoretical model, electric and magnetic transitions are found to be of single-particle character, but related to different physical mechanisms.

[Ton10] A. Tonchev *et al.*, Phys. Rev. Lett., **104**, 072501 (2010).

[Tso08] N. Tsoneva and H. Lenske, Phys. Rev. C, **77**, 024321 (2008).

In Fig. 6.20 QRPA results for the electric and

### 6.4.3 Dipole Excitations of $^{76}\text{Se}$ in the Energy Range 4–9 MeV

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The chains of Ge and Se isotopes are interesting from many nuclear structure points of view. The influence of increasing deformation on the pygmy resonance is investigated in the isotope  $^{76}\text{Se}$  using the 100% polarized and nearly-monoenergetic beam at HI $\gamma$ S to complement measurements made at Darmstadt. Determining and understanding the structure of this isotope is also important because of its role in the search for neutrinoless double-beta decay.

The chains of Ge and Se isotopes are interesting from many nuclear structure points of view. For the lighter isotopes, coexisting structures of different deformation are known. The heavier, stable or near-stable isotopes are transitional from spherical to deformed nuclei, as one moves away from the  $Z = 28$  shell closure. The influence of increasing deformation on the pygmy resonance is investigated in the isotope  $^{76}\text{Se}$ . Determining and understanding the structure of this isotope is also important because of its role in the search for neutrinoless double-beta decay.

The pygmy dipole resonance (PDR) is a structure of enhanced dipole strength, which is superimposed on the low-energy tail of the giant dipole resonance. The PDR has so far been studied mainly in nuclei near shell closures (see, e.g., Refs. [Sch96, Adr05, Wie09, Sav08]). The commonly used intuitive picture of the PDR is the vibration of a proton-neutron core against a neutron skin. Therefore the magnitude of the resonance is expected to become smaller in more neutron-deficient nuclei. A splitting of the PDR into isoscalar and isovector parts has been observed experimentally [Sav06, End09] and was recently treated in theory [Paa09].

The evolution of the PDR with deformation is not yet known. The nucleus  $^{76}\text{Se}$  is located 6 protons above the  $Z = 28$  shell closure, half-way between the closed shell and the mid-shell point. Because deformation is increasing ( $\beta_2(^{76}\text{Se}) = -0.28(1)$  compared to  $\beta_2(^{74}\text{Ge}) = -0.19(2)$ ), we can quantitatively investigate its effects on the strength and location of the PDR in  $^{76}\text{Se}$ . These results will be important for a further systematic analysis and interpretation of the nature of the PDR.

Another important aspect of  $^{76}\text{Se}$  is its role as the daughter nucleus in the neutrino-less double-beta decay of  $^{76}\text{Ge}$ . In order to derive a neutrino mass from searches for this exotic decay mode involving large volume  $^{76}\text{Ge}$  detectors, it will be necessary to know the nuclear matrix elements for the decay. However, those matrix elements can only be extracted from models like the shell model or the quasi-particle random-phase approximation (QRPA) (see, e.g., Ref. [Suh08]). Because QRPA calculations, in particular, are often used to describe the PDR (see the recent review article [Paa07]), a test of the QRPA against the measured dipole strength distribution should help validate the model's nuclear matrix elements.

The present experiment is one of a series of measurements being performed at Yale University, the Technischen Universität (TU) Darmstadt, and the University of Kentucky, probing low-spin structures in  $^{76}\text{Ge}$ ,  $^{76}\text{As}$ , and  $^{76}\text{Se}$ , using a variety of techniques. A pilot experiment at TU Darmstadt using nuclear resonance fluorescence had been performed in order to obtain the distribution and absolute excitation strengths of dipole states at energies up to 9 MeV. The experiment at HI $\gamma$ S also involved photon scattering, but using the fully polarized, nearly mono-energetic beams delivered by the free electron laser. The aim was to directly measure the parities of dipole excited states, in order to be able to separate E1 from M1 excitations. In addition, the photon flux at high energies is larger than that at TU Darmstadt from bremsstrahlung, allowing the observation of many more excited states.

Analysis of the spectra from our last run on  $^{76}\text{Se}$  at HI $\gamma$ S is nearly complete. In March

2010, we had 60 hours of beamtime and scanned the energy region from 5 to 9 MeV with about twenty energy settings. At each setting, states within the energy window of the beam were selectively excited. Figure 6.21 contains sample results showing the simulated photon beam and

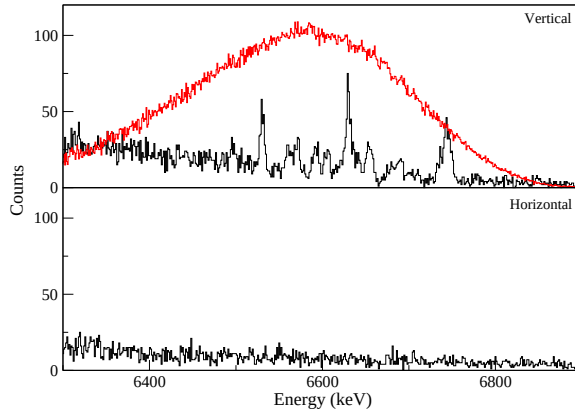


**Figure 6.21:** (Color online) Example spectra from the March run on  $^{76}\text{Se}$ . The simulated beam profile at the 6.6 MeV beam setting is shown along with the observed peaks from nuclear resonance fluorescence in that region. Peaks observed only in the vertical detectors (upper plot) correspond to ground state decays of E1 excited states.

Due to the rather high background from Compton-scattered photons, the analysis of transitions from dipole excited states to lower-lying excited states is only possible in a few cases, and only for transitions to the first excited  $2^+$  states. However, these cases can be compared to Darmstadt data to obtain multipole mixing ratios, especially for transitions from M1 excited states.

The determination of the parities is complete, and the results are shown in Fig. 6.22. Most observed states are E1 excitations, but a number of states with positive parity have also been observed. We are currently determining the excitation strengths of several newly observed states relative to those observed at TU Darmstadt, in order to obtain a complete picture of the E1 excitation strength in  $^{76}\text{Se}$  up to 9 MeV. This includes the region of the pygmy resonance. Future experiments will be dedicated to dipole states below 5 MeV, as well as to analogous experiments on the double-beta decay partner  $^{76}\text{Ge}$ .

One peak at about 5.3 MeV energy is ob-

served rather strongly in both the horizontal and vertical Ge detectors of the polarimeter setup. The solid angle of the detectors do not explain the observed strengths within about a 4-sigma confidence level. Therefore, it is likely that the observed peak is due to a doublet of transitions only few keV apart, containing both an M1 and an E1 excited state. This clearly demonstrates the power of the polarimeter setup.

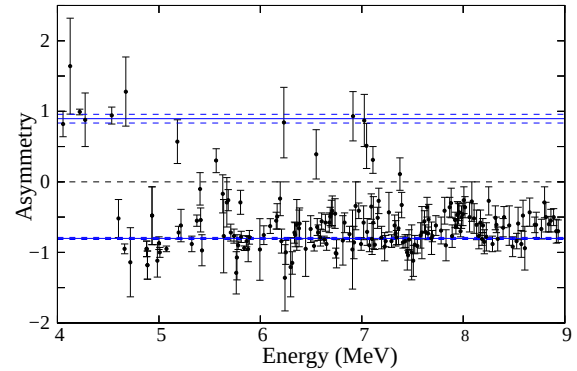


**Figure 6.22:** (Color online) Asymmetries for the observed states, states with values near -1 have negative parities, those with values near +1 have positive parity.

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- [Adr05] P. Adrich *et al.*, *Phys. Rev. Lett.*, **95**, 132501 (2005).
  - [End09] J. Endres *et al.*, *Phys. Rev. C*, **80**, 034302 (2009).
  - [Paa07] N. Paar *et al.*, *Rep. Prog. Phys.*, **70**, 691 (2007).
  - [Paa09] N. Paar *et al.*, *Phys. Rev. Lett.*, **103**, 032502 (2009).
  - [Sav06] D. Savran *et al.*, *Phys. Rev. Lett.*, **97**, 172502 (2006).
  - [Sav08] D. Savran *et al.*, *Phys. Rev. Lett.*, **100**, 232501 (2008).
  - [Sch96] R. Schwengner *et al.*, *Phys. Rev. C*, **78**, 064314 (1996).
  - [Suh08] J. Suhonen and M. Kortelainen, *Int. J. Mod. Phys. E*, **17**, 1 (2008).
  - [Wie09] O. Wieland *et al.*, *Phys. Rev. Lett.*, **102**, 092502 (2009).

#### 6.4.4 Cross-Section Measurements of the $^{180m}\text{Ta}(\gamma, n)$ Reaction and the Photo-Induced Depopulation of $^{180m}\text{Ta}$ Isomer

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Cross-section measurements were carried out at HI $\gamma$ S for the  $^{180m}\text{Ta}(\gamma, n)$  reaction with  $E_\gamma$  from 6.5 to 7.57 MeV. A  $4\pi$ ,  $^3\text{He}$  proportional counter was used to detect the emitted neutrons, and attempts were made to derive the cross section from their yield. Background from the Compton scattered photon beam was observed obscuring the neutron counts. Simultaneous measurements on the photo-deexcitation of the  $^{180m}\text{Ta}$  isomer were also carried out and have indicated positive results.

One of the key question in nuclear astrophysics pertains to the nucleosynthesis processes contributing to the observed abundances of the chemical elements in the universe. Production of elements beyond Fe ( $Z = 26$ ) is primarily attributed to  $s$ - and  $r$ -process neutron capture. In addition, there are 35 neutron-deficient nuclei, called the  $p$ -process nuclei, that cannot be produced by the neutron capture processes. These are often ascribed to photo-dissociation reactions in hot stellar environments. The  $^{180}\text{Ta}$  nucleus is the rarest isotope in the universe, existing only due to its isomer at 75.3 keV ( $J^\pi=9^-$ ) with a half-life greater than  $1.2 \times 10^{15}$  years. It is, in fact, the only naturally occurring isomer.

However, the puzzle is not in the rarity of the isotope but rather in its abundance. The  $^{180m}\text{Ta}$  nucleus sits beside the  $s$ -process path, which proceeds through the stable Hf isotopes directly to  $^{181}\text{Ta}$ . It is also shielded from  $r$ -process production by its stable isobar  $^{180}\text{Hf}$ . A number of possible production processes for  $^{180m}\text{Ta}$  have been pursued with no conclusive results. These include the  $p$ -process, neutrino nucleosynthesis, spallation reactions in the interstellar medium, photodisintegration reactions, and certain complex paths within the regular  $s$ -process [Ton00, Bel99]. The photodisintegration reaction on  $^{180m}\text{Ta}$  and neutron capture on  $^{179}\text{Ta}$  leading to the  $^{180m}\text{Ta}$  are experimentally unverified aspects of possible  $s$ - and  $p$ -process explanations for the origin and abundance of this isomer. They thus rely on model calculations [Gok06]. The first steps towards measuring the neutron-capture cross section on radioactive  $^{179}\text{Ta}$  have been presented in Ref. [Sch99].  $^{179}\text{Ta}$  was produced by the  $^{180}\text{Hf}(p, 2n)$  reaction, radiochemically separated, and used to measure the

thermal-neutron-capture cross section. Extending the measurements to stellar ( $n, \gamma$ ), however, remains an experimental challenge.

The proposal for measuring the  $^{180m}\text{Ta}(\gamma, n)$  cross section was presented in the HIGS-PAC-2009 and was approved for 50 hours of beam time. In April 2010, around 60 hours of beam time were used to carry out measurements at photon energies of  $E_\gamma = 6.50, 6.70, 6.85, 7.00, 7.15, 7.30$ , and 7.57 MeV. Natural Ta weighing 50.863 g was used as the target for the  $^{180m}\text{Ta}(\gamma, n)$  photodisintegration reaction. A  $4\pi$ ,  $^3\text{He}$  proportional counter shown in Fig. 6.23, designed and fabricated at LANL, was used to count the emitted neutrons from the photo-neutron reaction. At each energy, a Bi target with an approximately equal number of atoms was also measured at the neutron counter in order to estimate the background from beam photons that Compton scatter off the target and are incident on the detector. Bi was chosen because its atomic number (83) is close to that of Ta (73). Simultaneous to the neutron measurements, natural Ta and In foils of thickness 0.01 mm were activated at the exit end of the collimator and counted in the low-background counting facility to measure photo-induced depopulation of the  $^{180m}\text{Ta}$  isomer. The incident photon flux was monitored using Compton scattering from an aluminum plate into a 123% HPGe detector positioned downstream at an angle of  $8.3^\circ$  with respect to the beam.

The  $^3\text{He}$  proportional counter used for neutron counting was also found to be sensitive to  $\gamma$ -rays. From long overnight measurements of the average room background in the counter, we found the rate to be  $\sim 2.3$  counts/s. A similar rate was found in the blank-target measurements with the beam. However, Ta is a high-Z element with

a large number of electrons acting as scattering centers for the incident photon beam. This contribution from atomic scattering of the incident photons was found to be huge, overshadowing the neutron counts from the photodisintegration reaction of interest.



**Figure 6.23:** (Color online) The  $4\pi$   $^3\text{He}$  counter used for detecting neutrons from the  $^{180m}\text{Ta}(\gamma, n)$  reaction.

we plan to introduce additional Pb shielding around the target, in order to eliminate or reduce the  $\gamma$ -ray pileup. We have plans to position the  $^{180}\text{Ta}$  target further downstream, near the axial end of the counter, so that the high-energy Compton-scattered photons from the target can escape the counter without triggering it.

The activation of the Ta and In foils, carried out alongside the neutron measurements, have given positive results. Figure 6.24 shows a typical spectrum from counting the activated Ta foil in the low background area using a 20% HPGe detector. The photo-induced depopulation of the  $^{180m}\text{Ta}$  isomer is inferred from the observation of the Hf  $K_\alpha$  and  $K_\beta$  X-rays that originate from the EC decay of the  $^{180}\text{Ta}$  ground state with a half-life of  $T_{1/2} = 8.1$  h. The cross section for the depopulation of  $^{180m}\text{Ta}$  is expected to be derived from the observed Hf  $K_\alpha$  peaks, with no interference from background. The primary problem in deriving this depopulation cross section is that the cross section for photo-activation of In is poorly measured and cannot be reliably used for photon flux estimation. We are currently in the process of estimating the flux from simulations using the MCNP code and comparing these results with the scattered spectra measured with the 123% HPGe flux monitor.

In the next phase of the approved beam time,

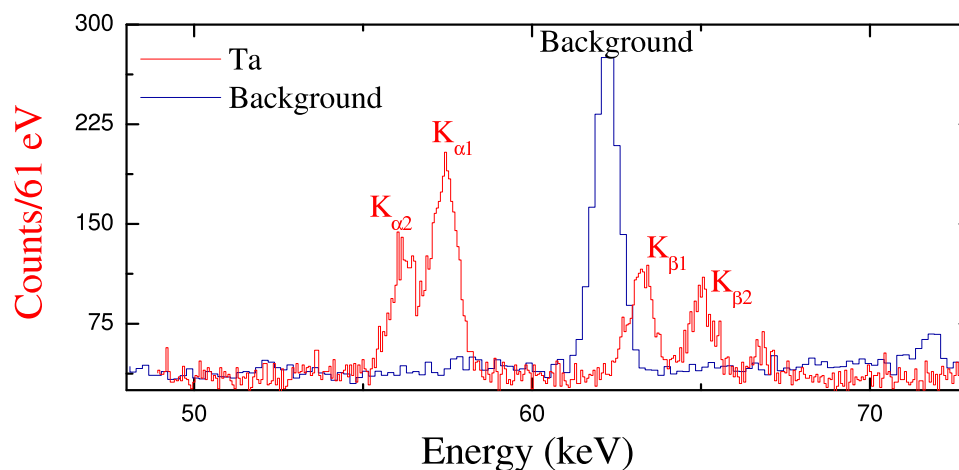


**Figure 6.24:** (Color online)  $^{180}\text{Hf}$  X-rays used to identify the photo deexcitation of the  $^{180m}\text{Ta}$  isomer.

[Bel99] D. Belic *et al.*, Phys. Rev. Lett., **83**, 5242 (1999).

[Gok06] S. Goko *et al.*, Phys. Rev. Lett., **96**, 192501 (2006).

[Sch99] M. Schumann and F. Käppeler, Phys. Rev. C, **60**, 025802 (1999).

[Ton00] A. P. Tonchev and J. Harmon, Appl. Rad. Isotopes., **52**, 873 (2000).

### 6.4.5 Dipole Strength Distribution in $^{232}\text{Th}$

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**Properties of low-energy dipole states in  $^{232}\text{Th}$  have been investigated with the nuclear-resonance-fluorescence technique using mono-energetic  $\gamma$ -ray beams at energies of 2-4 MeV from the High-Intensity  $\gamma$ -ray Source. Over 40 transitions corresponding to de-excitations to the ground state and to the first excited state were observed for the first time. Excitation energies, integrated cross sections, decay widths, branching ratios, and transition strengths for those states in  $^{232}\text{Th}$  were determined and compared with quasi-particle random-phase-approximation calculations.**

There have been numerous experimental and theoretical efforts to study the orbital magnetic dipole response over a wide mass region [Hey10]. However, most of the investigations of M1 excitations have focused on light nuclei or on deformed rare-earth nuclei [Hey10, End05], with limited experimental information on the actinides. Even less is known about E1 strength below the giant dipole resonance in the actinides. Until recently, the lack of polarized  $\gamma$ -ray beams made unambiguous identification of E1 strength very difficult.

This report describes nuclear-resonance-fluorescence (NRF) measurements on a  $^{232}\text{Th}$  target performed using nearly mono-energetic and 100% linearly-polarized  $\gamma$ -ray beams. The present search for dipole excitations in  $^{232}\text{Th}$  was performed at ten incident  $\gamma$ -ray energies between 2 and 4 MeV, with an average energy spread of FWHM = 5%. No data were taken at beam energies between 2.4 and 2.7 MeV due to the presence of a very strong background line at  $E_\gamma = 2.614$  MeV. The energy distributions of the incident photons were measured using a large volume HPGe detector positioned in the beam. The photon flux was monitored by the same detector positioned at an angle of  $8.3^\circ$  relative to the beam axis. This detector measured Compton scattering of the  $\gamma$ -ray beam from a 1.1 mm thick copper plate positioned 167 cm upstream and perpendicular to the beam axis (see Fig. 6.25). The absolute flux was determined using the Klein-Nishina formula from the spectrum of the Compton-scattered photons corrected for the detector response.

A schematic drawing of the experimental setup is shown in Fig. 6.25. The NRF  $\gamma$  rays from

the target were measured with a detector array positioned about 4.8 m downstream from the collimator. The array consists of four HPGe detectors with 60% efficiency relative to a  $7.62\text{ cm} \times 7.62\text{ cm}$  NaI scintillation detector. These detectors were positioned 10 cm away from the center of the target at  $90^\circ$  relative to the beam. Two of these detectors were located in the horizontal plane and the other two in the vertical plane. An additional HPGe detector was placed in the horizontal plane at a backward angle of  $140^\circ$ . This detector configuration allows for the unambiguous determination of the multiplicities (E1, M1, and E2) of observed  $\gamma$ -ray transitions. The detectors had passive shielding and absorbers composed of Pb and Cu. This helped to reduce contributions from low-energy background.

A total of 20 states that decay to the ground state as well as to the  $2^+$  state were identified. The branching transitions to the  $2^+$  state were identified from the 49-keV energy differences of the observed peaks. Five levels were observed without detectable branching to the  $2^+$  state. An upper limit has been set on the branching ratio for each of these five levels. The level energies deduced for these states, the integrated cross sections, the branching ratios, the decay widths to the ground state, and the strengths have been determined for all of the transitions.

In Fig. 6.26, the strength distributions of the M1 and E1 excitations observed in this work are presented along with previous experimental data from Heil *et al.* [Hei88]. For the previously known dipole excitations, which are below 2.5 MeV, M1 strengths of 1.34(13), 0.79(9), and 0.39(4)  $\mu_N^2$  were determined for the states observed at  $E_x = 2.043, 2.249$  and  $2.296$  MeV, re-

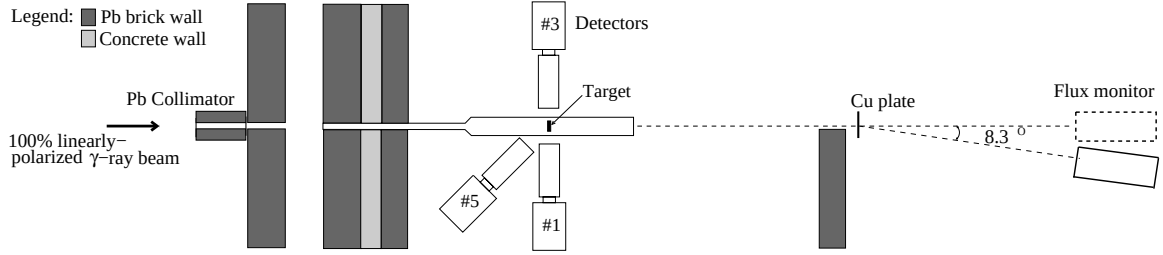


**Figure 6.25:** Schematic diagram of the experimental layout showing two HPGe detectors at  $90^\circ$  and one at a backward angle of  $140^\circ$  in the horizontal plane. The other two HPGe detectors, located in the vertical plane, are not shown. The flux monitor at  $0^\circ$  ( $8.3^\circ$ ) is indicated as a dashed (solid) rectangle. The figure is not drawn to scale

spectively. These values agree reasonably well with the M1 strengths of 1.48(9), 0.56(7) and 0.31(6)  $\mu_N^2$ , respectively, reported in Ref. [Hei88]. All the states above 2.5 MeV are observed for the first time. No E2 transitions were observed within the  $2\sigma$  detection limit.

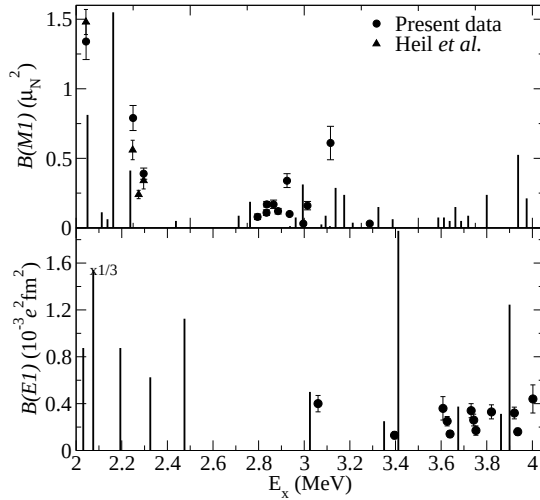


**Figure 6.26:** Comparison of experimental and calculated  $B(M1)$  (upper panel) and  $B(E1)$  (lower panel) values in  $^{232}\text{Th}$ . The solid line in both panels represents QRPA calculated values. The calculated E1 transition at 2.1 MeV has been scaled down by a factor of 3.

Theoretical calculations of low-lying electric and magnetic dipole states in  $^{232}\text{Th}$  within the quasi-particle random-phase-approximation (QRPA) approach [Kul10] are shown as solid lines in Fig. 6.26. An observed summed E1 strength of  $3.3(7) \times 10^{-3} e^2 \text{fm}^2$ , with a mean excitation energy of 3.7(8) MeV, was obtained for the

first time, and the observed summed M1 strength of 4.3(6)  $\mu_N^2$ , with mean excitation energy of 2.5(3) MeV, is in good agreement with the other actinides and with the systematics of the scissors mode in deformed rare-earth nuclei [Ade10].

The fragmentation of the M1 strengths spreading from 2.0 to 3.3 MeV is consistent with the general trend of QRPA calculations. The difference between the data and the details of the calculations is attributed most likely to the fragmentation of the strength into transitions that are below the present detection limit. It is also possible that these transitions do not exist.

The high quality beams from HI $\gamma$ S allowed the observation of more than 20 discrete de-excitations to the ground state, and the branching transitions to the first excited state were identified for most of them. Twelve E1 and eleven M1 excitations are observed in this work for the first time.

We thank E. B. Norman of UC Berkeley for loaning us the  $^{232}\text{Th}$  target, and D. R. Ticehurst, J. R. Tompkins, R. Raut, G. Rusev, W. Tornow and A. P. Tonchev for help in taking data and for helpful discussions.

[Ade10] A. S. Adekola *et al.*, Submitted, (2010).

[End05] J. Enders *et al.*, Phys. Rev. C, **71**, 014306 (2005).

[Hei88] R. D. Heil *et al.*, Nucl. Phys., **A476**, 39 (1988).

[Hey10] K. Heyde *et al.*, Rev. Mod. Phys., (2010), (accepted).

[Kul10] A. A. Kuliev *et al.*, Eur. Phys. J. A, **43**, 313 (2010).

### 6.4.6 Implementation of Nuclear Resonance Fluorescence Support in GEANT4

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**A new physics process implementation has been developed for the GEANT4 Monte-Carlo simulation toolkit to support  $(\gamma, \gamma')$  resonance reactions associated with individual isotopes. The features of this extension are described.**

GEANT4 is a widely used C++ toolkit for conducting Monte-Carlo simulations of the propagation of particles through matter. While it offers elaborate support for most nuclear processes, it lacks the ability to simulate nuclear resonance fluorescence (NRF), the process by which a  $\gamma$  ray incident on a target isotope excites a dipole resonance which quickly decays, releasing another  $\gamma$  ray with comparable energy. This  $\gamma$ -ray emission is isotropic for an unpolarized incident beam, but polarizing the incoming  $\gamma$  rays creates a pronounced angular dependence in the plane of polarization, particularly in even-even nuclei. Little energy is lost to recoil, due to the Mössbauer effect in solids.

Physics processes in GEANT4 work by calculating a table of mean-free-paths for incident particle energies and materials at the beginning of the simulation. This table is used to determine the probability of a physical process occurring when a particle passes through a particular material. Based on the probabilities of the various user-registered processes occurring, the GEANT4 code stochastically determines whether a physical event will occur, and if so, which one. If a process is selected to occur, the GEANT4 code calls a function unique to that process to carry out the interaction solution.

The NRF removes deletes the incident  $\gamma$  ray and generates a new photon with identical energy and random momentum direction. The nucleus is not considered as a recoil product because, for the NRF regime with which we are concerned (elastic scattering), this recoil is negligible.

NRF spectral lines typically have widths of tens of meV. Since these widths are small relative to the energies at which they occur, the stock class with which GEANT4 creates the mean

free path table cannot resolve the resonance lines without resorting to a multidimensional array of a size hopelessly impractical for typical hardware. The GEANT4 code was therefore modified to create the mean free path table for the NRF process by only binning the values corresponding to the energies around the registered resonance lines instead of using the same binning resolution for the entire range of energies. Mean free paths are binned as nearly rectangular pulses which rise from zero to full value in roughly 1/1000th the width of the resonance line.

Resonance lines are registered individually by calling a function that inputs the resonance line width, its cross section, its energy, and the mass number and atomic number of the corresponding isotope. These are stored in private data vectors of the modified cross-section-handler class.

While this relatively simple model is, when based on experimental data, a fairly accurate reconstruction of NRF, it does not take into account all possibilities. When a nucleus is excited to an energy state above its ground level, it is possible that there will be more than one decay path for re-emission of the absorbed energy. The possibility of decaying to multiple states can allow for the reliable identification of certain isotopes such as  $^{238}\text{U}$ , which generates two NRF peaks spaced about 50 keV apart originating from the same excited state. Given the variety of possible decay paths, it would be very difficult to develop a general process to account for all of them; it would be more practical for individual users to modify the code to model their particular situations. Additionally, the model currently does not account for the angular dependence of photon emission. This feature will be included in the near future.

### 6.4.7 Nuclear Self-Absorption Experiment on $^{11}\text{B}$

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The first nuclear self-absorption experiment at HI $\gamma$ S is reported. Measurements were carried out at beam energies of 7.3 and 8.9 MeV with the goal of reducing the uncertainty of the widths of the levels at 7.285 and 8.920 MeV in  $^{11}\text{B}$ .

Most of the previous photon-scattering experiments relevant to nuclear astrophysics and nuclear structure studies at energies close to the neutron-separation energy were carried out with bremsstrahlung beams.  $^{11}\text{B}$  was used as a calibration standard in those experiments, providing a few strong levels up to 9 MeV. Therefore, the accuracy of the results from the photon-scattering experiments strongly depend on the precision of the level widths in  $^{11}\text{B}$ . The widths of the levels at 7.285 and 8.920 MeV are known with a relative uncertainty of not better than 7% and 5%, respectively. We report an effort to reduce these uncertainties through the first experiment based on the nuclear self-absorption method [Met59] at HI $\gamma$ S. This activity is a continuation of our previous investigation of the multipole mixing ratios of the ground-state transitions in levels of  $^{11}\text{B}$  [Rus09].

The experiment was performed at the upstream target room (UTR) with circularly polarized photon beams with energies of 7.3 and 8.9 MeV. The energy distribution of the beam measured with a large HPGe detector placed in the beam is shown in Fig. 6.27 (a). For each beam energy, we carried out four measurements: three with  $^{11}\text{B}$  absorbers positioned behind the collimator and one measurement without any absorber. The thicknesses of the absorbers were 2.495(5), 4.987(7), and 8.802(9) g/cm<sup>2</sup>. Two detector setups consisting of four 60% relative efficiency and two 100% relative efficiency HPGe detectors were used to measure the attenuation of the photon beam at the energy of the levels in  $^{11}\text{B}$  by means of photon scattering from thick  $^{11}\text{B}_4\text{C}$  targets. In total the measurements lasted between 1.5 and 3 hours to collect about  $10^4$  counts from the sum spectrum of all six detectors. An example of the spectrum measured at 8.9 MeV is shown in Fig. 6.27 (b). We also carried out a measurement with the thickest boron absorber but without the  $^{11}\text{B}_4\text{C}$  targets in order to test the Pb shielding between the collimator

room and the UTR. The collected spectrum is presented in Fig. 6.27 (c), which clearly shows an absence of a peak at 8.920 MeV. The analysis of the data collected is currently in progress.

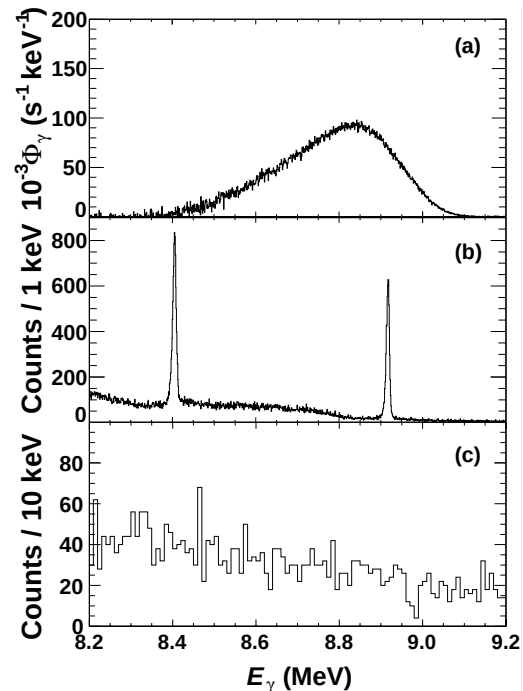


Figure 6.27: Spectra from the measurement at 8.92 MeV. (a) Spectra of the incident beam showing energy distribution of the photon flux,  $\Phi_\gamma$ , (b)  $\gamma$  rays scattered off of  $^{11}\text{B}_4\text{C}$  targets (the single-escape peak is visible at 8.409 keV), (c) measurement with  $^{11}\text{B}$  absorbers, but without any targets, revealing how effective the Pb shielding was.

[Met59] F. R. Metzger, *Prog. Nucl. Phys.*, **7**, 54 (1959).

[Rus09] G. Rusev *et al.*, *Phys. Rev. C*, **79**, 047601 (2009).



# Applications of Nuclear Physics and Nuclear Data Evaluation

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Chapter 7

- Homeland and National Nuclear Security
- Pyroelectric Research
- Nuclear Data Evaluation

## 7.1 Homeland and National Nuclear Security

### 7.1.1 Photoneutron Yield Ratios of $(\gamma, n)$ Reactions in the GDR Region

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Photoneutron angular distributions from  $(\gamma, n)$  reactions measured at HI $\gamma$ S are powerful observables that yield insight into the nature of this reaction. Studies of eight different materials have been conducted in two measurement efforts during the past year, and anisotropies have been observed with respect to rotations about the beam axis. Preliminary analyses of the actinide data reveal that the largest ratios are produced by neutrons with energies near the maximum possible from the  $(\gamma, n)$  reaction.

The detection of photoneutrons emitted following the absorption of 100% linearly-polarized  $\gamma$  rays with energies relevant to the GDR is a means to study the structure of nuclei. The angular distribution of these neutrons has been studied in the past using unpolarized  $\gamma$ -ray beams [Bak61, Hus67, Nai77]. The present work extends previous studies at TUNL that used linear polarization [Sta09]. Polarization effects in the angular distribution can be studied by measuring the yields of the neutrons emitted perpendicular,  $I_{\text{perp}}$ , and parallel,  $I_{\text{par}}$ , to the plane of polarization, which is parallel to the floor. The ratio  $I_{\text{par}}/I_{\text{perp}}$  as a function of the emitted neutron energy  $E_n$  may provide insight into the physics of the  $(\gamma, n)$  reaction.

Two experiments have been conducted during the past year to study the following materials: Pb,  $^{235}\text{U}$ ,  $^{238}\text{U}$ , Cd, Sn, Ta,  $^{239}\text{Pu}$ , and  $^{232}\text{Th}$ . The neutrons were detected using the detector array for photoneutrons (see Sect. 9.2.1) with the 1.0 m frame in the first data collection effort and the 0.5 m frame in the second. Data for each of these have been acquired at  $\gamma$ -ray energies between 11.0 and 15.5 MeV with  $\gamma$ -ray fluxes on target between  $10^6$  and  $10^7$   $\gamma$  rays per second. This is the first systematically measured set of neutron angular distributions using 100% linearly-polarized  $\gamma$ -ray beams.

The measured neutron energy spectra are continuous from the detector threshold,  $E_n = 2$  MeV, to  $\sim 10$  MeV. They were rebinned into 0.5 MeV wide bins, which were used to form the ra-

tio previously mentioned. Differences in the solid angle coverage and responses of the detectors can lead to systematic errors in the formed ratios. Corrections for these were made using data obtained with circularly-polarized  $\gamma$ -ray beams, since these must produce ratios of 1.0.

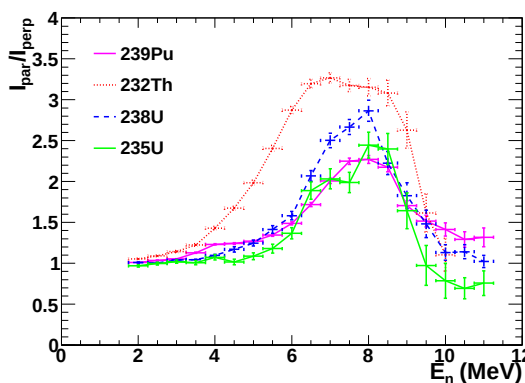


Figure 7.1: (Color online) A comparison of the ratios from the actinide targets as a function of  $E_n$  for  $E_\gamma = 15.5$  MeV at  $\theta = 90^\circ$ . (Note that  $^{232}\text{Th}$  corresponds to  $E_\gamma = 15.0$  MeV.)

A comparison of the ratio as a function of  $E_n$  at  $E_\gamma = 15.5$  MeV indicates that for  $^{238}\text{U}$ ,  $^{235}\text{U}$ , and  $^{239}\text{Pu}$ , the ratio decreases as fissility increases (see Fig. 7.1). The fissility parameter  $Z^2/A$  for these three nuclides has values of 35.6 ( $^{238}\text{U}$ ), 36.0 ( $^{235}\text{U}$ ), and 37.0 ( $^{239}\text{Pu}$ ). This observation cannot be extended to  $^{232}\text{Th}$  (fissility parameter of 34.9) because it corresponds to a

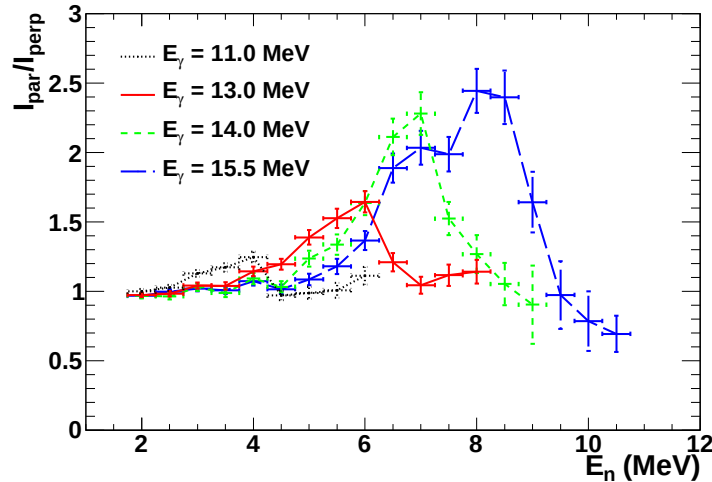


**Figure 7.2:** (Color online) The  $^{235}\text{U}$  ratio as a function of  $E_n$  for various  $E_\gamma$ . The data are truncated at  $\sim 0.3$  MeV above the maximum neutron energy produced by a  $(\gamma, n)$  reaction at the corresponding  $E_\gamma$ .

different  $\gamma$ -ray energy. Despite differences in the magnitude of the ratio, the general trends as a function of  $E_n$  are similar. The ratio spectrum for each of these materials has one large peak produced by the higher energy neutrons, and a double hump is present in this peak for  $^{232}\text{Th}$  and  $^{235}\text{U}$ . The neutrons corresponding to the maximum ratio are consistently  $\sim 1$ - $2$  MeV below the maximum energy possible from the  $(\tilde{\gamma}, n)$  reaction (see Fig. 7.2). The linearity of the relationship between the energy of these neutrons and  $E_\gamma$  indicates that they are the result of decays to excited states in the daughter nucleus during a  $(\tilde{\gamma}, n)$  reaction rather than during processes such as  $(\gamma, 2n)$  or  $(\gamma, f)$ . However, it is unclear why the location of the peak in the ratio at each  $E_\gamma$  is consistently below the maximally allowed neutron energy.

One further observation is that the neutrons with  $E_\gamma \approx 2$  MeV are uniformly emitted into the parallel and perpendicular detectors at a given  $\theta$  for all of the targets. For the actinides, the ratio decreases at the lower neutron energies, approaching unity below  $3.0$  MeV. This observation also holds for Pb.

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- [Bak61] R. G. Baker and K. G. McNeill, Can. J. Phys., **39**, 1158 (1961).
  - [Hus67] S. M. Hussain and K. G. McNeill, Can. J. Phys., **45**, 2851 (1967).
  - [Nai77] S. Nair *et al.*, J. Phys. G., **3**, 965 (1977).
  - [Sta09] S. Stave *et al.*, TUNL Progress Report, **XLVIII**, 115 (2009).

### 7.1.2 Photofission Neutron Yield Ratios on $^{238}\text{U}$ near $E_\gamma = 6.2$ MeV using Linearly Polarized $\gamma$ rays

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Neutron yields and the ratios of the yields measured parallel and perpendicular to the plane of  $\gamma$ -ray polarization ( $I_{\text{par}}/I_{\text{perp}}$ ) have been measured for the first time for a  $^{238}\text{U}$  target near the  $(\gamma, n)$  threshold of  $E_\gamma \simeq 6.2$  MeV. Measurements were performed at  $\gamma$ -ray energies of 5.7 MeV (near the photofission threshold), through the  $(\gamma, n)$  threshold, and continuing up to 6.5 MeV. The  $I_{\text{par}}/I_{\text{perp}}$  data taken with the nearly 100% linearly polarized beams at HI $\gamma$ S have values of 3 to 4 in the pure fission region below the  $(\gamma, n)$  threshold, decreasing to about 2 at energies just above the  $(\gamma, n)$  threshold. In an effort to understand these new data, a model has been developed in which the neutrons are emitted isotropically in the center-of-mass frame of the fission fragments. The fission-fragment angular distributions are taken from previous  $\gamma$ -ray- and neutron-induced fission data and are used to predict the values of  $I_{\text{par}}/I_{\text{perp}}$  for both the fission fragments and the neutrons.

Linearly polarized  $\gamma$  rays with energies at and above the fission threshold can be a powerful tool for the interrogation of materials. In addition to their ability to penetrate shielding, they also induce the emission of several-MeV neutrons. The ratio of neutron yields parallel and perpendicular to the plane of  $\gamma$ -ray polarization as a function of outgoing neutron energy ( $I_{\text{par}}/I_{\text{perp}}$ ) can provide a unique signature of isotopes. Reference [Sta08] and Sect. 7.1.1 provide details about studies with  $\gamma$  rays between 10 and 15.5 MeV on various actinide targets and shielding/background materials.

Neutron yield ratios  $I_{\text{par}}/I_{\text{perp}}$  have been measured using a  $^{238}\text{U}$  target near the  $(\gamma, n)$  threshold of  $E_\gamma \simeq 6.2$  MeV for the first time. At these energies, the neutrons from the  $(\gamma, n)$  reaction either do not exist or have energies below the detection threshold for the neutron detectors that were used during the experiment. (See Sect. 9.2.1 for more details on the detectors and the neutron detector array). Figure 7.3 shows the total cross section for  $^{238}\text{U}(\gamma, f)$  as a function of incident  $\gamma$ -ray energy measured in March 2010. The results using  $\gamma$ -ray beam energies from 5.7 (near the photofission threshold) through the  $(\gamma, n)$  threshold up to 6.5 MeV are compared with cross-section data from Ref. [Dic75] that was convoluted with the measured energy spread of the  $\gamma$ -ray beam. Twelve neutron detectors filled with BC-501A liquid scintillator were placed both in and out of the plane of  $\gamma$ -ray polarization at azimuthal angles of  $\phi = 0^\circ$  (in the plane of the polarization vector),  $90^\circ$ ,  $180^\circ$  and  $270^\circ$  and at

polar angles of  $\theta = 75^\circ$ ,  $90^\circ$  and  $125^\circ$ . The range of  $\theta$  angles allowed for a measurement of the unpolarized angular distribution. The differential cross sections at each angle were determined by first averaging over the  $\phi$  angles and then scaling by the appropriate efficiency corrections as well as solid angle, target thickness, and beam intensity. The differential cross sections were then fit with Legendre polynomials to give the angle-integrated yield at each energy.

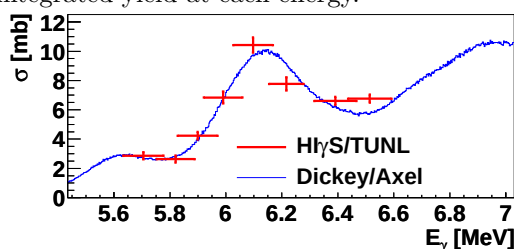


**Figure 7.3:** (Color online) The  $^{238}\text{U}(\gamma, f)$  cross section from Ref. [Dic75] convoluted with the  $\gamma$ -ray beam energy spread compared with the measured cross section determined at HI $\gamma$ S.

A typical neutron energy spectrum is shown in Fig. 7.4. The neutrons in Fig. 7.4 were detected at  $\theta = 90^\circ, \phi = 0^\circ$  for  $E_\gamma = 6.2$  MeV. The neutrons were detected at a rate of approximately 600 in 10 minutes for 10 grams of  $^{238}\text{U}$  with a  $\gamma$ -ray flux of  $10^7$   $\gamma$ /s. This type of detected neutron rate is promising for possible use as an indicator of the presence of fissionable materials. At  $E_\gamma = 6.2$  MeV on  $^{238}\text{U}$ , neutrons can only be produced by fission. At, or slightly above this en-

ergy, neutrons with energies above 1.5 MeV could be used to signal the presence of  $^{238}\text{U}$  and other fissionable materials including  $^{232}\text{Th}$ ,  $^{233}\text{U}$ ,  $^{235}\text{U}$ ,  $^{237}\text{Np}$ ,  $^{239}\text{Pu}$ , and  $^{241}\text{Am}$ .

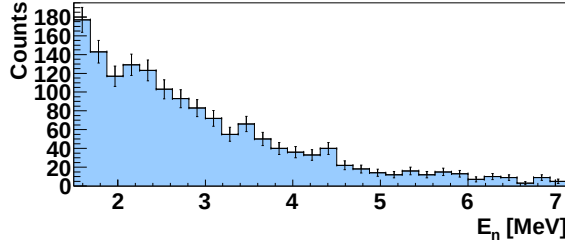


Figure 7.4: (Color online) Neutron counts for  $^{238}\text{U}(\gamma, f)$  versus neutron energy at  $E_\gamma = 6.2$  MeV,  $\theta = 90^\circ$ ,  $\phi = 0^\circ$ .

As shown in Fig. 7.5, the  $I_{\text{par}}/I_{\text{perp}}$  data taken with the nearly 100% linearly polarized beams at HI $\gamma$ S have values ranging from 3 to 4 in the pure fission region below the  $(\gamma, n)$  threshold to about 2 at energies just above the  $(\gamma, n)$  threshold. Figure 7.5 shows this variation as a function of incident  $\gamma$ -ray energy for neutrons with energies between 2 and 5 MeV. This new physics discovery could also be an indicator of the presence of fissionable materials especially if the observed ratio is distinct for different isotopes. Further studies near the fission and  $(\gamma, n)$  thresholds on other actinides are planned.

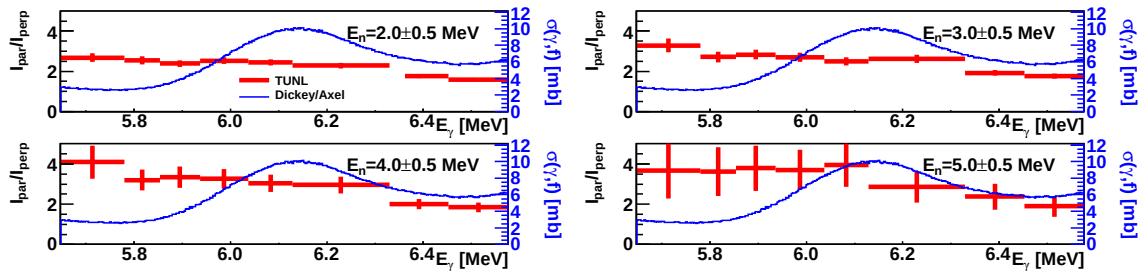


Figure 7.5: (Color online)  $I_{\text{par}}/I_{\text{perp}}$  at  $\theta = 90^\circ$  as a function of  $\gamma$ -ray energy for 1 MeV wide neutron energy slices. The cross section from Ref. [Dic75] is plotted for reference to show the energy region at which the  $(\gamma, n)$  channel opens.

In an effort to understand these new fission data, a model has been developed where the neutrons are emitted isotropically in the center-of-mass frame of the fission fragments. The fission fragment angular distributions are taken from previous  $\gamma$ -ray induced fission data [Rud88] and, when combined with the angular momentum formalism from Ref. [Rat82], are used to predict the values of  $I_{\text{par}}/I_{\text{perp}}$  for both the fission fragments and the neutrons. The neutrons are evaporated isotropically off of the fission fragments in the fission fragment center-of-mass frame and boosted back into the laboratory frame. The neutron evaporation spectra are adjusted to give the same neutron energy distributions as those measured using an “unpolarized” beam. The angular momentum formalism from Ref. [Rat82] is then employed to properly handle the linearly polarized  $\gamma$ -ray interaction. This model is still in its early stages, but it has qualitative agreement with the data. Further work is being performed to refine the model and improve the agreement

with the data.

To conclude, the  $^{238}\text{U}(\gamma, f)$  cross section near threshold has been measured at HI $\gamma$ S and found to agree well with previous data. The ratio  $I_{\text{par}}/I_{\text{perp}}$  was measured for the first time on  $^{238}\text{U}$  and found to deviate significantly from unity for neutrons with energies between 2 and 5 MeV. This finding combined with the presence of neutrons above 1.5 MeV may provide a way of identifying fissionable materials. The development of a model of the new findings is underway.

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- [Dic75] P. Dickey and P. Axel, Phys. Rev. Lett., **35**, 501 (1975).  
[Rat82] R. Ratzeck *et al.*, Z. Phys. A, **308**, 63 (1982).  
[Rud88] V. Rudnikov *et al.*, Sov. J. Nucl. Phys., **48**, 414 (1988).  
[Sta08] S. Stave *et al.*, TUNL Progress Report, **XLVIII**, 115 (2008).

### 7.1.3 Measurement of $\gamma$ -Ray Induced Activation of $^{235}\text{U}$

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A photofission experiment on  $^{235}\text{U}$  was performed at HI $\gamma$ S using 11, 13, and 15 MeV linearly polarized  $\gamma$ -ray beams. After exposure to the beam for approximately 12 hours, the  $^{235}\text{U}$  target was placed in front of a HPGe detector, and data were accumulated for a period of about 10 hours. Fission fragments and subsequent decay-chain isotopes were identified using characteristic  $\gamma$ -rays and their lifetimes. The fragment mass distributions for photofission and thermal-neutron-induced fission were compared. Potential applications include active interrogation of cargo containers.

Photofission experiments at HI $\gamma$ S are used to understand the dynamics of the photofission reaction mechanism. A comparison of the fission-fragment mass distributions for photofission and neutron-induced fission may give insight into the photofission mechanism. For example, thermal-neutron-induced-fission fragments of  $^{235}\text{U}$  have a double humped mass distribution, and relative yields for a fission fragment of mass number  $A$  and atomic number  $Z$  are known [Eng92]. However no such measurements exist for photofission on this nucleus.

a viable method for active interrogation of cargo containers. Interrogating cargo containers in domestic ports would lower the likelihood of the successful smuggling of nuclear materials.

To accomplish these goals, a photofission experiment on a  $^{235}\text{U}$  target was performed at HI $\gamma$ S. Prior to exposure to the beam, a  $\gamma$ -ray spectrum of the target was obtained using a HPGe detector. The target was then exposed to the beam for approximately 12 hours at  $\gamma$ -ray energies of 11, 13, and 15 MeV. The  $\gamma$ -ray intensities were  $10^7\gamma/s$  on target. After exposure, the target was placed in front of the same HPGe detector, and data were taken overnight for approximately 10 hours. This process was repeated for two consecutive days.

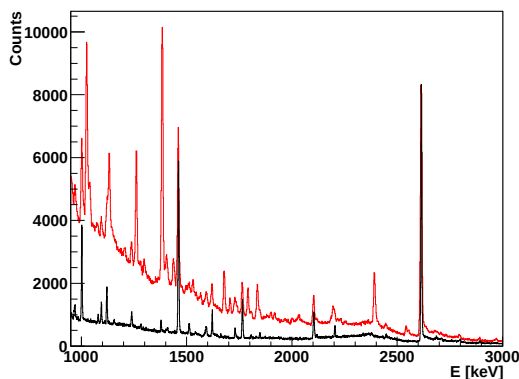


Figure 7.6: (Color online) Comparison of the pre-(black, lower) and post-activation (red, upper) spectra of the  $^{235}\text{U}$  target.

In addition to improving the understanding of the photofission process, there is an interest in potential applications of this work to national security. Identifying characteristic  $\gamma$ -rays emitted only upon photofission of  $^{235}\text{U}$  may lead to

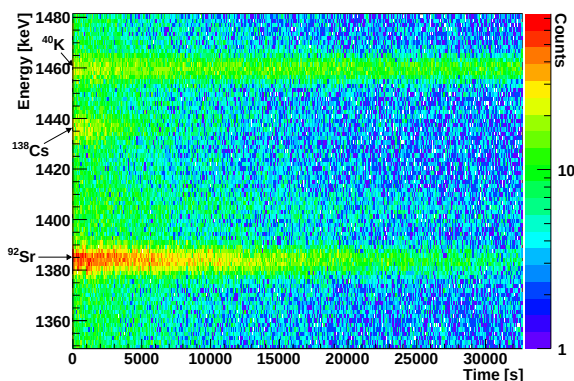


Figure 7.7: (Color online) Energy of the  $\gamma$  rays versus time since exposure to the beam for  $E_\gamma$  between 1350 and 1480 keV. Lines from  $^{92}\text{Sr}$ ,  $^{138}\text{Cs}$ , and  $^{40}\text{K}$  are indicated.

Table 7.1: Identified Photofission Fragments

| Isotope Identified | Characteristic $\gamma$ -rays (keV) | NDS $T_{1/2}$    | Observed $T_{1/2}$ | Relative Yield | Relative $\gamma$ -ray Yield |
|--------------------|-------------------------------------|------------------|--------------------|----------------|------------------------------|
| $^{88}\text{Kr}$   | 2392.1                              | $2.84 \pm .03$ h | $2.86 \pm .09$ h   | 9.1            | 3.1                          |
|                    | 834.8                               |                  |                    |                | 1.2                          |
|                    | 1529.8                              |                  |                    |                | 1.1                          |
| $^{92}\text{Sr}$   | 1383.9                              | $2.71 \pm .04$ h | $2.85 \pm .04$ h   | 10.0           | 9.0                          |
| $^{133}\text{I}$   | 529.9                               | $20.8 \pm .1$ h  |                    | 31.5           | 27.4                         |
| $^{134}\text{I}$   | 847.0                               | $52.5 \pm .2$ m  |                    | .15            | .14                          |
|                    | 884.1                               |                  |                    |                | .10                          |
| $^{135}\text{I}$   | 1260.4                              | $6.57 \pm .03$ h |                    | 21.5           | 6.2                          |
|                    | 1131.5                              |                  |                    |                | 4.9                          |
| $^{138}\text{Cs}$  | 1435.6                              | $33.4 \pm .2$ m  |                    | .60            | .46                          |
|                    | 2639.6                              |                  |                    |                | .05                          |
| $^{142}\text{La}$  | 641.3                               | $1.52 \pm .01$ h | $1.59 \pm .13$ h   | 2.6            | 1.2                          |
|                    | 2397.8                              |                  |                    |                | .35                          |
|                    | 2542.7                              |                  |                    |                | .26                          |

The pre-exposure spectrum measured  $\gamma$ -rays from the decays of various isotopes in the target, as well as background contributions, as shown in Fig. 7.6. Subsequent photofission of the target generated unstable fission fragments, some of which emitted  $\gamma$ -rays when they decayed. The additional  $\gamma$ -rays in our post-exposure spectrum are attributed to decays of these photofission fragments. The energies of these additional  $\gamma$ -rays can be used to identify specific isotopes that were generated during the photofission process.

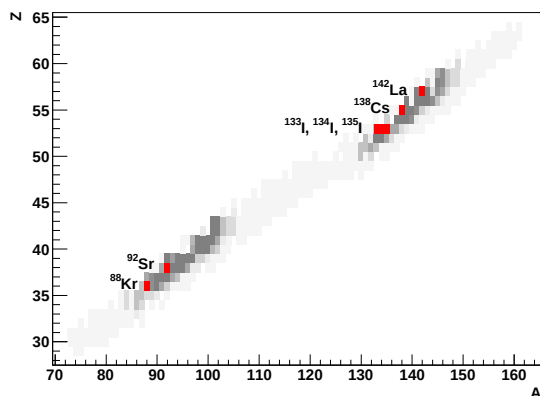


Figure 7.8: (Color online) Mass distribution of the photofission fragments (red or dark squares) and thermal neutron induced fission fragments (squares in shades of gray).

During the activation measurement, the energy of the detected  $\gamma$  ray and the time since exposure were recorded. The energy distribution of the detected  $\gamma$  rays are shown as a function

of time in Fig. 7.7. The half-lives of various fission fragments were measured by fitting the  $\gamma$ -ray intensities for a given line in the spectrum as a function of time with the function  $c_0 + c_1 \cdot e^{-t/c_2}$ , where  $t$  is the elapsed time and the  $c$  quantities are fitting constants, with  $c_2$  yielding the half-life. The  $\gamma$ -ray energy and half-life measurements were used to uniquely identify several photofission fragments.

A comparison between photofission-fragment mass distributions and thermal-neutron-induced-fission-fragment mass distributions is shown in Fig. 7.8. The photofission fragments coincide with the familiar double-humped mass structure of the thermal-neutron-induced-fission fragments. This implies similarities in the reaction mechanisms of photofission and neutron-induced fission.

A summary of the results is shown in Table 7.1. The observed  $T_{1/2}$  (or half-life) errors are from fitting only. Due to its high yield and low background contributions, the  $\gamma$ -ray at 1383.9 keV, emitted in the decay of  $^{92}\text{Sr}$ , is the most identifiable peak which is directly linked to photofission of  $^{235}\text{U}$ . Future work will investigate the feasibility of interrogating cargo containers for  $^{235}\text{U}$  by exposing them to a  $\gamma$ -ray beam and subsequently identifying the 1383.9 keV  $^{92}\text{Sr}$  peak.

[Eng92] T. England and B. Rider, *Evaluation and Compilation of Fission Yields*, 1992, ENDF-349, LA-UR-94-3106, Extracted from ENDF.

### 7.1.4 Linearly Polarized Beam Induced Photo-Neutron Yield Ratios in $^9\text{Be}$ between 10.5 and 15.5 MeV

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The ratio of photo-neutron yield parallel to the yield perpendicular (with respect to the plane of polarization of the beam) from  $^9\text{Be}$  has been measured using nearly 100% linearly polarized photons for 5  $\gamma$ -ray energies at the HI $\gamma$ S facility. The energies were chosen to study the asymmetries both in resonance regions (11.3, 11.8 and 13.8 MeV) and far from resonances (10.5 and 15.5 MeV) in  $^9\text{Be}$ . Preliminary analysis of the data indicates the presence of large photo-neutron yield ratios.

In July 2010, we measured photo-neutron yields from  $^9\text{Be}$  as part of the program to measure the ratio of neutron yields parallel and perpendicular to the plane of polarization as a function of outgoing neutron energy for actinides, metals and other materials of interest for cargo interrogation. A 2.54 cm thick  $^9\text{Be}$  cylindrical target of diameter 1.9 cm was placed axially in the beam. Twelve detectors were located nominally 58 cm from the target with 4 detectors each at angles of  $55^\circ$ ,  $90^\circ$  and  $125^\circ$ . These detectors were located “up” and “down” or perpendicular to the beam polarization plane and “right” and “left” or parallel to the beam polarization plane. An additional 3 pairs of detectors were located 58 cm from the target in plane and out of plane at angles of  $72^\circ$ ,  $107^\circ$  and  $142^\circ$ . The apparatus used in these measurements is described in Section 9.2.1. For this initial report, we will discuss the data from the 4 detectors at  $90^\circ$ , labeled “Top”, “Bottom”, “Left” and “Right” in the figures below.

The photo-neutron yields from  $^9\text{Be}$  were measured using both a circularly (Fig. 7.9) and linearly (Fig. 7.10) polarized beam at 15.5 MeV. The plots show the left, right, top and bottom detector yields at  $90^\circ$ . The spectra show structure in the regions of the energies associated with decays through the ground, first and part of the second excited states in  $^8\text{Be}$  with respective energies of 1.665 MeV, 4.565 MeV, and 13.07 MeV relative to the ground state in  $^9\text{Be}$  [Coc68]. The energies of the expected neutrons emitted at  $90^\circ$  for the decay to the ground state ( $n_0$ ), the first excited state ( $n_1$ ) and the second excited state ( $n_2$ ) are indicated on the figures.

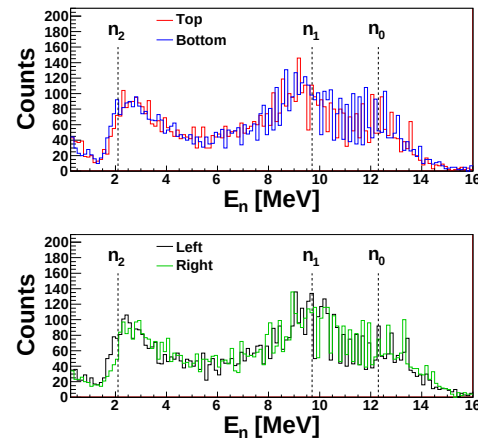


Figure 7.9: [Color online] Photo-neutron yields at  $90^\circ$  from  $^9\text{Be}$  for 15.5 MeV circularly polarized  $\gamma$  rays.

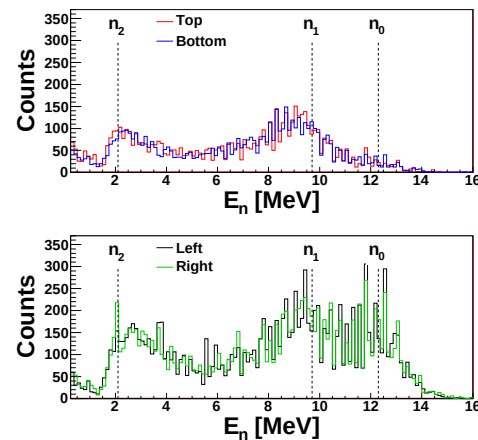


Figure 7.10: [Color online] Photo-neutron yields at  $90^\circ$  from  $^9\text{Be}$  for 15.5 MeV linearly polarized  $\gamma$  rays.

As expected, the yield spectra are nearly the same in each detector for the circularly polarized beam runs. For the case of linearly polarized  $\gamma$  rays at 15.5 MeV, it is clear in the spectra of Fig. 7.10 that there are more counts in-plane than out-of-plane.

The greater yield from in-plane detectors compared to out-of-plane for the linearly polarized  $\gamma$ -ray beam is consistent with E1 photo-absorption. However, the resonance levels in  $^9\text{Be}$  include [Til04] 11.28 MeV, 11.81 MeV, and 13.79 MeV each with an assigned negative parity. Photo-absorption excitation of these resonances would be expected to proceed via M1 and/or E2 followed by the emission of neutrons having odd  $l$ -values. The data suggests that the photo-neutron reaction proceeds through some combination of direct capture, which is predominantly E1, and resonance reactions which are predominantly M1 and E2.

We measured the ratio of yields parallel to perpendicular ( $\frac{I_{\text{par}}}{I_{\text{perp}}}$ ) for an additional 4 incident energies both near and far from the resonance states in  $^9\text{Be}$ . Figure 7.11 shows the yield ratio in the  $90^\circ$  detectors for the 5 incident  $\gamma$ -ray energies. Note that the ratios are very large in comparison with those which we have measured in other nuclei. (See 7.1.5, and 7.1.1.) A direct capture plus resonance model is being developed

in an attempt to interpret these results.

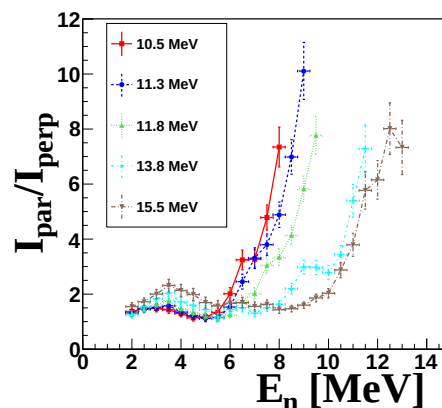


**Figure 7.11:** (Color online) Photo-neutron yield ratios from  $^9\text{Be}$  for linearly polarized  $\gamma$  rays at 5 energies and lab angle of  $90^\circ$ .

[Coc68] C. Cocke and P. Christensen, Nuc. Phys. A **111** 623, (1968).

[Til04] D. Tilley *et al.*, Nuc. Phys. A **745** 155, (2004).

### 7.1.5 Polarized ( $\gamma, n$ ) reaction studies of $^{nat}\text{Cd}$ , $^{nat}\text{Sn}$ , and $^{181}\text{Ta}$

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**HI $\gamma$ S was used to measure asymmetries in neutron emission from linearly polarized  $\gamma$  rays incident on  $^{nat}\text{Cd}$ ,  $^{nat}\text{Sn}$ , and  $^{181}\text{Ta}$ . Neutrons were detected both parallel and perpendicular to the plane of polarization at six photon energies between 11.0 and 15.5 MeV. The curves formed by plotting ratios of neutron yields parallel to yields perpendicular as a function of neutron energy were found to be distinct from those of previously studied targets at HI $\gamma$ S.**

Asymmetrically produced neutrons from linearly polarized  $\gamma$  rays incident on fissile and nonfissile nuclei make it possible to form a ratio of counts parallel to counts perpendicular ( $I_{par}/I_{perp}$ ) to the plane of  $\gamma$ -ray polarization. By plotting this observable as a function of outgoing neutron energy, a “signature” curve can be constructed for each target isotope. These isotopic signatures can be used in many ways, including as a means of photon cargo interrogation.

Intense, nearly 100% linearly polarized  $\gamma$  rays between 11.0 and 15.5 MeV were produced by HI $\gamma$ S, passed through a 1” collimator, and impinged upon the targets. Neutrons produced by processes including ( $\gamma, n$ ), ( $\gamma, F$ ), and ( $\gamma, 2n$ ) were detected by an array of 18 liquid-scintillator (BC-501A) detectors. These detectors were mounted above, below, to the right, and to the left of the beam line at angles in the range  $\theta_{lab} = 55^\circ - 142^\circ$  (see Sect. 9.2.1). Plates of thickness 0.25”, 0.2”, and 0.188” of  $^{nat}\text{Cd}$ ,  $^{nat}\text{Sn}$ , and  $^{181}\text{Ta}$ , respectively, were positioned in the center of the array, 0.5 m away from each detector. To limit the effects of multiple scattering, the target plates were oriented at  $\theta = 45^\circ$ ,  $\phi = 45^\circ$ , thus minimizing the amount of target material the neutrons pass through while exiting the target.

The results for  $^{nat}\text{Cd}$ ,  $^{nat}\text{Sn}$ , and  $^{181}\text{Ta}$  were added to a preexisting catalog of isotopic signatures determined at HI $\gamma$ S since March 2009. Amongst the previously studied targets are the fissile actinides  $^{235}\text{U}$  and  $^{238}\text{U}$ , as well as the nonfissile  $^{209}\text{Bi}$ ,  $^{nat}\text{Pb}$ , and  $^{nat}\text{Fe}$  [Sta09]. Due to the nonfissile nature of  $^{nat}\text{Cd}$ ,  $^{nat}\text{Sn}$ , and  $^{181}\text{Ta}$  as well as their ( $\gamma, 2n$ ) thresholds being 16.4, 15.8, and 14.3 MeV, respectively, the measured asymmetries result unambiguously from the ( $\gamma, n$ ) re-

action. The targets were chosen due to their commercial accessibility, their relatively low ( $\gamma, n$ ) thresholds (9.4, 6.5, 7.6 MeV for  $^{nat}\text{Cd}$ ,  $^{nat}\text{Sn}$ , and  $^{181}\text{Ta}$ , respectively), and their nonunitary expected  $I_{par}/I_{perp}$  values. Additionally,  $^{181}\text{Ta}$  is isotopically pure, meaning physical conclusions can more easily be drawn from experimental results.

In July 2010, data were collected for  $^{nat}\text{Cd}$ ,  $^{nat}\text{Sn}$ , and  $^{181}\text{Ta}$  as summarized in Table 7.1.5.

**Table 7.2: Incident  $\gamma$ -ray energies used.**

| Target            | 11.0 | 12.0 | 13.0 | 14.0 | 15.0 | 15.5 |
|-------------------|------|------|------|------|------|------|
| $^{nat}\text{Cd}$ | -    | -    | X    | X    | X    | X    |
| $^{nat}\text{Sn}$ | -    | -    | X    | -    | X    | X    |
| $^{181}\text{Ta}$ | X    | X    | X    | X    | -    | X    |

$^{nat}\text{Cd}$  was not measured at 11.0 and 12.0 MeV because its ( $\gamma, n$ ) threshold combined with the  $\sim 2$  MeV hardware cut do not allow for many neutrons to be seen at these energies.

Outgoing neutrons were distinguished from Compton-scattered photons by two-dimensional cuts on the time-of-flight (TOF) vs. pulse-shape discrimination plots. These highly nonrelativistic neutrons then had their energies ( $E_n$ ) determined using TOF techniques. Additional data for each target at 15.5 MeV were taken using circularly polarized  $\gamma$  rays. These data were then used to correct for differences in the neutron detection efficiency in each detector. The same neutron detection efficiency corrections were applied to the  $E_n$  spectra from the linearly polarized runs.

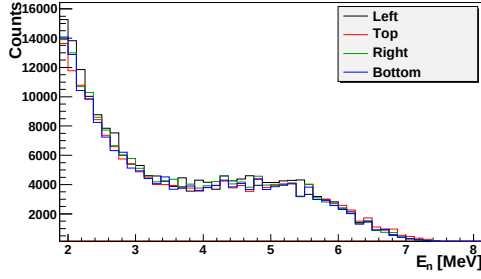


Figure 7.12: (Color online) Energy spectra for  $^{nat}\text{Cd}$  with 15.5 MeV circularly polarized  $\gamma$  rays.

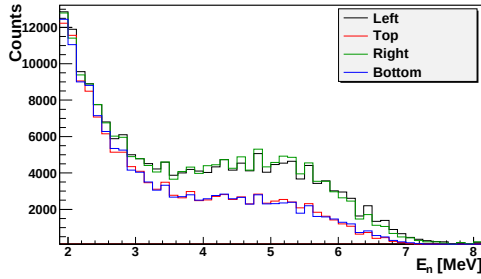


Figure 7.13: (Color online) Energy spectra for  $^{nat}\text{Cd}$  with 15.5 MeV linearly polarized  $\gamma$  rays.

For each detector angle, the  $E_n$  spectra were plotted and compared using circular polarization (Fig. 7.1.5) as well as using linear polarization (Fig. 7.1.5). It is clear that the neutron energy distribution is the same for each detector when using a circularly polarized beam. However, with a linearly polarized beam the left and right detectors received noticeably greater neutron counts than the top and bottom detectors.

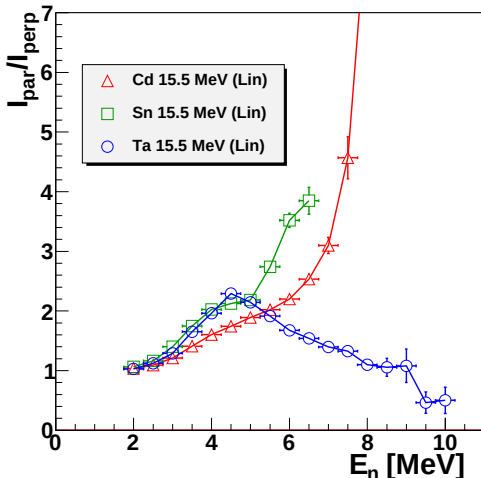


Figure 7.14: (Color online) Ratios plotted as a function of neutron energy for  $^{nat}\text{Cd}$ ,  $^{nat}\text{Sn}$ , and  $^{181}\text{Ta}$ .

The disagreement between the two planes of detectors warrants the calculation of  $I_{par}/I_{perp}$  values across the outgoing neutron energy range, which, when plotted, form isotopic signature curves (Fig. 7.1.5). Interestingly enough, despite similar values of  $Z$  for  $^{nat}\text{Cd}$  and  $^{nat}\text{Sn}$ , their curves seem to be distinct. Also, the ratio for  $^{181}\text{Ta}$  peaks at 2.4 around 4.5 MeV, a lower energy than previously studied targets. These data do not take into account instrumental asymmetries, but the adjustment is not expected to change the results by more than  $\sim 20\%$ .

As mentioned in previous reports [Sta09], an expression for the ratio  $I_{par}/I_{perp}$  was derived from Satchler's work on  $(\gamma, n)$  angular distributions [Sat55]:

$$\frac{I_{par}}{I_{perp}} = \frac{1 - 2a_2}{1 + a_2}. \quad (7.1)$$

Here,  $a_2$  is a dimensionless coefficient from the neutron angular distribution assuming pure electric dipole absorption - a reasonable assumption for gamma ray energies between 10 and 20 MeV. The measured  $I_{par}/I_{perp}$  ratios are compared to the calculated ratios from previously measured  $a_2$  values [Bak61] in Table 7.1.5.

Table 7.3: Data collected at HI $\gamma$ S using linear polarization at 15.5 MeV compared to previous predictions.

| Target            | Measured Ratio  | Predicted Ratio |
|-------------------|-----------------|-----------------|
| $^{nat}\text{Cd}$ | $2.15 \pm 0.02$ | $2.1 \pm 0.1$   |
| $^{nat}\text{Sn}$ | $2.05 \pm 0.02$ |                 |
| $^{181}\text{Ta}$ | $1.86 \pm 0.02$ | $1.9 \pm 0.2$   |

The measured ratios at HI $\gamma$ S agree very well with the ones calculated from  $a_2$  measurements despite the experimental differences (see [Sta09]).

Signature curves plotting  $I_{par}/I_{perp}$  as a function of  $E_n$  were produced from linearly polarized photon-induced neutron emission data for  $^{nat}\text{Cd}$ ,  $^{nat}\text{Sn}$ , and  $^{181}\text{Ta}$ . Although only a preliminary analysis has been performed, the curves for the three targets and previously studied targets at HI $\gamma$ S appear to be substantially distinct.

[Bak61] R. G. Baker and K. G. McNeill, Can. J. Phys., **39**, 1158 (1961).

[Sat55] G. Satchler, Proc. Phys. Soc. A, **68**, 1041 (1955).

[Sta09] S. Stave *et al.*, TUNL Progress Report, **XLVIII**, 115 (2009).

### 7.1.6 Simulation of Background from Neutron Detector Array and from $(\gamma, n)$ on $^{14}\text{N}$ in the Target Room

J.A. WALKER, *TUNL*

Neutron backgrounds in multi-detector array from multiple scattering in neighboring detectors and from the beam passing through air were simulated using geant4. Realistic light output curves and detector construction were used to properly model the detector response. The effect of multiple scattering between two detectors positioned  $18^\circ$  from each other was studied as well as the effect of  $(\gamma, n)$  on a long  $^{14}\text{N}$  target.

The photofission experiment used an array of scintillator detectors (see Sect. 9.2.1) to measure outgoing neutron asymmetries from  $(\gamma, n)$  and  $(\gamma, fission)$  on various targets. The detectors in the array were close enough to each other for multiple scattering in the detectors to be a concern.

The goal of the present work was to evaluate the importance of multiple scattering events as well as to determine the background induced by the gamma ray beam passing through the air in the target room. These effects were simulated using a simplified detector setup in GEANT4.

The detectors themselves were realistically modeled in GEANT4 in order to give correct light response curves [Per10]. Each modeled detector included a cylinder of liquid scintillator (5.08 cm length and 6.34 cm radius) which was enclosed in an Aluminum container and backed by a phototube made entirely of air.

#### 7.1.6.1 Multiple Detector Scattering

Detectors were defined at positions  $(r, \theta, \phi)$  of (58 cm, 0, 0) (Det. 1) and (58 cm,  $18^\circ$ , 0) (Det. 2) measured with respect to the neutron source. Neutrons of 2, 4, and 6 MeV were then fired uniformly into a cone covering, and slightly exceeding, Det. 1. The neutron beam did not hit Det. 2. Any particle seen in Det. 2 must have already interacted in Det. 1.

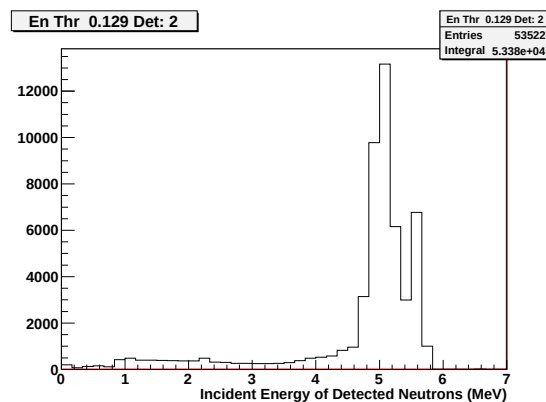


Figure 7.15: The energy spectrum of neutrons in Det. 2 resulting from scattering of 6 MeV neutron beam in Det. 1.

In [Fig. 7.15] we see 2 peaks, one at .85 of the initial energy which comes from scattering off of  $^{12}\text{C}$  in the scintillator fluid, and one at .95 of the initial energy which comes from scattering off of  $^{27}\text{Al}$  in the detector. The results of the simulation for three neutron energies are given in [Table 7.4].

The multiple scattering effect for a given detector must be summed over the effect due to each of the other detectors. This can be approximated using the known flux due to one detector, and assuming that each detector creates the same contribution to the multiple scattering per solid angle. Due to solid angle effects, the closest detectors contribute the most of the multiple scattering counts. Using this result we evaluated the aggregate effect of all other detectors on a single detector in the array. The detector located at 90 degrees was selected since it has most nearly located neighbors. The calculated yields are given in row 3 of [Table 7.4]. While this estimate assumes isotropic neutron distribu-

tions with respect to theta, the effect of the lack of isotropy should be much smaller than that of the distance.

**Table 7.4: Counts in each detector at various incident neutron energies**

|        | 2 MeV            | 4 MeV            | 6 MeV            |
|--------|------------------|------------------|------------------|
| Det. 1 | $5.0 \cdot 10^7$ | $4.4 \cdot 10^7$ | $3.7 \cdot 10^7$ |
| Det. 2 | $4.9 \cdot 10^4$ | $6.0 \cdot 10^4$ | $5.4 \cdot 10^4$ |
| Sum    | $1.6 \cdot 10^5$ | $1.9 \cdot 10^5$ | $1.7 \cdot 10^5$ |
| Ratio  | .3%              | .4%              | .5%              |

The ratios of total multiple scattering events to total single scattering events for mono-energetic incident neutron energies are given in row 4 of [Table 7.4]. If each detector recieved, at 6 MeV, a signal equal to the number of counts in Det. 1, then the top 90° detector would likely see about 1/200 of it's signal due to multiple scattering from the other detectors. This background would not have energy of 6 MeV, rather, as can be seen in [Fig. 7.15] most of the background occurs at some fraction of the initial energy. The value of this fraction depends on the scatter ring angle between the 2 detectors. Since the most relevant detectors are near 90 degrees, we can approximate that all of the multiple scattering hits take place at .85 of the initial energy.

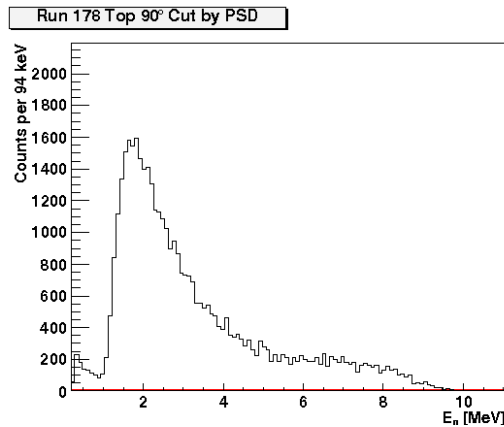


**Figure 7.16: Energy spectrum seen in top 90° detector from incident circularly polarized 15.5 MeV  $\gamma$ -ray beam on  $^{238}\text{U}$**

In [Fig. 7.16] we see that there are about

200 counts in the 6 MeV bin. If all detectors saw a similar spectrum then the bin corresponding to  $6 \cdot .85 = 5.1$  MeV (which also contains about 200 counts) would contain an additional 1/215 counts or about 1 count as multiple scattering background, this is a signal to background ratio of about 1 in 200. Similar calculations for 4 and 2 MeV yield about 2 counts (out of 500) at 3.4 MeV and 5 counts (out of 1200) at 1.7 MeV.

#### 7.1.6.2 $(\gamma, n)$ in Air

We evaluated background originating from the presence of air in the target room. The 15.5  $\gamma$ -ray beam was fired at an 8 m long air target at standard density. For comparison, a 6.6 mm thick  $^{238}\text{U}$  target was used in the same conditions. Detectors were defined at  $(58\text{ cm}, 165^\circ, 0)$  (Det. 1), and  $(58\text{ cm}, 15^\circ, 0)$  (Det. 2). It should be noted that these simulated detectors are closer to the beamline than any of the detectors in the actual array. This means that the background simulated should be higher than the actual background encountered in any detector. The neutron counts above 2 MeV per  $1.6 \cdot 10^8$   $\gamma$ -rays in each detector are shown in [Table 7.5].

**Table 7.5: Neutron counts in each detector for each target**

|        | Air           | $^{238}\text{U}$ | Ratio             |
|--------|---------------|------------------|-------------------|
| Det. 1 | $0.4 \pm 0.1$ | $75 \pm 9$       | $0.5\% \pm 0.1\%$ |
| Det. 2 | $0.4 \pm 0.1$ | $90 \pm 9$       | $0.4\% \pm 0.1\%$ |

The background to signal ratio is given in the third column of [Table 7.5], it is on the order of about .5%.

In summary, both the background from multiple detector scattering and from  $(\gamma, n)$  on  $^{14}\text{N}$  are on the order of 0.5%. Further studies can be done for multiple scattering by including the entire array and using realistic energy and angular distributions.

[Per10] B. A. Perdue, Ph.D. thesis, Duke University, 2010.

### 7.1.7 New Electric and Magnetic Dipole Transitions in $^{238}\text{U}$

S.L. HAMMOND, A.S. ADEKOLA, C.T. ANGELL, C.R. HOWELL, H.J. KARWOWSKI, J.H. KELLEY, E. KWAN, G. RUSEV, A.P. TONCHEV, W. TORNOW *TUNL*

**Precise experimental information on the distribution of M1 and E1 transitions in  $^{238}\text{U}$  has been obtained with the nuclear resonance fluorescence technique for ground-state deexcitations and for decays to the  $2^+$  state using photon beams with incident energies between 2.0 and 5.5 MeV. These measurements are compared with a modern QRPA calculation.**

Much experimental effort has been focused on measuring the magnetic dipole and electric dipole strengths in heavy-mass nuclei near stability. These dipole states are important because they can characterize the collective nature of the nuclear excitations [Hey10]. Below the neutron separation energy ( $S_n$ ) in the actinide nuclei, narrow energy regions have been selectively chosen in order to measure the orbital M1 “scissors” mode. Previous nuclear resonance fluorescence experiments on  $^{238}\text{U}$ , for example, have primarily measured the summed strength of this mode between 1.7 and 2.5 MeV [Hei88, Zil95]. However, current theoretical calculations using the quasi-particle random phase approximation (QRPA) suggest that substantial  $\gamma$ -ray strength from both M1 and E1 excitations should exist between the “scissors” mode and the giant dipole resonance (GDR) in neutron-rich, deformed nuclei [Kul10, Sol99]. Above  $S_n$ , the GDR has been studied extensively and is not of concern for this work.

There are also important nuclear forensic interests in the low-energy dipole states of  $^{238}\text{U}$ . The spectroscopic data obtained can be used for isotope identification of special nuclear materials (SNM) within shipment containers and for situations where tracing the origin of an SNM is important to national security. Currently the existing spectroscopic nuclear data about the scissors mode states [Hei88] are used within exploratory techniques for shipment interrogation. Yet it is known that higher energy  $\gamma$  rays are more penetrating than lower energy ones, even though a decrease in strength is associated with states excited by higher energy  $\gamma$  rays. Further identification of  $\gamma$  rays from  $^{238}\text{U}$  can help to improve isotope identification in shipment interrogation. In a similar fashion, nuclear resonance fluorescence techniques could also prove useful in the

management and control of nuclear-waste assays.

The measurements described in this report were performed at the HI $\gamma$ S facility using nearly monoenergetic, high-intensity, and 100% linearly-polarized photon beams at excitation energies of 2.0 to 5.5 MeV. The energy spread of the photon beam, shaped by a 1.9 cm lead collimator, was  $\sim 2$ –5%. The beam was polarized in the horizontal plane. The scattered  $\gamma$  rays were detected with six high-purity germanium (HPGe) detectors: two detectors were placed perpendicular (vertical) and two were placed parallel (horizontal) to the polarization plane, with two additional detectors at the backward polar angles of  $135^\circ$  in the horizontal scattering plane. All detectors were furnished with passive copper and lead shielding. A similar configuration was used with highly segmented HPGe detectors. Specific details for both detector arrays are described in [Ham09] and references therein. The detectors were placed about 10 cm away from a  $^{238}\text{U}$  target with a mass of either 12.9 or 19.2 g, depending on the intensity of the photon beam. The target was positioned inside an evacuated plastic tube in order to reduce the background in the measured spectra. The photon beam irradiated the target for 6 to 8 hours per energy.

The photon beam energy was measured at low flux with an HPGe detector placed in the path of the beam. The photon fluxes during data collection ranged from  $3 \times 10^6$  to  $1 \times 10^7$   $\gamma$ /s as measured by the HPGe detector placed at  $11.2(1)^\circ$  relative to the beam direction and by observing Compton scattering from a 1.1-mm thick copper plate.

New spectroscopic data—including excitation energies, integrated cross sections, decay widths, parities, branching ratios, and transition strengths—were determined in  $^{238}\text{U}$  below  $S_n$ . Data collected at photon beam energies of 2.8 to

4.2 MeV have been analyzed so far. The dipole states found in the current work were studied by comparing spectra measured in the horizontal, vertical, and backward-angle detectors. This enabled the identification of 27 E1, ten M1, and one E2 states. In addition to the deexcitation to the ground state, strong transitions to the first excited state, located at an excitation energy of 45 keV, were also observed for all states. See Ref. [Ham09] for  $^{238}\text{U}$  spectra at an excitation energy of 3.1 MeV.

For incident  $\gamma$ -ray energies in the range of 2.84 to 4.20 MeV, the summed M1 strength was found to be  $4.7(8) \mu_N^2$  with a mean excitation energy  $\omega_{M1}$  of 3.1(2) MeV, and the summed E1 strength was  $115(10) \times 10^{-3} e^2\text{fm}^2$  with an  $\omega_{E1}$  of 4.0(1) MeV.

The strengths of the dipole states found in the current work were of a similar magnitude to the strengths predicted by QRPA calculations done on  $^{238}\text{U}$  [Kul10]. This calculation by Kuliev *et al.* was fully renormalized and involved numerical calculations using a Warsaw deformed Woods-Saxon potential on  $^{232}\text{Th}$ ,  $^{236}\text{U}$ , and  $^{238}\text{U}$  to obtain the single particle energies and the summed strengths. For  $E_\gamma = 2.0$  to 4.0 MeV, the calculation for  $^{238}\text{U}$  predicts a summed M1 strength of  $\sim 6 \mu_N^2$  with an  $\omega_{M1}$  of 2.8 MeV and a summed E1 strength of  $\sim 33 \times 10^{-3} e^2\text{fm}^2$  with an  $\omega_{E1}$  of 3.0 MeV.

Although the calculation was able to predict the existence of both M1 and E1 states between 2.7 and 4.0 MeV (see Fig. 7.17), it was not able to predict well the details, such as the location of each state, its strength, and the distribution of the strength over the interval studied. It underestimated the summed M1 strength by 40% and the summed E1 strength by 72% in the energy interval of 2.7 to 4.0 MeV. Over half of the predicted M1 strength lies between 2.0 and 2.5 MeV and is a part of the scissors-mode strength. Away from this narrow energy region, there is less M1 strength predicted. This is reproduced in the experiment where few states above the detector sensitivity were found away from the scissors mode, and no discrete M1 states at all were detected above 3.5 MeV. As for the E1 strength, the number of states should increase as the excitation energy moves toward  $S_n$  and the region where the GDR is dominant. However, the E1 states may be a part of a low-lying pygmy resonance which exists separately from the GDR. A comparison of the strength from the tail of the GDR that would be in this energy region with the experimental strength needs to be made in order to determine whether the observed states are from a pygmy resonance [Ton10].

We plan to finish the analysis of the data for

$^{238}\text{U}$  from  $E_\gamma = 2.0$  to 5.5 MeV. This involves (1) identification of any new states between 2 and 3 MeV, (2) comparison of the strengths for known states found in this work with those from previous measurements, and (3) investigation of the continuum within the entire range. These new data will help to improve the understanding of M1 and E1 excitations found in deformed nuclei. This is necessary to constrain modern QRPA calculations.

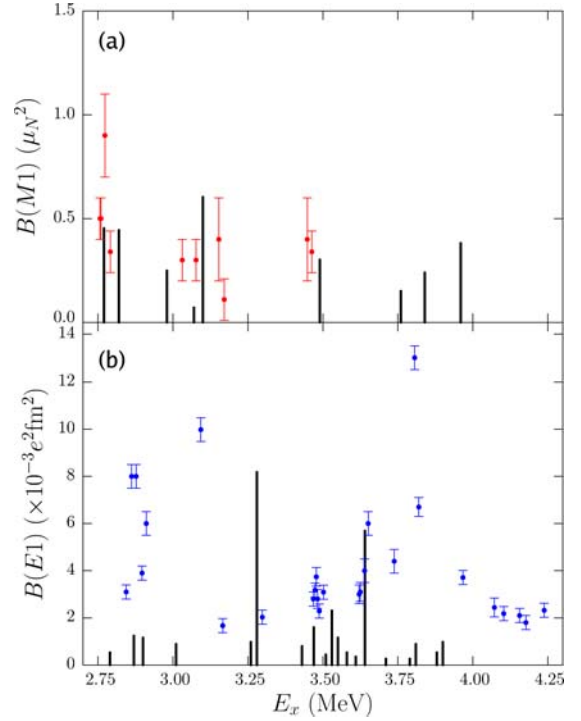


**Figure 7.17:** (Color online) Experimental (a) M1 and (b) E1 strengths (points with statistical error bars) compared with QRPA calculation (vertical bars).

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- [Ham09] S. L. Hammond *et al.*, TUNL Progress Report, **XLVIII**, 111 (2009).
  - [Hei88] R. D. Heil *et al.*, Nucl. Phys., **A476**, 39 (1988).
  - [Hey10] K. Heyde *et al.*, Rev. Mod. Phys., (2010), (accepted).
  - [Kul10] A. A. Kuliev *et al.*, Euro. Phys. J., **A43** (2010).
  - [Sol99] V. G. Soloviev *et al.*, J. Phys. G, **25**, 1023 (1999).
  - [Ton10] A. Tonchev *et al.*, Phys. Rev. Lett., **104**, 072501 (2010).
  - [Zil95] A. Zilges *et al.*, Phys. Rev. C, **52**, R468 (1995).

## 7.2 Pyroelectric Research

### 7.2.1 Neutron Production with a Pyroelectric Double-Crystal Assembly Without Nano-Tip

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Two cylindrical  $\text{LiTaO}_3$  crystals facing each other's deuterated circular face were exposed to deuterium gas at an ambient pressure of about 12 mTorr. With a distance of about 4 cm between the  $z^+$  and  $z^-$  crystal faces, neutrons were produced via the  $^2\text{H}(d, n)^3\text{He}$  fusion reaction during the heating and cooling phase of the crystals. The 2.5 MeV neutrons were detected with organic liquid scintillation detectors. During the cooling phase deuterium ion beam ( $\text{D}_2^+$ ) energies of up to 400 keV were obtained as deduced from the associated electron bremsstrahlung endpoint energy. In contrast to earlier studies, an electric-field enhancing nano-tip was not employed. Neutron yields up to 500 per thermal cycle were observed, resulting in a total neutron production yield of about  $1.6 \times 10^4$  neutrons per thermal cycle.

Since the ground-breaking work of the UCLA [Nar05] and RPI [Geu06] groups in 2005, the production of neutrons with pyroelectric crystals has been the subject of considerable interest, but also of some skepticism, which is based on the lack of reproducibility. In the present work we removed the two main sources of potential irreproducibility, the nano-tip and any issues related to the detection of 2.5 MeV neutrons in the presence of intense and high-energy bremsstrahlung X rays. We adopted the double-crystal scheme [Geu06] of the RPI group, and for the first time observed the production of neutrons during both the heating and cooling phase of the crystal assembly.

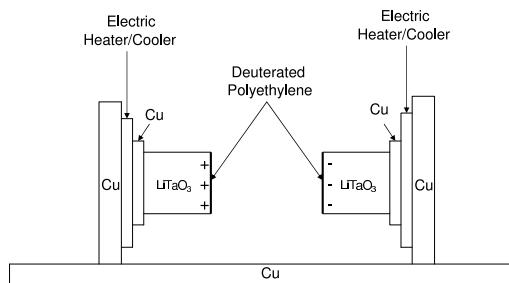


**Figure 7.18: Cartoon of double-crystal arrangement. The polarity of the polarization charges shown is for the cooling phase.**

Following our recent work [Tor10] where acceleration potentials of up to 310 kV have been achieved with a single pyroelectric crystal, we as-

sembled two 2.5 cm long and 2.5 cm diameter  $\text{LiTaO}_3$  crystals. Figure 7.18 shows a cartoon of the double-crystal assembly. The crystal to the left was  $z$ -cut to provide a positive polarization charge during cooling, while at the same time the  $z$ -cut crystal shown on the right side provided a negative polarization charge. During the heating phase of the crystals the two polarization charges are inverted. Deuterated (99.3 %) polyethylene with thickness of  $0.3 \text{ mg/cm}^2$  was evaporated on the crystal faces. The separation between the two crystal faces was 3.9 cm, and the deuterium gas pressure was typically 10 to 13 mTorr. The heating phase from room temperature to  $130^\circ\text{C}$  lasted 30 minutes, while the optimal cooling time from  $130^\circ\text{C}$  to  $0^\circ\text{C}$  was found to be 20 minutes. Typically, during the heating and cooling phases we experienced two and three discharges, respectively. Discharges occur once the electrostatic potential between the two crystals or between the crystal and their surroundings exceeds the breakdown potential of the ionized gas. Ultimately, discharges were the limiting factor in reaching higher potentials than 400 kV. A HPGe planar detector positioned outside of the vacuum chamber was used to determine the potential energy. Two 5" diameter and 2" thick neutron detectors (filled with Bicron 501A liquid scintillator fluid) were positioned on opposite sides of the vacuum chamber. They were encased within cylinders made of lead with 1.25 cm thick front face and 1.25 cm wall thickness to provide sufficient X-ray attenuation for reliable neutron detection. In ad-

dition, two 2" diameter and 2" thick neutron detectors, also surrounded by lead, were placed on top of the chamber. The neutron detectors have excellent neutron-gamma pulse-shape discrimination properties and were connected to a MPD-4 module from Mesytec which provided an amplified pulse-height spectrum and a pulse-shape spectrum with clear separation between gamma-ray/X-ray and neutron induced events.

Figure 7.19 shows a typical two-dimensional pulse-shape (horizontal axis) versus pulse-height (vertical axis) spectrum obtained with a discriminator threshold set to one-fourth times the Compton edge of  $^{137}\text{Cs}$  gamma rays, *i.e.*, 85 keV. This electron-energy threshold corresponds to about 450 keV neutron energy for the scintillator type used in the present work. The maximum neutron energy expected from the  $^2\text{H}(d,n)^3\text{He}$  reaction is about 2.5 MeV at the angular position of the neutron detectors. Our four neutron detectors were gain-matched and they have well-known neutron detection efficiencies [6]. The events located inside of the rectangular gate of Fig. 7.19 are almost exclusively due to the neutrons of interest, while the band to the left, which extends to larger pulse heights, is due to room-background  $\gamma$  rays.

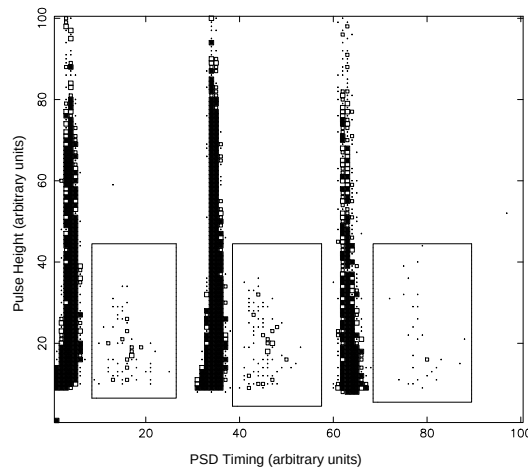


**Figure 7.19:** Two-dimensional spectra of pulse shape versus pulse height for our neutron detectors. The horizontal axis shows the zero-crossing time of X ray and room background  $\gamma$ -ray induced pulses (strong vertical bands) and neutron induced pulses (surrounded by rectangles) for the two large neutron detectors (left and center spectrum) and for the two small neutron detectors added together (right spectrum). The vertical axis displays the pulse height.

During a complete thermal cycle which typically lasts about one hour, neutrons of substantial rate above background were produced only during a few time intervals each lasting one to five minutes. These time intervals are separated by discharges and the associated recovery time. A maximum net rate of 110 neutrons per minute has been observed. Using the neutron detection efficiencies, the geometry of our experimental set-up and the neutron attenuation in the lead shield placed around the neutron detectors, we find that the maximum yield of 493 neutrons per thermal cycle found in the present work corresponds to  $16250 \pm 1620$  neutrons generated. This yield is about 60% higher than the most recent yield reported by the RPI group in [Gil09] using an electric field enhancing nano-tip. However, it is about a factor of 3.7 lower than the maximal yield reported in [Geu07] by the same group. Taking into account the considerably higher energies achieved in the present work and the fact that neutrons were produced both during the heating and cooling phase of the crystals, a substantially higher neutron yield could have been expected. Obviously, the nano-tips used in [Nar05, Geu06, Geu07] are providing a large enhancement factor. This conjecture will be explored in the near future.

The authors acknowledge the contributions of B. Carlin, A.S. Crowell, G. Rich, and S.M. Shafroth to this work.

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- [Geu06] J. Geuther, Y. Danon, and F. Saglime, *Phys. Rev. Lett.*, **96**, 054803 (2006).
  - [Geu07] J. Geuther and Y. Danon, *J. Appl. Phys.*, **90**, 174103 (2007).
  - [Gil09] D. Gillich *et al.*, *Nucl. Instrum. Methods A*, **602**, 306 (2009).
  - [Nar05] B. Naranjo, J. Gimzewski, and S. Putterman, *Nature*, **434**, 1115 (2005).
  - [Tor10] W. Tornow, S. Lynam, and S. Shafroth, *J. Appl. Phys.*, **107**, 063302 (2010).

## 7.3 Nuclear Data Evaluation

### 7.3.1 Nuclear Data Evaluation Activities

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The Nuclear Data Evaluation Group at TUNL is part of the United States Nuclear Data Program and the International Nuclear Structure and Decay Data network. After the retirement of Fay Ajzenberg-Selove in 1990, TUNL assumed responsibility for evaluation of nuclides in the mass range  $A = 3$  to 20. The status of the published evaluations and preliminary reviews is presented in Table 7.6.

Along with producing evaluations of the  $A = 3$  to 20 nuclei in the “Energy Levels of Light Nuclei” series that is published in Nuclear Physics A, the Nuclear Data Evaluation Group has been charged with providing the corresponding updates to the Evaluated Nuclear Structure Data Files (ENSDF) database that is maintained at the National Nuclear Data Center (NNDC) at Brookhaven National Laboratory. We also provide a web-based service for the nuclear science and applications communities at <http://www.tunl.duke.edu/nucldata/>.

#### 7.3.1.1 Publications

Table 7.6 displays the status of our most recent published evaluations and preliminary reviews. A first draft of a new evaluation for  $A = 11$  is anticipated for fall 2010.

**Table 7.6: Current publication status.**

| Nuclear Mass         | Publication                           | Institution          |
|----------------------|---------------------------------------|----------------------|
| Published:           |                                       |                      |
| $A = 3$              | Nucl. Phys. A474 (1987) 1             | TUNL                 |
| $A = 4$              | Nucl. Phys. A541 (1992) 1             | TUNL <sup>a</sup>    |
| $A = 5$ to 7         | Nucl. Phys. A708 (2002) 3             | TUNL <sup>a, b</sup> |
| $A = 8$ to 10        | Nucl. Phys. A745 (2004) 155           | TUNL <sup>c</sup>    |
| $A = 11, 12$         | Nucl. Phys. A506 (1990) 1             | Penn <sup>d</sup>    |
| $A = 13$ to 15       | Nucl. Phys. A523 (1991) 1             | Penn <sup>d</sup>    |
| $A = 16, 17$         | Nucl. Phys. A564 (1993) 1             | TUNL                 |
| $A = 18, 19$         | Nucl. Phys. A595 (1995) 1             | TUNL                 |
| $A = 20$             | Nucl. Phys. A636 (1998) 247           | TUNL <sup>e</sup>    |
| Reviews in Progress: |                                       |                      |
| $A = 3$              | Submitted to Nucl. Phys. A, June 2010 | TUNL                 |
| $A = 11$             | Expected late 2010                    | TUNL                 |
| $A = 12, 13$         | Expected 2011                         | TUNL                 |

<sup>a</sup> Co-authored with G.M. Hale, LANL.

<sup>b</sup> Co-authored with H.M. Hofmann, Universität Erlangen-Nürnberg, Germany.

<sup>c</sup> Co-authored with D.J. Millener, BNL.

<sup>d</sup> F. Ajzenberg-Selove, University of Pennsylvania.

<sup>e</sup> Co-authored with S. Raman, ORNL.

#### 7.3.1.2 Evaluated Nuclear Structure Data Files

The ENSDF files contain concise nuclear structure information such as tables of adopted level energies and tables of properties for levels that have been observed in various nuclear reactions and decays. The ENSDF files are updated concurrently with the last published reviews in the “Energy Levels of Light Nuclei” series.

Work on the  $A = 3$  and  $A = 11$  to 13 ENSDF files is presently underway.

#### 7.3.1.3 Experimental Unevaluated Nuclear Data List

TUNL has taken responsibility for creating  $A = 2$  to 20 data sets for the Experimental Unevaluated Nuclear Data List (XUNDL) beginning in April 2009. This activity was developed at McMaster University by Dr. Balraj Singh, who aimed to quickly provide the most current data to users in the high-spin community. The nuclear structure data in recent references is compiled in XUNDL with minimal evaluation effort. Since becoming involved, TUNL has prepared roughly 100 data sets, a rate of 6 per month on average. The data sets are reviewed by Dr. Singh and then added to the database at NNDC.

#### 7.3.1.4 World Wide Web Services

Our group continues to develop web-based services for the nuclear science and applications communities. The website layout and contents are constantly revised and kept up to date to ensure high-quality service and accurate information. Figure 7.20 displays the usage of our website from the nuclear science communities since

April 2002.

The following items are currently available:

- Ground-State Decay Data to provide evaluated data from recent work on ground-state  $\beta$  decays and charged-particle decays as well as compiled data from earlier measurements has been completed for nuclides with  $A = 3$  to 20.
- Thermal Neutron Capture Data on  $A = 2$  to 20 nuclei is provided based on compiled data.
- PDF and HTML documents are online for TUNL's and Fay Ajzenberg-Selove's reviews from 1959 to the present. The PDF versions include hyperlinks for references, Tables of Recommended Level Energies, Electromagnetic Transitions Tables, General Tables, Energy Level Diagrams, and Erratum to the Publications. The HTML documents are more comprehensive than the PDF documents, as they include hyperlinks to tables in the PDF and PS formats, reactions and reaction discussions, TUNL and NNDC references, Energy Level Diagrams, and General Tables.

We have essentially completed the recreation of PDF files for our publications, in order to provide the most current NNDC reference keys and to correct all errors found since the articles went to press. We

will continue to work on the corresponding HTML and table/PS/PDF files.

- Energy Level Diagrams for publication years from 1959 to the present are provided in GIF, PDF and EPS/PS formats.
- Tables of Energy Levels provides a brief listing of the tables of recommended energy levels (in PDF and PS formats) from the most recent publications for nuclides with  $A = 4$  to 20.
- General Tables that reference theoretical work related to TUNL's most recent reviews are available on our website for the masses  $A = 5$  to 10. The tables include dynamic links to the NSR (Nuclear Science References) database.
- ENSDF information for  $A = 3$  to 20 nuclides is available through the NNDC site.
- A link to NuDat (Nuclear Structure and Decay Data), which allows users to search and plot nuclear-structure and nuclear-decay data interactively, is available through the NNDC site.
- Links to the National Nuclear Data Center and other useful sites, as well as to the on-line electronic journals that the nuclear science communities use most often, are provided. There is also a sitemap that contains a complete listing and links to everything on the website.

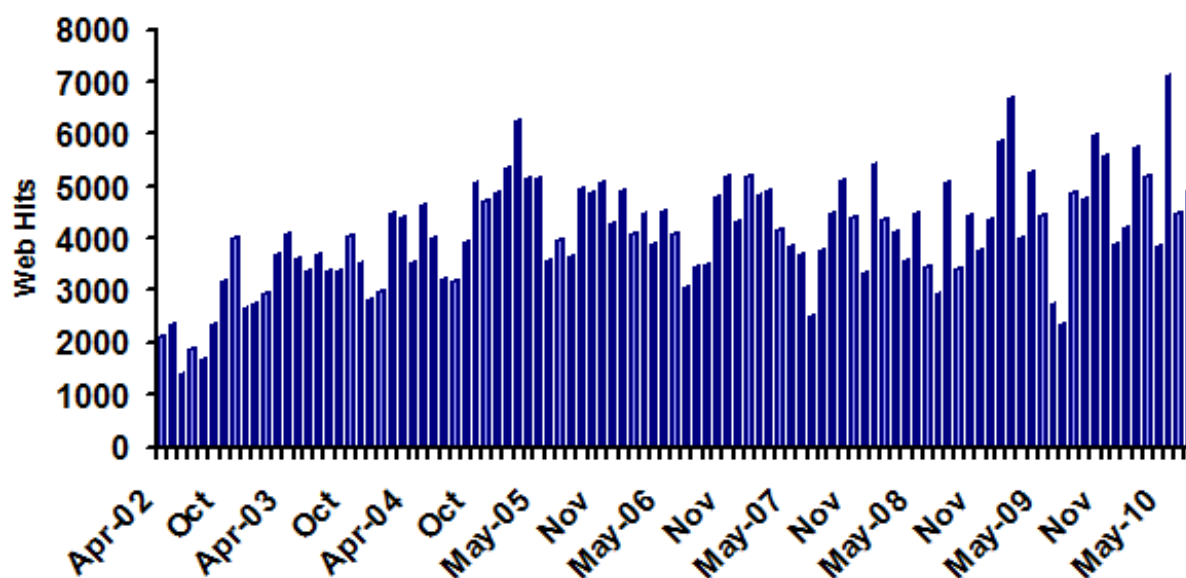


Figure 7.20: (Color online) Overview of web usage deduced from Analog Web Analysis Package



# Accelerator Physics

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Chapter 8

- The High Intensity Gamma Ray Source (HI $\gamma$ S)
- The FN Tandem Accelerator and Ion Source
- The LENA Accelerator and Ion Sources

## 8.1 The High Intensity Gamma Ray Source (HI $\gamma$ S)

### 8.1.1 Developing New and Enhanced Gamma-ray Capabilities for HIGS Research: I : $E_\gamma = 60$ MeV Operation and Helicity Switch

Y.K. WU, J. LI, S.F. MIKHAILOV, V.G. POPOV, P. WALLACE, *TUNL*

**In 2010, the HIGS research and development was focused on producing high-performance gamma-ray beams for user experiments with a high degree of consistency and predictability, and on developing new gamma-ray beam capabilities. The new capabilities include the gamma-beam helicity switch using the OK-5 FEL, and a high-flux, high-energy gamma-beam operation at 60 MeV. Using 190 nm mirrors, the operation energy of HIGS gamma-beams will be extended to about 100 MeV in the near future.**

During the last reporting period (Aug. 2009 to Jul 2010), we focused on improving the predictability of producing high-performance gamma-ray beams for user experiments and on developing new capabilities for HIGS. Using newly acquired high-reflectivity 240 mirrors, we extended the HIGS user operation from about 45 MeV in 2009 to about 60 MeV in 2010. With circularly polarized OK-5 FEL, we developed a new capability of switching the helicity of the HIGS gamma-ray beam in a few minutes.

One major direction of the continued HIGS development is to increase the energy of the Compton gamma-ray beam at a high flux for user experiments. This requires us to develop reliable FEL mirrors in the deep UV and VUV region. One of our mirror vendors, Laser Zentrum Hannover (LZH), Germany, is a world leader in developing special radiation-resistive mirror coatings in a wide range of wavelengths. Over the years, the visible and UV mirrors produced by this company have proven to have a higher degree of radiation hardness and a longer mirror lifetime than mirrors produced by other companies. In 2009, we worked with LZH closely to develop high-reflectivity, multilayer dielectric mirrors at 450, 350, 240, and 190 nm. In May and June, 2010, we commissioned HIGS operation with new 350 and 240 nm mirrors. Using the low-loss 350 nm mirrors, a very high level of gamma-ray flux can be realized. For example, operating the storage ring at 701 MeV, a 26 MeV gamma-ray beam was produced with an on-target flux of  $1\text{--}2 \times 10^7$   $\gamma$ /s after a 12 mm diameter collimator. Subsequently, these mirrors were used to produce 15 – 26 MeV gamma-ray beams for user experiments. With 240 nm mirrors, we were able to produce

a 60 MeV gamma-ray beam with good stability and a flux level adequate for the planned user experiments.

As of June, 2010, we have a set of production FEL mirrors in house to cover a wide range of gamma-ray energies from 1 MeV to 60 MeV. Using the newly acquired 190 nm mirrors, we plan to reach the next gamma-ray energy milestone of about 100 MeV in 2011.

To reduce systematic errors in experiments using circularly polarized gamma-ray beams, many experiments require the switch of the gamma-ray beam helicity. At HIGS, the helicity of the gamma beam can be changed by switching between left- and right-circular polarizations of the FEL beam produced by the helical OK-5 wiggler. The helicity of the OK-5 wiggler, an electromagnet, can be switched by reversing the direction of the DC current in one of the two sets of wiggler coils. In our system, the current reversion is realized using a solid-state DC current switch rated for a maximum current of 3 kA. The wiggler helicity switch is performed in three steps: (1) the wiggler current is first ramped to zero; (2) the solid-state switch reverses the direction of the current in one of wiggler coils; and (3) the wiggler current is ramped back to the operational value. During this process, the magnetic optics of the storage ring have to undergo a series of transitions accordingly in order to sustain a large circulating beam current in the storage ring without causing beam loss.

The wiggler helicity switch system was commissioned in Fall, 2009. This system can be operated with either one, or two OK-5 wigglers, depending on the configuration of the FEL. Operating the OK-5 FEL with a single wiggler at

770 nm, we demonstrated the gamma-ray beam helicity switch (see Fig. 8.1). Reversing the wiggler current (from 2.3 kA to 0 to  $-2.3$  kA) was carried in less than 90 seconds. No significant electron beam loss was observed. Additional time was spent on optimizing the FEL operation by tuning up the FEL optical resonator, and on recovering the FEL power by refilling the storage ring to bring the electron beam current back to a level before the helicity switch-over. The total time needed for the helicity switch and subsequent FEL tuning is about 5 to 10 minutes. We plan to speed up the helicity switch process to reduce the switch time to less than 5 minutes while minimizing the gamma-ray flux variation before and after the helicity switch.

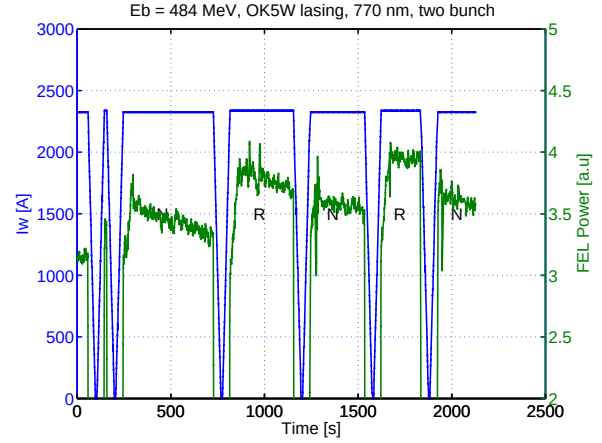


**Figure 8.1:** (color online). Helicity switch demonstration between the normal and reversed polarity with the OK-5 FEL lasing at 770 nm. The corresponding gamma-ray beam energy is 7.1 MeV. The blue curve is the wiggler current and the green curve is the extracted FEL power.

### 8.1.2 Developing New and Enhanced Gamma-ray Capabilities for HIGS Research: II: Mirror Performance Monitoring

Y.K. WU, J. LI, S.F. MIKHAILOV, V.G. POPOV, P. WALLACE, *TUNL*

In 2010, the HIGS research and development was focused on producing high-performance gamma-ray beams for user experiments with a high degree of consistency and predictability, and on developing new gamma-ray beam capabilities. The new capabilities include a mirror performance monitoring program.

The maximum total gamma-flux produced at the HIGS facility is up to  $10^{10}$   $\gamma/s$  around 10 MeV. Production of this high level of flux requires a very large average FEL power inside the resonator, exceeding 1 kW. The high-power FEL operation can cause significant degradation of the FEL mirrors due to very intense wiggler harmonic radiation, especially when operating the FEL in the UV region at a high electron beam energy. Taking advantage of the fact that higher-order harmonic radiation of the helical wiggler is peaked off-axis, we have limited the high-energy, high-flux HIGS operation mostly to circular polarization. To ensure the predictability and stability of the HIGS operation for user research programs, we have developed a comprehensive program to monitor the performance of the FEL mirrors on a regular basis. This program has enabled us to use a particular set of FEL mirrors for a few hundred hours of high gamma-flux operation with predictable performance.

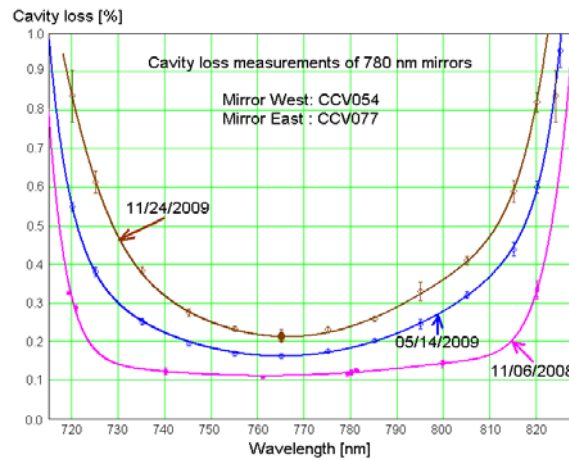
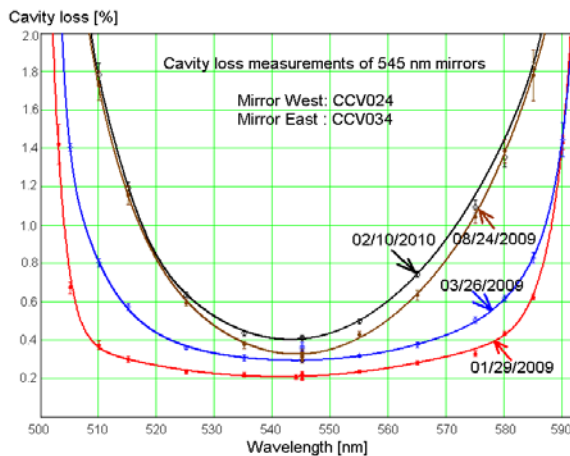


**Figure 8.2:** (color online). The measured FEL cavity losses over time. Upper plot: FEL cavity loss for 780 nm mirrors; Lower plot: FEL cavity loss for 540 nm mirrors;



The degradation of the FEL mirrors clearly shows up in the measured cavity loss curve as a function of wavelength. The mirror degradation can be monitored using three measurable effects, namely (1) an increase of the minimum cavity loss; (2) a shift of the wavelength at the minimal cavity loss toward the longer wavelength region; and (3) a reduction of the high-reflectivity band. Fig. 2 shows the measured FEL cavity losses as a function of wavelength over a period of more than 12 months for two production mirror sets at 780 and 540 nm. For these mirrors, the minimal cavity loss doubled after being used for high-flux user experiments for about 380 (780 nm) and 520 hours (540 nm), respectively (see Fig. 8.3). These mirrors are expected to be useful for additional two to three hundred hours of high-flux operation for user experiments.

For the present HIGS operation, we have a number of production mirrors with their center wavelengths around 1060, 780, 540, 450, 350, and

240 nm. The performance degradation of these mirrors is measured and evaluated after each period of extended use. This mirror performance monitoring program has enabled us to reliably project the performance of the gamma-ray beam as mirrors degrade. Based upon the measured mirror loss curve, we can deploy a set of used FEL mirrors with confidence for a specific user experiment, knowing that this mirror set will be able to produce the required gamma-beam performance. This practice extends the useful duration of the FEL mirrors without compromising the performance of the gamma-ray beam. It also makes it possible to plan for the procurement of new mirrors for future HIGS operation.

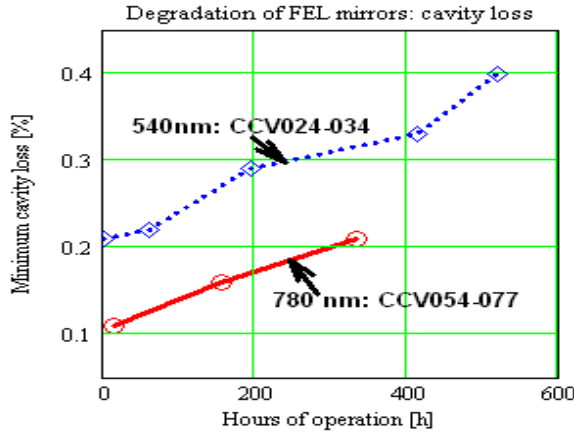


**Figure 8.3:** (color online). The measured increase of the minimum FEL cavity loss as a function of hours of operation for 780 and 540 nm FEL mirrors.

Currently, we focus on two areas of FEL mirror development. The first one is the development of special long wavelength mirrors from infrared to UV. Working closely with mirror vendors, we will develop new FEL mirrors which will allow high-flux HIGS operation in energy regions which are poorly covered by the stock of in-house mirrors. In addition, we are investigating the possibility of developing high-reflectivity, dual-band mirrors which can be used to produce high-flux gamma-ray beams in two different energy regions. The use of this type of mirrors will

significantly reduce the number of FEL mirror changes, therefore reducing the effort and risk associated with each change of FEL mirrors installed in an ultra-high vacuum system.

Our second focus is to develop durable VUV FEL mirrors for high-energy gamma-ray production. In Spring 2010, we received our first VUV FEL mirrors at 190 nm. Using these mirrors, we expect to increase the energy range of the HIGS operation to about 100 MeV. To extend the HIGS operation toward and beyond the pion-threshold energy of about 150 to 160 MeV, radiation-resistive 150 nm FEL mirrors with reasonably high reflectivity ( $> 90\%$ ) should be developed. Unlike mirrors above 190 nm which use Oxygen based materials for mirror substrates and coating, VUV mirrors below 190 nm requires the use of Fluoride based materials. This change of materials for substrates and coatings requires the vendor to optimize the coating technique to produce high-density Fluoride coatings and to develop effective protective overcoat layers to enhance the radiation resistance of the mirror. Working closely with LHZ, we plan to develop prototype Fluoride based mirrors at about 175 nm to test their durability. These mirrors will allow us to produce gamma-ray beams with a maximum energy of 115 MeV. If the development of prototype 175 nm mirrors is successful, we will move on to the development of 150 nm mirrors which are critical for photo-pion physics research.

The VUV mirrors are significantly lossy compared with mirrors in the visible region. A higher gain FEL with four OK-5 wigglers will be necessary for the HIGS operation with VUV FEL mirrors. This requires the installation of two additional OK-5 wigglers in the FEL straight section of the Duke storage ring. To retain the linear polarization capability of the HIGS which is enabled by the planar OK-4 wigglers, we are developing a wiggler switchyard system to mechanically switch between two planar OK-4 wigglers and two helical OK-5 wiggler in the middle of the FEL straight section. This wiggler switchyard will be installed and commissioned in 2011.

### 8.1.3 Accelerator Physics Program: I : Free-Electron Laser Research

Y.K. WU, *TUNL*

**The accelerator physics program at the DFEL is focused on making a direct impact on the HI $\gamma$ S research programs by enhancing accelerator performance and creating new capabilities. The FEL research is aimed at increasing the FEL power and gain using various wiggler configurations and low-loss FEL mirrors. This research will lead to a higher gamma-ray flux and will extend the HIGS operation towards 100 MeV and above.**

The accelerator physics research is critical to the continued development of the High Intensity Gamma-ray Source (HIGS) to enhance its performance and create new capabilities. At the present time, we focus our research effort in two important areas: (1) the FEL physics research to increase the FEL power and FEL gain, and to reduce losses in the optical resonator; (2) the beam instability research to stabilize electron beam operation at a higher beam current. The effort in these areas can make a direct impact to the HIGS development, by increasing the gamma-ray flux and extending the gamma beam energy first to 100 MeV, and later to above the pion-threshold energy ( $> 150$  MeV). We report here on the FEL physics research.

The Duke storage ring is a dedicated accelerator driver for FELs. Four FEL wigglers are currently installed in the 34 m long straight section, including two planar OK-4 wigglers in the middle section and two helical OK-5 wigglers on the sides (see Fig. 8.4). The FEL wigglers can be configured in several ways to produce coherent radiation with different polarizations, and for either high-power or high-gain operation. Commonly used FEL configurations include (1) high-power FEL configurations with a single wiggler, either a planar OK-4 wiggler or a helical OK-5 wiggler; (2) high-gain FEL configurations with an optical klystron using either two OK-4 wigglers or two OK-5 wigglers; (3) the highest gain configuration with a distributed optical klystron FEL (DOK-1) with all four wigglers [Wu06]. By colliding an intense electron beam inside the laser cavity, the FEL beam is used as the photon drive to power the High Intensity Gamma-ray Source (HIGS) [Wel08].

The storage ring based oscillator FELs are the main coherent light source at the DFEL. The Duke storage ring FEL has been operated in a wide wavelength range from infrared ( $\lambda \sim$

1 to 2 microns) to vacuum ultraviolet (VUV) (194 nm). In the recent years, we have developed various experimental and simulation techniques to study the storage ring FEL.

The electron beam energy spread is a very important parameter for understanding the longitudinal beam dynamics and beam instabilities. For the storage ring FEL, the induced energy spread determines the FEL power. The electron beam energy spread also determines the minimal energy spread of a collimated HIGS gamma beam. We have recently developed a versatile method to accurately measure the electron beam relative energy spread from  $10^{-4}$  to  $10^{-2}$  using the radiation from an optical klystron which consists of two FEL undulators (or wigglers) sandwiching a buncher magnet. A novel numerical model based upon the Gauss-Hermite expansion has been developed to treat both spectral broadening and modulation on an equal footing. A large dynamic range of the measurement is realized by properly configuring the optical klystron. In addition, a model based scheme has been developed to compensate the beam emittance induced inhomogeneous spectral broadening effect. Using this technique, we have successfully measured the relative energy spread of the electron beam in the Duke storage ring from  $6 \times 10^{-4}$  to  $6 \times 10^{-3}$  with a high degree of accuracy [Jia10].

Using the newly developed energy spread measurement technique, an experimental study on the FEL power scaling with the electron beam current, energy, and energy spread has been carried out. Measurements have been made to directly link the FEL power to the measured energy spread of the electron beam. The experimental results (Fig. 8.5) show that the relation between the FEL power and induced energy spread holds well for different optical detuning conditions. This research is expected to enable us to predict the FEL power and FEL induced

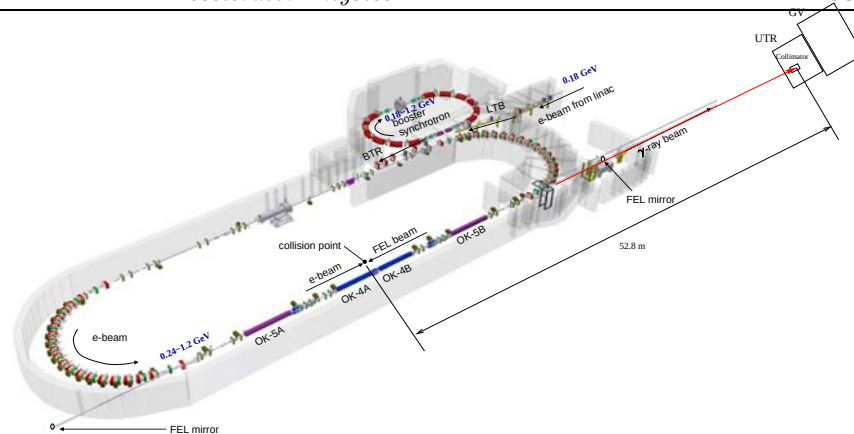


Figure 8.4: (color online). The schematic of the Duke storage ring accelerator facility including the linac pre-injector, full-energy top-off booster injector, and the storage ring.

energy spread for different levels of optical cavity loss as the FEL mirrors degrade. A reliable prediction of the FEL beam parameters will enable us to produce detailed projections of the gamma-ray beam performance, therefore allowing further optimization of the user experiments using the HIGS gamma-ray beam.

One focus of our FEL research program is to realize FEL lasing at VUV wavelengths (200 - 150 nm) with FEL mirrors which have a lower reflectivity than visible mirrors. The VUV FEL research will require a higher gain FEL with a long wiggler system which can be realized at Duke with four helical OK-5 wigglers. In addition to two existing OK-5 wigglers, two more OK-5 wigglers need to be installed in the middle of the FEL straight section (Fig. 8.4). In order to preserve the linear polarization capability of the planar OK-4 FEL, we have devised a wiggler switchyard system to mechanically move in/out either two planar OK-4 or two helical OK-5 wigglers in the straight section. The mechanical design of the wiggler switchyard system is well under way, which will be followed by the fabrication of related vacuum and electrical components for the upgrade. In the meantime, research is being carried out to design magnetic optics compensation schemes to overcome the adverse effects of turning on all four FEL wigglers. These compensation schemes will be used to develop transitional magnetic optics to allow switching of the helicity of the VUV FEL. To minimize the impact of the wiggler switchyard project on the HIGS research programs, we have planned to carry out the project in two steps. First, we will design, fabricate, and prepare on the bench all switchyard related hardware components while operating HIGS for the user experiments. Second, we

will plan a relatively short shutdown to install wiggler switchyard system in 2011 to reduce the operation downtime and the impact on the subsequent HIGS operation after the upgrade.

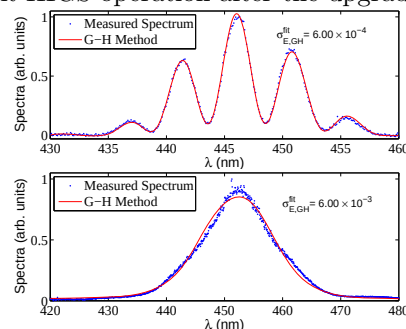


Figure 8.5: (color online). Measured optical klystron spectra with a very small and very large energy spread. Upper: The electron beam energy is 280 MeV, the single-bunch beam current is 0.045 mA, and the FEL is off. The measured relative electron beam energy spread is  $\sigma_E = (6.00 \pm 0.015) \times 10^{-4}$ . Lower: The electron beam energy is 400 MeV, the single-bunch beam current is 40 mA, and the OK-5 FEL is turned on to increase the energy spread of the electron beam. The relative measured electron beam energy spread is  $\sigma_E = (6.00 \pm 0.029) \times 10^{-3}$ .

- [Jia10] B. Jia *et al.*, Phys. Rev. ST Accel. Beams, **13**, 080702 (2010).
- [Wel08] H. Weller *et al.*, Prog. Part. Nucl. Phys., (2008).
- [Wu06] Y. Wu *et al.*, Phys. Rev. Lett., page 224801 (2006).

### 8.1.4 Accelerator Physics Program: II: Beam Instabilities Research and Fast Feedback Systems

Y.K. Wu, *TUNL*

The accelerator physics research program at the DFEL provides new insight into the relations between various parameters of the electron beam and FEL resonator and the performance of the FEL optical beam. Using advanced bunch-by-bunch longitudinal and transverse feedback systems, the beam instability research is aimed at increasing the electron beam current for stable, high-flux HIGS operation. We will also report other accelerator research activities which are important to the further development of the Duke storage ring and other similar accelerators.

The accelerator physics research is critical to the continued development of the High Intensity Gamma-ray Source (HIGS) to enhance its performance and create new capabilities. One of the areas of our effort is in the beam instability research to stabilize electron beam operation at a higher beam current. The effort in these areas can make a direct impact to the HIGS development, by increasing the gamma-ray flux and extending the gamma beam energy first to 100 MeV, and later to above the pion-threshold energy ( $> 150$  MeV).

The accelerator research program at the HIGS facility also covers a broader range of topics, including the nonlinear dynamics of charged particles, polarized electron beam research, advanced accelerator design and optimization, and novel light source development.

In the Duke storage ring, the maximum beam current in the multi-bunch mode is limited by longitudinal coupled bunch instabilities. To combat these instabilities, a bunch-by-bunch longitudinal feedback (LFB) system has been developed. This system employs an integrated Gigasample processor (iGp) and a broadband, waveguide overloaded kicker cavity specially designed for the Duke storage ring. The LFB system has been very effective in suppressing longitudinal instabilities with a number of bunch fill-patterns, including symmetric 2-, 4-, 8-, 16-, 32-bunch modes and the completely filled 64-bunch mode. The LFB system has played an important role in realizing and stabilizing high-flux HIGS operation with a high electron beam current, especially at a low electron beam energy where natural radiation damping is lacking, or with UV mirrors which have a lower reflectivity, but a higher level of thermal loading. Fig. 8.6 shows the effect of the LFB system to stabilize a 16-bunch electron beam at 1.15 GeV, a high

energy storage ring operation critical for VUV FEL research. When the high ambient temperature in the summer causes significant thermal drifts in a variety of hardware systems, the LFB system has been effective in many cases to suppress beam instabilities, thus preventing electron beam loss.

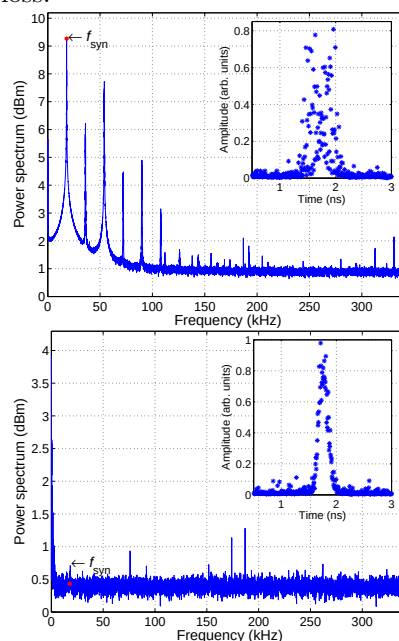


**Figure 8.6:** (color online). The LFB system brings the 1.15 GeV, 16-bunch electron beam to stability. The total beam current is about 78 mA and charge is almost evenly distributed in all bunches. Upper: the LFB is off. The beam is unstable with substantial synchrotron oscillation sidebands and unstable longitudinal distribution (inset); Lower: the LFB is turned on and the beam is stable.

The maximum current in a single electron

bunch is limited by transverse instabilities. Recently, we started to develop a bunch-by-bunch transverse feedback (TFB) system by upgrading an analogy system to an field-programmable gate array (FPGA) based digital system using the same integrated Gigasample processor as the LFB system. This upgraded TFB is currently operational but further tuning and adjustment are being carried out to optimize its performance. The effectiveness of TFB to extend the beam current per bunch in realistic operational conditions has yet to be demonstrated.

Both the LFB and TFB systems have been used as diagnostic tools to study beam instabilities in the storage ring. These studies will help gain new insight into mechanisms of various instabilities and help us develop remedies to effectively eliminate or suppress these instabilities while extending the stable electron beam operation to a higher current.

Other research activities at DFELL include (1) accurate measurements the electron beam energy in the storage ring using the HIGS gamma-ray beam; (2) the development of novel end-to-end gamma spectrum reconstruction technique for the Compton gamma-ray beam; (3) a study of electron beam polarization process at 1.15 GeV; and (4) a research program to explore nonlinear dynamics of charged particles in a circular accelerator.

The HIGS gamma-ray beam has been used as an advanced diagnostic tool to measure electron beam parameters. Recently, we have developed techniques to accurately measure the centroid energy of the electron beam in the storage ring with a relative uncertainty of a few times  $10^{-5}$  for low energy beams at a few hundreds of MeV [Sun09a].

In addition, we have developed a novel end-to-end gamma spectrum reconstruction method using a numerical model which simulates the entire process of gamma beam production (via Compton scattering), collimation, and detection [Sun09b]. This method allows us to construct a detailed energy distribution of a Compton gamma-ray beam at various energies, in particular between 10 and 15 MeV in which the conventional spectrum reconstruction techniques have difficulties in producing a truthful gamma-ray energy distribution due to a complex detector response.

The electron beam in the storage ring can build up polarization due to the Sokolov-Ternov effect. The polarized electron beam will have a reduced Touschek loss rate due to electron collision inside a bunched beam. Beam lifetime mea-

surements have been used to study the radiative polarization buildup process of a 1.15 GeV electron beam, by measuring the time constant of the process and equilibrium degree of the polarization [Sun10]. To make such an experiment successful, we worked hard to establish highly reproducible beam conditions to allow repeatable beam lifetime measurements as a function of beam currents. In addition, the accuracy of the beam lifetime measurement has to be improved to better than about 5%. We found that the 1.15 GeV electron beam could become highly polarized with a degree of polarization of 85%.

The research with polarized electron beams can have a direct impact to HIGS research programs. For a Compton gamma-ray beam, an accurate and direct measurement of its energy in the tens to about 130 MeV region remains a challenge. One effective method to determine the gamma-beam energy is to measure the energy of the electron beam used in Compton scattering. A polarized electron beam can be used to accurately measure its centroid energy using the resonant spin depolarization technique.

Nonlinear dynamics are a critical issue for the light source storage rings as well as future circular accelerators with strong nonlinear magnetic elements. Our recent work focuses on the study of nonlinear dynamics of charged particles in a circular accelerator using scaling techniques. For example, we have studied the beam dynamics with varying strengths of nonlinear elements in a circular accelerator with a fixed structure, or by varying the number of repetitive cells of the accelerator with each cell retaining the similar focusing arrangement. We have developed a new scaling law between the particle's nonlinear dynamics and the number of repetitive cells in the circular accelerator. This so-called "lattice-scaling" allows us to compare beam dynamics of different storage rings of different sizes and beam emittances. It also allows us to predict the degradation of beam dynamics as the chromatic compensation is increased in a certain manner. The scaling methods developed in this research are expected to become a very useful technique in studying the nonlinear dynamics of charged particles in the circular accelerators.

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[Sun09a] C. Sun *et al.*, Phys. Rev. ST Accel. Beams, **12**, 062801 (2009).

[Sun09b] C. Sun *et al.*, Nucl. Instrum. Methods A, **606**, 312 (2009).

[Sun10] C. Sun *et al.*, Nucl. Instrum. Methods A, **614**, 339 (2010).

### 8.1.5 Gamma Imagers for HIGS User Experiments

Y.K. WU, C. SUN, M. EAMIAN, J. LI, W.Z. WU, *TUNL*

Two gamma imagers have been developed and deployed in the UTR and GV experimental areas for routine HIGS user operation. A gamma imager is a critical instrument for aligning the collimator and experimental apparatus with the gamma-ray beam. A third gamma imager in the SW optical room is being developed as a diagnostic to stabilize the gamma-beam pointing and potentially as an integrated flux monitor.

The  $\text{HI}\gamma\text{S}$  beam is produced by colliding a high intensity electron beam and a high power FEL beam inside the FEL cavity. The highest energy Compton scattered photons are concentrated in a small solid angle along the direction of the electron beam. A collimator is used to select a small portion of the gamma-ray beam with a desirable energy resolution. To minimize the energy spread and maximize the flux of the gamma beam, the alignment of the collimator is critical for all nuclear physics experiments, especially for experiments with a long target system such as a gas cell. At the  $\text{HI}\gamma\text{S}$ , we have developed high-resolution gamma imagers to “see” the gamma-ray beam directly in order to align the collimator with the gamma-ray beam, and align the experimental apparatus with the collimated gamma-ray beam.

#### 8.1.5.1 Gamma Imagers for HIGS Operation

Since 2008, we have successfully developed three different gamma imagers, with spatial resolution better than 0.5 mm, and contrast sensitivity better than 5%. Two of the imagers, the UTR imager and GV imager, are installed in the UTR and GV experimental areas, respectively (see upper panel of Fig. 8.7). These imagers are used to align the gamma-ray beam with the collimator and experimental apparatus in the two target rooms (lower panel of Fig. 8.7), by looking upstream at the shadow of the collimator and experiment apparatus made in the gamma-ray beam. The UTR imager is located about 60 m downstream from the collision point where the Compton gamma-ray beam is produced, and has a 2 in diameter field of view. It is the newest imager, developed with a set of compact optics to minimize the use of valuable floorspace in the UTR. The GV imager is located about 70.2 m down-

stream from the collision point, and has a 3 in diameter field of view. The GV imager is a versatile system with reconfigurable optics to provide different magnifications and fields of view. Both imagers are mounted on translational platforms, which provide movement of the imagers into and out of the gamma beam by remote control. The remotely controlled translation stage for the GV imager has been operational since Jan, 2010 and the remote control mechanism for the UTR imager is nearly completed.

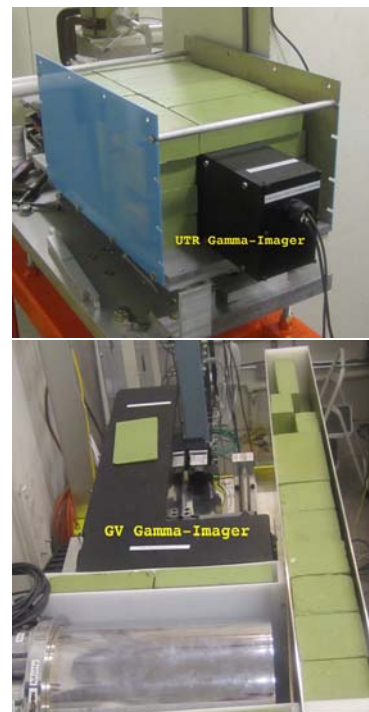


**Figure 8.7:** (color online). Two gamma imagers deployed in the UTR and GV areas. (a) Upper: the UTR gamma imager with a 2 in field of view; (b) Lower: the GV gamma imager with a 3 in field of view.

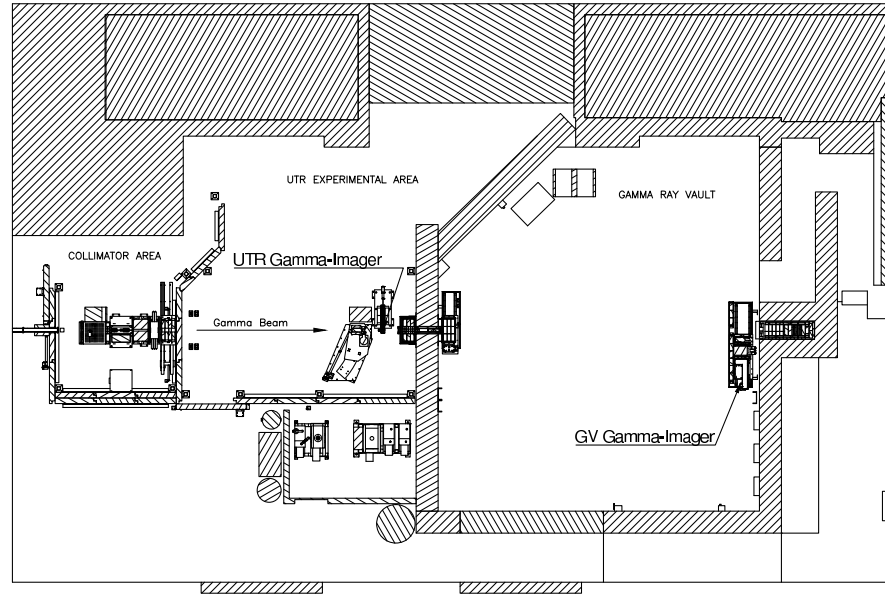


Figure 8.8: Locations of gamma imagers inside the UTR and GV experimental areas.

In Dec. 2009, we established a remote control user interface to control CCD cameras in the UTR and GV imagers from the accelerator control room. Since Jan. 2010, both the UTR and GV imagers have been used for all HIGS user experiments. When the misalignment is small, the gamma-ray beam is aligned with the collimator by changing the direction of the electron beam at the collision point. Fig. 3 shows the gamma-beam images with the collimator before and after performing alignment.

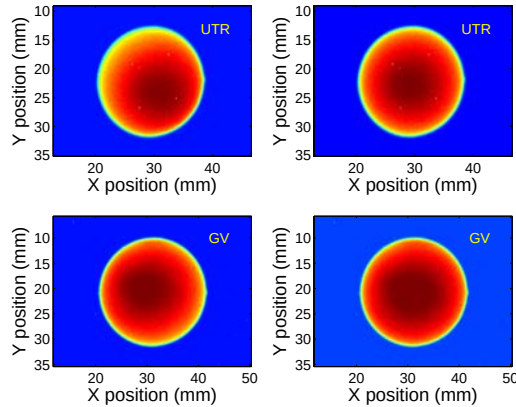


Figure 8.9: (color online). Gamma-imagers are used to align the collimator with the gamma-ray beam. Upper images: gamma beam images taken using the UTR imager – left: misaligned; right: aligned. Lower images: gamma beam images taken using the GV imager – left: misaligned; right: aligned. For all images, a 15.5 MeV gamma beam produced by a 625 MeV electron beam is imaged after a 19 mm (0.75 in) diameter lead collimator.

#### 8.1.5.2 Development of SE Gamma Imager

A third gamma imager has been installed downstream from an FEL mirror inside the southeast (SE) optical room. This system has been developed for monitoring the gamma-beam centroid motion and gamma-beam flux. By direct monitoring the gamma-ray beam centroid position, this system will allow us to improve the pointing stability of the gamma-beam. This is critical for many user experiments which require frequent changes of the gamma energy, resulting in changes of the electron beam orbit around the collision point. We are also investigating the capability of this gamma-imager as a device for monitoring the integrated gamma-beam flux. As an integrating flux monitor, it is expected to have a very wide dynamic range, selectable by changing the integration time. However, we have to find effective ways to deal with issues related to the photon background, bad CCD pixels, and nonlinear response of the imager with the varying gamma beam energy. We expect to report our findings on this system in the next reporting period.

### 8.1.6 HIGS Accelerator and Gamma-ray Beam Operations

Y.K. WU, P. WANG, P. WALLACE, S.F. MIKHAILOV, *TUNL*

During the period from August 1, 2009 through July 31, 2010, the HIGS operated 2539 hours for a variety of research programs and activities, and achieved a high level of reliability of about 96%. A total of 1452 hours of on-target gamma-ray beamtime were delivered to various HI $\gamma$ S user research programs.

#### 8.1.6.1 HI $\gamma$ S Operation: Aug. 2009 – Jul. 2010

During the period from August 1, 2009 through July 31, 2010, the HIGS accelerators operated 204 days, providing 2539 hours for a variety of research programs and activities. The accelerator and light source operation was carried out mainly with a two-shift, five-day operation schedule. Overall, operation of HIGS accelerators and light sources was at a very high level of reliability, near 96%, exceeding the typical performance goal set for national synchrotron light sources (95%). This level of reliability was realized in spite of the complex and challenging operation of the free-electron lasers and Compton light source. A detailed break-down of accelerator operation hours are summarized in Table 8.1 and Fig. 8.10.

In the last twelve months, we delivered 1452 hours to research programs using the HIGS gamma-ray beam, for both basic and applied nuclear physics research. The accelerator research and development used 243 hours of beamtime. Some of this beamtime was spent on developing future capabilities, including the development of new operation modes of the longitudinal feedback system to stabilize multi-bunch electron beams and commissioning of a transverse feedback system. A substantial amount of time (844 hours) was used to perform the setup and tune-up of accelerators, FELs, the Compton gamma source, and other activities. The gamma-ray user programs in this period demanded frequent changes of gamma-beam parameters, including gamma-beam energy, flux, and polarization. These changes required frequent changes of the FEL mirrors. With each mirror change, time is spent on conditioning and aligning FEL mirrors, and on setting up accelerators, FELs, and the Compton gamma-ray source. These 844 hours also include the beamtime spent on the commissioning of the OK-5 helicity switchyard

system, on the testing and commissioning of the new UTR personal protection system (PPS), including radiation surveys around the UTR and along the gamma beamline.

**Table 8.1: Summary of DFELL accelerator and light source beamtime from August 1, 2009 to July 31, 2010. The commissioning time of the UTR experimental area has been included in the time for accelerator setup and tuning.**

| Activities                               | Beamtime<br>(hrs) | %     |
|------------------------------------------|-------------------|-------|
| HI $\gamma$ S user research              | 1,452             | 54.9% |
| Acc. R&D                                 | 243               | 9.2%  |
| Acc./FEL/HI $\gamma$ S<br>setup and tune | 844               | 31.9% |
| Unscheduled downtime                     | 108               | 4.1%  |
| Total scheduled beamtime                 | 2647              | 100%  |

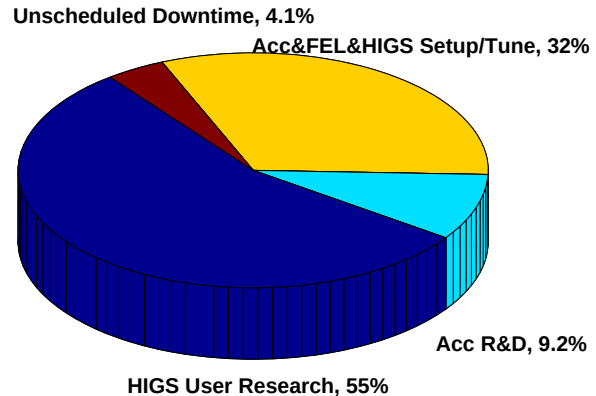


**Figure 8.10: (color online). Beamtime distribution for various research programs and accelerator activities from Aug. 1, 2009 to Jul. 31, 2010.**

A monthly distribution of HI $\gamma$ S user beamtime is shown in Fig. 8.11. Due to the installation of the UTR, there was no HIGS operation for three and half months from the middle of September, 2010 to the early part of January, 2010. The delivered monthly gamma-ray beam-

time in the remaining 8.5 months is about 170 hours per month. In August 2009 and July 2010, week-long three-shift operations were carried out continuously for five days and four nights. This increased the HIGS beamtime on target in these two months to 205 and 245 hours, respectively. During the UTR shutdown, accelerators were run mainly for accelerator and FEL research with limited staff support. About 71% of accelerator and FEL research beamtime (172 hr) was produced from Oct. to Dec. 2009 during this shutdown period.

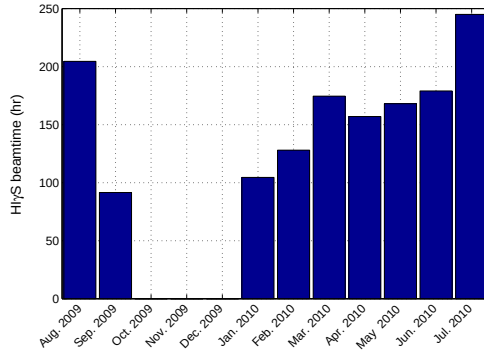


**Figure 8.11: (color online). Monthly distribution of gamma-ray beamtime hours delivered to the HI $\gamma$ S experiments (Aug., 2009 – Jul., 2010).**

Among the total scheduled 2647 accelerator operation hours, the unscheduled downtime was about 4.1%, or 108 hours. In the last twelve months, most of the accelerator failures can be categorized in the four groups: (1) the failure of the cathode in the electron gun; (2) problems with ring kickers; (3) problems with secondary DC power supplies; and (4) failures of the RF system. The longest unscheduled downtime was due to the double failure of the electron gun cathode in March 2010 after only eight months of operation. Two days were used to replace the cathode, condition the electron gun, and recover the accelerator operation. Five days later this newly installed cathode failed, and three more days were used to install another and to perform a much more conservative program of thermal and RF conditioning. The most frequently encountered accelerator problems are the stability of kicker systems of the storage ring. These are a new generation of fast pulse systems, and the kicker drivers need frequent tuning to keep them near the optimal operation condition. Also, in this period, high voltage protection components have been added to the kicker thyatron tubes to protect these from over-voltage during the firing of the kickers, and these protection components have a finite lifetime, the length of which we are only coming to have a measure of now. With continued improvements to the kicker systems, the

kicker stability problems are expected to be less frequent in the coming year.

Due to unusually high temperatures in June and July, 2010, we suffered from a number of beam instability triggered beam losses after a RF trip. This problem seems to occur in the afternoon when the outside ambient temperature is rising fast to above 95 F (32 C). In some cases, the use of the longitudinal bunch-by-bunch feedback seemed to be able to stabilize electron beam instabilities, thus allowing continued HIGS operation. We are also investigating whether the RF system has a reduced capability dealing with electron beam induced oscillations due to aging of its amplifier tubes and malfunctions of its feedback loops. In July 2010, a combination of a high ambient temperature and an unusually intensive HIGS operation schedule resulted in 12% of unexpected downtime while producing the largest amount of beamtime on target of 245 hours.

The overall high reliability can be attributed to a successful preventive maintenance program. Over the years, we have been able to establish a maintenance schedule for critical hardware systems using the projected mean time to failure. In addition, we continuously monitor hardware systems for any sign of degraded performance. A checkup will then be scheduled for the system in question. Ideally, the maintenance activities would be performed every two to three weeks. Fewer frequent mirror changes in the later part of the reporting period have reduced our flexibility to schedule maintenance tasks.

In the long term, the reliability of accelerators and light sources will depend on the availability of spare hardware in house. The timely procurement of expensive spare hardware will remain a challenge as we push to operate the accelerators with higher energy and beam current, and for longer durations to deliver more user beamtime.

#### 8.1.6.2 Near-future HI $\gamma$ S Operation

In the next 12- to 18-month period, a major shutdown is expected, to install the wiggler switchyard system. The total duration of this shutdown is expected to be on the order of 12 weeks. To increase the number of beam hours for HIGS research programs, we plan to take advantage of fixed energy operation for some nuclear physics experiments, and to schedule some weeks with 24-hour operation. Because of the very limited staffing level at the HIGS, we can only carry out a few weeks of 24-hr operations in a year. This type of operation is expected to reduce the overall reliability of the accelerator operation, as we do not have the staff to perform quick repairs of minor hardware problems during the second- and third-shift operations.

## 8.2 The FN Tandem Accelerator and Ion Sources

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### 8.2.1 Tandem Accelerator Operation

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C.R. WESTERFELDT, J.H. ADDISON, E.P. CARTER, J.D. DUNHAM, R. O'QUINN, *TUNL*

#### 8.2.1.1 Tandem Operation

The TUNL FN tandem accelerator was operated 198 days for 2163 hours at terminal potentials ranging from 0.2 MV to 8.7 MV during the period August 1, 2009 to July 30, 2010. Beams accelerated during this period include unpolarized protons and deuterons and also 4He. The terminal operating potential during the reporting period is shown graphically in Fig. 8.12.

An opening of the tandem was made on March 30 for routine maintenance and to repair several pressure leaks of tank insulating gas at the high-energy end of the tank. No bad column resistors were found at this opening. We discovered that the high-energy charging chain was failing however. The chain was extremely old having been used for about ten years. While it could have been repaired, it was decided to install a new chain that was purchased in 2008 as a spare. This new chain was discovered to be too short to install despite having the same number of links. This was due to the worn bushings in the failing chain. Two additional links were installed to permit the chain to be joined. The chain was run and the stretch monitored. We quickly had to remove one link as the chain stretched rapidly. We consulted with the manufacturer (NEC) and they advised that what we were seeing was normal. We removed two more links and continued to run the chain. The stretching seemed to stop so the tank was closed on April 16 and operations resumed on April 17. On March 3, the chain stretch interlock on the high-energy chain tripped and an emergency entry was made. One additional link was removed and it was discovered that the tension on the high-energy chain was set too high. One weight was removed and the interlock was adjusted as it seemed to have tripped prematurely. The tank was closed on May 4 and operations resumed May 5. No further problems have occurred with this chain. We will plan on purchasing a spare chain for the low-energy end

as it is of the same age and starting to show signs of deterioration as well.

During the first opening, we made measurements needed to design a mount for the new mid-plane idler pulley that we have constructed. It is hoped that it will be installed during the spring 2011 opening. Plans are to test it in air with a spare chain and pulley system that we have on hand before installing it in the tandem. The tank was closed on April 16th, 2010. On May 3, the high-energy chain break interlock opened and a quick entry was made to shorten the new chain and reduce the chain tension. The tank was closed again on May 4 and operations resumed.

#### 8.2.1.2 Laboratory Projects

The Direct Extraction Negative Ion Source was overhauled mechanically and electronically during the year to improve its output for new classes of experiments that require more beam than we were presently getting. The extraction geometry was modified by changing some of the inter-electrode gaps. A new extraction aperture was manufactured from solid Molybdenum rod to replace the pressed in insert and stainless steel holder that had been previously used. It was thought that this was causing problems in that the Molybdenum has a much lower thermal expansion coefficient than the stainless steel which it was pressed into and so became loose when heated by the arc. We also noticed that the arc often struck to the outside edge of the insert so we desired to eliminate that interface. With these changes, analyzed negative proton and deuteron beam with intensities of 30 plus microamperes are now available for acceleration at the low energy araday cup. A time dependent instability remains, however it is not significant enough to affect experiments.

The cooling system for the shielded source experimental area was rebuilt following repeated failures with this system. Previously it required

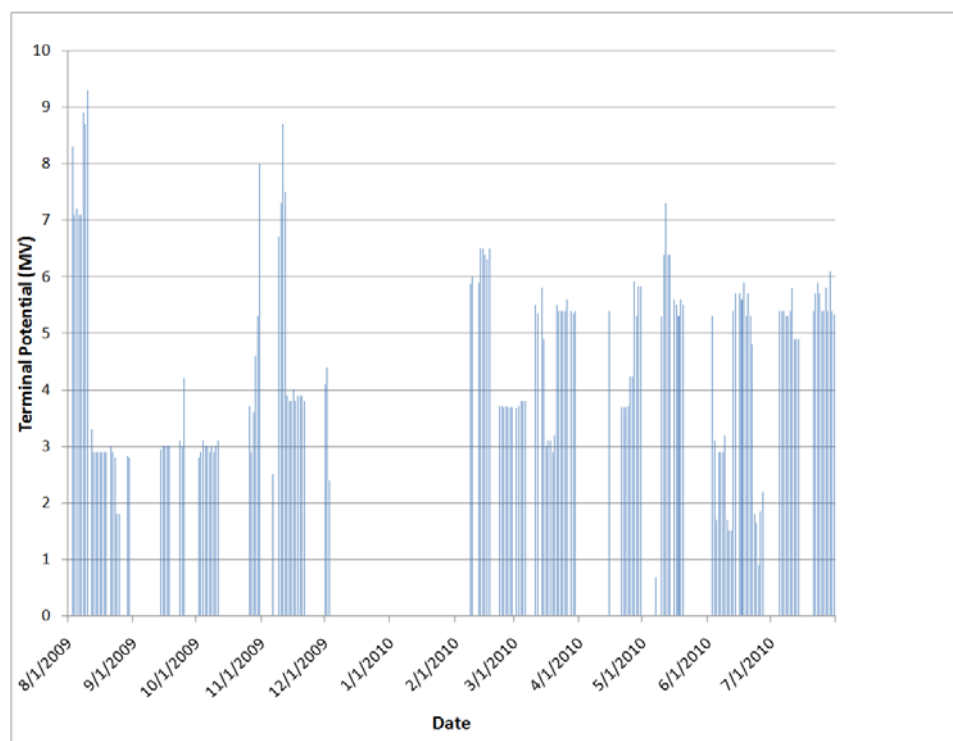


Figure 8.12: (Color online) The TUNL FN Tandem Operating Potential.

manual filling with distilled water periodically. The new system is completely automatic requiring the researcher only to turn it on and off. Visible flow indication and quick disconnect fittings were installed near the water cooled neutron production gas cell to verify flow and to provide tool-free connection and disconnection of the water lines for rapid exchange of gas cells which may be activated.

#### 8.2.1.3 Shielding Changes

In order to reduce the neutron radiation exterior to the building in the vicinity of the NTOF room, additional concrete shielding was installed along two walls inside the NTOF room. This necessitated the relocation of the fume hood in this room and also the Tritium stack monitor. Initial surveys confirm the effectiveness of this change.

The entry maze to the 20-70 magnet vault was reconfigured in June by repositioning two large 6 ton water tanks. Two improvements were

accomplished: increasing the shielding between the tandem high-energy faraday cup and the control room, and blocking a direct line-of-sight between the 20-70 magnet and the low energy bay entrance area. Subsequent surveys and environmental dosimetry indicate that the desired reduction in the radiation in these areas was accomplished.

#### 8.2.1.4 Pneumatic Transfer System

A contract has been signed to install a 4 pneumatic transfer system between the NTOF room in the TUNL building and the growth chamber area in the adjacent Phytotron building. This will be installed in the fall of 2010 and will be used to transport short half-live isotopes from the production cell in TUNL to the plant research station in the Phytotron. The capsule is expected to have a transit time of approximately 30 seconds which is critical for  $^{13}\text{N}$  which has only a 9.9 minute half-life.

## 8.3 The LENA Accelerator and Ion Sources

### 8.3.1 Status of the LENA ECR Accelerator

J.M. CESARATTO, A.E. CHAMPAGNE, T.B. CLEGG, *TUNL*

We have begun using a new electron-cyclotron-resonance (ECR) ion source and acceleration system for experiments at the Laboratory for Experimental Nuclear Astrophysics (LENA). The LENA ECR ion source is capable of producing  $>1$  mA proton beam on target for energy ranges 90 to 200 keV. In the past year, steps have been taken to improve the stability of the acceleration system. Two low-energy resonances of the reactions  $^{18}\text{O}(p,\gamma)^{19}\text{F}$  and  $^{27}\text{Al}(p,\gamma)^{28}\text{Si}$  were measured to test the high voltage acceleration system. Recently, a manuscript was submitted for publication describing LENA's ECR ion source and accelerators.

The electron-cyclotron-resonance (ECR) ion source at LENA operates with input rf power of 100 to 500 W at 2.45 GHz. A cylindrical array of NdFeB permanent magnets produces the axial 87.5 mT field necessary for the electron-cyclotron resonance. The  $\text{H}^+$  beam is extracted from a plasma chamber in this magnetic field by an “accel-decel” extraction lens system and is accelerated to the target with energies up to 215 keV. A full description of the LENA ECR ion source has been submitted for publication [Ces10].

#### 8.3.1.1 New control instrumentation

The ECR source has been run extensively over the past year, and this experience has revealed several shortcomings, which we have addressed. One was in accelerator control and metering. The existing set of control and metering instruments were used with the new source but were found to be unsuitable. In particular, very poor spark protection, subtle connections to the JN-Van-de-Graaff accelerator control system, and numerous ground loops were noted. These issues were brought to our attention by two separate incidents (September 2008 and January 2009) in which the high-voltage platform discharged to ground. The surge found its way back into the control equipment and damaged eight National Instruments FieldPoint modules, numerous operational amplifiers in the terminal-potential stabilizer circuit and corona-current metering circuit for the JN, a pulse-width modulating chip in the upcharge supply of the JN, and a diode in the vacuum-panel-gate-valve logic.

To prevent this from recurring, careful steps were taken to install an entirely new control and metering system solely for the ECR accelerator. This task included adding a new fiber optic communication line, Compact FieldPoint modules, shielded cables, and conduit. New control equipment was housed in a shielded cabinet, where conduits provided the path for shielded cables from the cabinet to the associated high voltage equipment. All ground cables were tied to one point, and care was taken to eliminate ground loops. Homemade surge suppression circuits were added to all control and metering signals on this new system. As an extra measure, we added a surveillance and digital video recorder system to help in locating any source of future discharge. In the months since employing the new control system, we have not had any incidents of discharges causing further damage.

#### 8.3.1.2 Accelerator characterization

The quality of beam from the ECR accelerator was evaluated by measuring two low-energy resonances. One was the well-known  $E_R = 150.82 \pm 0.09$  keV resonance [Bec95] in the  $^{18}\text{O}(p,\gamma)^{19}\text{F}$  reaction. It corresponds to  $\Gamma_{lab} \leq 0.5$  keV [Vog90] and has  $Q_{p\gamma} = 7994.8 \pm 0.6$  keV [Aud03]. The second resonance used was at  $E_R = 202.8 \pm 0.9$  keV [End98] in the  $^{27}\text{Al}(p,\gamma)^{28}\text{Si}$  reaction and has  $Q_{p\gamma} = 11585.11 \pm 0.12$  keV [Aud03]).

As a check of the voltages read out from the acceleration supplies and our subsequent knowledge of the energy of the beam, excitation functions (i.e.,  $\gamma$ -ray yield versus bombarding energy) for both resonances were measured in order to de-

termine both resonance energy and energy resolution. Values measured for the  $^{18}\text{O}(p,\gamma)^{19}\text{F}$  resonance were  $E_R = 150.6 \pm 0.1$  keV, with a corresponding energy resolution of  $0.84 \pm 0.07$  keV at fwhm. The resonance energy in the  $^{27}\text{Al}(p,\gamma)^{28}\text{Si}$  reaction was  $E_R = 200.9 \pm 0.1$  keV, with a corresponding energy resolution of  $1.44 \pm 0.17$  keV. Thus small corrections must be made in order to normalize the energies determined from the power supply to the literature values. The measured energy widths are a factor of 2.8 to 3.6 greater than what is expected from the ripple and stability specifications of the power supplies (better than 0.1% and 0.01%, respectively, [Gla07] for the 200 kV supply). However, we cannot rule out some contribution from contaminants or non-uniformities in the targets.

### 8.3.1.3 Future improvement

The microwave supply which drives the ECR ion source plasma is quite unstable; its output power can vary  $\pm 30$  W at 250 W running power. This, in turn, changes the driven plasma, which can change the plasma meniscus at the beam extraction point. Unfortunately, this can modify the beam focussing and change the size and shape of the beam. Optical parameters can be tuned to try to compensate for this, but such problematic

retuning is not reproducible. In the next year, we would like to purchase a new, well-regulated microwave power supply capable of producing 1 kW output. This, would improve the reliability of the source, and the increased power capacity should boost beam output to what is needed during pulsed beam operation.

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- [Aud03] G. Audi, A. H. Wapstra, and C. Thibault, *Nuclear Physics A*, **729**, 337 (2003).
  - [Bec95] H. W. Becker *et al.*, *Z. Phys. A*, **351**, 453 (1995).
  - [Ces10] J. M. Cesaratto *et al.*, *Nucl. Instrum. Methods A*, (July 2010), submitted for publication.
  - [End98] P. M. Endt, *Nucl. Phys. A*, **633**, 1 (1998).
  - [Gla07] Glassman High Voltage Inc., 124 West Main Street, PO Box 317 High Bridge, NJ 08829, *Instruction Manual PK Series*, 2007.
  - [Vog90] R. B. Vogelaar *et al.*, *Phys. Rev. C*, **42**, 753 (1990).



# Nuclear Instrumentation and Methods

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Chapter 9

- Targets
- Detector Development and Characterization
- Facilities
- Data Acquisition Hardware and Software Development

## 9.1 Targets

### 9.1.1 A New $^3\text{He}$ -Target Design for Compton Scattering Experiments

H. GAO, M. HUANG, G. LASKARIS, Q. YE, Q.J. YE, W. ZHENG, Y. ZHANG *TUNL*

**Compton scattering from polarized  $^3\text{He}$  is designed to measure neutron spin polarizabilities by using a circularly polarized  $\gamma$ -ray beam at HI $\gamma$ S. A uniform magnetic field is required to maintain the  $^3\text{He}$  spin polarization in the longitudinal direction. We are planning to use a single-layer solenoid instead of Helmholtz coils for providing the field. We are also planning to add a pair of tungsten collimators for shielding against the background generated from the target windows. A new  $^3\text{He}$  target system is designed to accomplish these tasks easily.**

Nucleon spin polarizabilities describe the stiffness of the nucleon spin to external electric and magnetic fields. Compared to the nucleon electric and magnetic polarizabilities, very little is known about nucleon spin polarizabilities. The only quantities that have been determined experimentally are the forward and backward spin polarizabilities,  $\gamma_0$  and  $\gamma_\pi$ . Recently, double-polarized elastic Compton Scattering from polarized  $^3\text{He}$  has been investigated and sensitivity to the neutron spin polarizabilities ( $\gamma_1 \dots \gamma_4$ ) has been demonstrated [Cho07]. The double-polarized Compton experiment requires circularly polarized  $\gamma$  rays and a polarized  $^3\text{He}$  target. We need a uniform magnetic field along the cylindrical axis of the target chamber for maintaining the  $^3\text{He}$  polarization. In previous polarized  $^3\text{He}$  experiments, a pair of Helmholtz coils was used. However, the Helmholtz coils will not be used in this experiment so that we can position the NaI detectors near the polarized  $^3\text{He}$  target. Instead, a single layer solenoid is being developed to provide the holding field for the polarized  $^3\text{He}$  target.

The solenoid is designed in a single-layer configuration and wound around a 106 cm long PVC pipe (outer diameter = 40.64 cm) by using 1.02-mm diameter copper wire (AWG 18). There are 1000 turns in the solenoid, and the current applied is 1 A. The coil-winding system is established in the machine shop of the Duke Physics department. After the winding, we applied epoxy to glue the wires together. We also used Kapton tape to protect the wires. The single-layer solenoid is shown in Fig. 9.1.

For mapping the magnetic field ( $B_x, B_y, B_z$ ) inside the solenoid, a three-axis magnetic field

mapper is designed. It uses a motor-system, a Gaussmeter, two different probes (one for  $B_z$ , the other for  $B_x$  and  $B_y$ ), and the data-acquisition system. Details are given in Ref. [Ye110]. The probes are placed on a non-magnetic arm that is capable of incremental three-axis motion using a three-axis motor. With the motor, the probes can scan the different points in the space in steps of 1.27 cm. Inside the solenoid, the cylindrical axis of the target chamber is not the same as the axis of the solenoid; the offset is about 6.12 cm. A cuboid which includes the target chamber and pumping chamber is scanned as the region of interest (ROI). The whole system is controlled by a PC that can store the magnetic-field value vs. position ( $x, y, z$ ) for future analysis.



**Figure 9.1: (Color online) A single-layer solenoid for Compton scattering experiments**

We simulated the solenoid magnetic field by using the code COMSOL and compared the results with the field-mapping results. Our measurements show consistency with the simulation results (except for some constant offsets). More

details are given in Ref. [Ye110]. The measured magnetic-field values in the ROI are shown in Fig. 9.2; the units are in inches. The results show the outstanding uniformity of the solenoid magnetic field in the ROI.

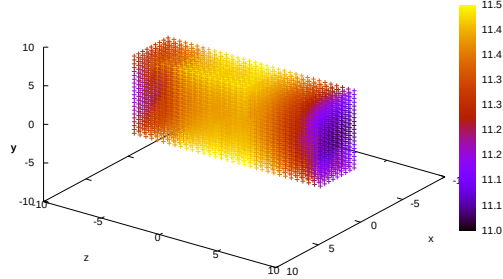


**Figure 9.2:** (Color online) Magnetic field mapping of the ROI. The  $B$ -field is given in Gauss. Details are in Ref. [Ye110]

During the experiment, a high polarization  $^3\text{He}$  target is important, and an inhomogeneous magnetic field can contribute to the depolarization of polarized  $^3\text{He}$  according to the relation [Cat88]:

$$\frac{1}{T_1} = D \frac{|\nabla B_x|^2 + |\nabla B_y|^2}{B_z^2}. \quad (9.1)$$

Here  $\frac{1}{T_1}$  is the relaxation rate and  $D$  is the self-diffusion coefficient, here assumed to be  $D = 0.28 \text{ cm}^2/\text{s}$ . The quantities  $\nabla B_x$  and  $\nabla B_y$  are the gradients of the transverse field components, and  $B_z$  is the magnitude of the holding field. From our field-mapping result in the region of interest,  $|\nabla B_x|^2 + |\nabla B_y|^2 = 80.41 \text{ (mG/cm)}^2$ . For a holding field of  $B_z = 11.3 \text{ G}$ , we obtain a value of  $T_1 = 1493 \text{ hr}$ . Compared with other effects, such as dipole-dipole collisions and interactions with glass wall, depolarization effects from magnetic field gradients is negligible.

A pair of tungsten collimators will be employed in the experiment. The goal of the target collimators is to shield against photons generated from the target windows. These are considered as the major background contribution to elastic Compton-scattering events. Each collimator is a 9.5-cm-long tube with an outer diameter of 7.2 cm (2.83 in.) and an inner diameter of 3.2 cm (1.26 in.). The inner diameter is 0.2 cm larger than the diameter of the target chamber, so that we can move the collimators without scratching the cells.

Considering the limited space inside the solenoid, a careful and feasible design of the target system is being developed. Figure 9.3 shows

the conceptual design of the  $^3\text{He}$  target system. The support structure for the target system is not shown here since it depends on the design of the table for the HI $\gamma$ S NaI Detector Array (HINDA). During the experiment, a  $^3\text{He}$  target cell and a  $\text{N}_2$  reference cell (a cell used for background measurement, having the same dimensions as the target cell but filled with  $\text{N}_2$  instead of  $^3\text{He}$ ) can move up and down together with the solenoid, in and out of the  $\gamma$ -ray beam, using a motor-controlled support.

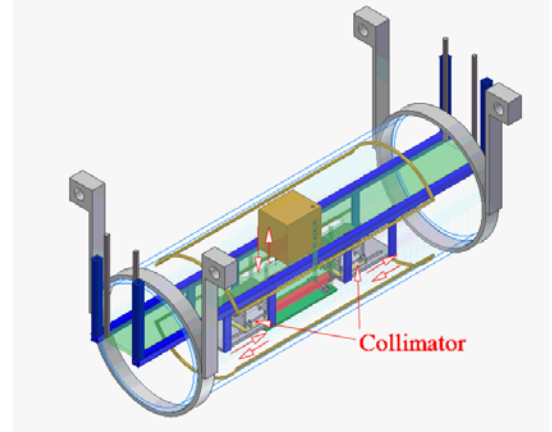


**Figure 9.3:** (Color online) A conceptual design of the  $^3\text{He}$  target system for Compton-scattering experiments

A combination of rails and ball bearings are used to move each collimator along the target-chamber axis in the horizontal plane by using another motor system. In this way, we can switch between two different sets of target cell + collimators and reference cell + collimators to study background effects. The possible movements are labeled as arrows in Fig. 9.3. In order to make the alignment simple, we are planning to align the target cell, reference cell, and collimators outside the solenoid with lasers. After the alignment, the solenoid is moved to the designed position with the target system inside, instead of moving the aligned cells and collimators.

Our next step is to build the target system, including the tungsten collimators, the motor-controlled support, and the support for the solenoid. Once we set up the new target system, we will test it in our laboratory.

[Cat88] G. D. Cates *et al.*, Phys. Rev. A, **37**, 2877 (1988).

[Cho07] D. Choudhury *et al.*, Phys. Rev. Lett., **98**, 232303 (2007).

[Ye110] Q. J. Ye, In [www.phy.duke.edu/~qy4](http://www.phy.duke.edu/~qy4), 2010.

### 9.1.2 Scintillating Target for $d(\vec{\gamma}, \gamma)d$ at HI $\gamma$ S

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**We plan to use the HI $\gamma$ S facility to extract the neutron's electric and magnetic polarizabilities,  $\alpha_n$  and  $\beta_n$  respectively, using Compton scattering of 65-80 MeV  $\gamma$  rays from a scintillating deuterium target. Here we discuss the progress being made on the scintillating target for this experiment.**

The electric and magnetic polarizabilities,  $\alpha_{E1}$  and  $\beta_{M1}$  respectively, provide information on the internal structure of the nucleon. The polarizabilities are given by the effective interaction [Pas07]

$$H_{\text{eff}}^{(2)} = -4\pi \left[ \frac{1}{2} \alpha_{E1} \vec{E}^2 + \frac{1}{2} \beta_{M1} \vec{H}^2 \right]. \quad (9.2)$$

For the proton, the Particle Data Group at Lawrence Berkeley National Laboratory gives current averages for  $\alpha_p$  and  $\beta_p$  determined through Compton-scattering experiments with a proton target:

$$\alpha_p = (12.0 \pm 0.6) \times 10^{-4} \text{ fm}^3 \quad (9.3)$$

$$\beta_p = (1.9 \pm 0.5) \times 10^{-4} \text{ fm}^3. \quad (9.4)$$

The best current fit (using a Baldin sum rule constraint) to world data gives neutron polarizability values of [Hil05]

$$\alpha_n = (11.6 \pm 1.5 \pm 0.6) \times 10^{-4} \text{ fm}^3 \quad (9.5)$$

$$\beta_n = (3.6 \mp 1.5 \pm 0.6) \times 10^{-4} \text{ fm}^3 \quad (9.6)$$

where the first quoted error is statistical, and the second is from the Baldin constraint. Some of the data from which these were obtained come from elastic Compton scattering off a deuteron target,  $\gamma d \rightarrow \gamma d$  [Luc94, Lun03, Hor00].

We plan to complement the previous experiments by adding a deuterated liquid scintillator (NE-232,  $\text{C}_6\text{D}_{12}$  with  $6.58 \times 10^{22} \text{ D/cm}^3$  and  $3.36 \times 10^{22} \text{ C/cm}^3$ ) contained in a small glass cell with dimensions of 4.18 cm diameter by 3.7 cm long. In a scattering event, the recoil of the deuteron produces scintillation light in the target, allowing us to tag the  $\gamma$  ray that elastically scattered from the deuteron.

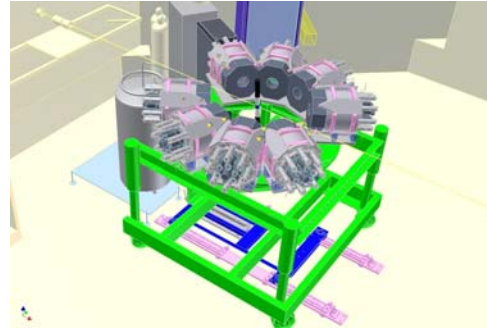


**Figure 9.4: (Color online) HI $\gamma$ S NaI Detector Array with scintillating target**

The scattered  $\gamma$  rays will be detected in the 8-element HI $\gamma$ S NaI Detector Array (HINDA). The eight elements of HINDA can be placed  $35^\circ$  apart (between centers). Starting on beam right at  $150^\circ$ , three other detectors will be set at angles of  $115^\circ$ ,  $80^\circ$ , and  $45^\circ$ . The remaining four detectors would be placed at the same angles on beam left, producing the setup shown in Fig. 9.4.

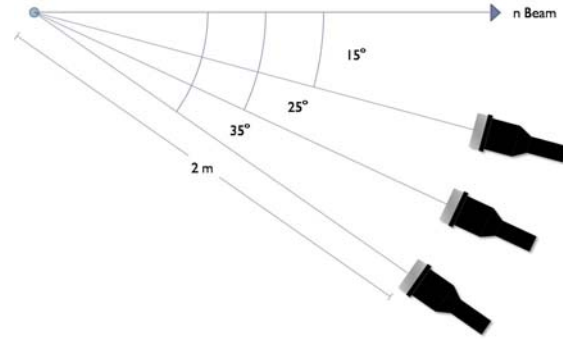


**Figure 9.5: (Color online)  $d(n,n)d$  setup with the three neutron detectors at  $15^\circ$ ,  $25^\circ$ , and  $35^\circ$**

The response of the scintillating detector was tested by placing it in a neutron beam at TUNL,

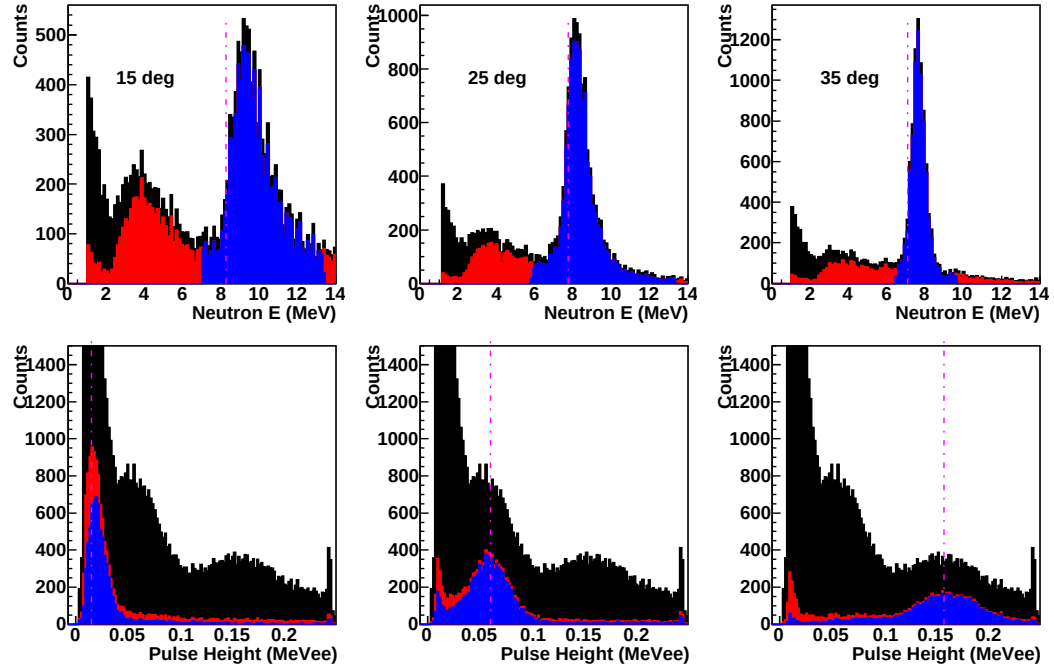


Figure 9.6: (Color online) Results for  $d(n,n)d$  at an incident neutron energy of 8.525 MeV, with the three neutron detectors at 15°, 25°, and 35°, corresponding to scattered neutron energies of 8.24, 7.75, and 7.08 MeV respectively (top), and recoil deuteron energies of 0.29, 0.78, and 1.45 MeV respectively (bottom, shown in MeV electron equivalent, or MeVee, to account for the scintillator response to deuterons). Each panel displays the spectra uncut (black), cut on PSD (red/light gray), and cut on PSD and TOF (blue/dark gray). The dashed vertical lines indicate the expected values.

and looking at the reaction  $d(n,n)d$ . Three neutron detectors were arranged at various angles (as shown in Fig. 9.5), and a coincidence trigger was established between the scintillating target detector and a neutron detector.

By properly choosing the angles of the neutron detectors and the energy of the incident neutron, the energy of the recoil deuteron is equivalent to the energy of a recoil deuteron in the proposed Compton-scattering experiment at HI $\gamma$ S. For the lower beam energy requested for the Compton experiment, 65 MeV, the  $\gamma$  rays scattered into the most forward, 45°, HINDA detector correspond to a recoil deuteron energy of 0.653 MeV. Therefore, the goal for this test was to observe recoils in this energy region. Sample results from this test are shown in Fig. 9.6.

A test was then performed at HI $\gamma$ S using the same scintillating detector but in coincidence with a HINDA detector. Due to the high fluxes available, the target experiences a high rate of atomic Compton scattering and deuteron photo-disintegration. Previous tests had resulted in the

tube experiencing a form of saturation from an insufficient “relaxation” time. The bias on the tubes was increased to reproduce this same problem, confirming our suspicions of its cause. However, when run at the level needed to observe the desired events (as determined through the test at TUNL), the system performance was quite satisfactory.

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- [Hil05] R. Hildebrandt *et al.*, 2005, Arxiv preprint nucl-th/0512063.
  - [Hor00] D. Hornidge *et al.*, *Phys. Rev. Lett.*, **84**, 2334 (2000).
  - [Luc94] M. Lucas, Ph.D. thesis, University of Illinois, 1994.
  - [Lun03] M. Lundin *et al.*, *Phys. Rev. Lett.*, **90**, 192501 (2003).
  - [Pas07] B. Pasquini *et al.*, *Phys. Rev. C*, **C76**, 015203 (2007).

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### 9.1.3 Status of the HI $\gamma$ S Frozen-Spin-Target Transverse Coil at TUNL

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**The status of the HI $\gamma$ S Frozen-Spin-Target Transverse Coil at TUNL is reported.**

We describe the design, construction, and performance of a set of saddle coils used to maintain the spin of a polarized proton target in the transverse direction with respect to the incident  $\gamma$ -ray beam direction. The transverse coil assembly consists of two racetrack shaped coils formed from a single strand of thin NbTi superconducting wire. Four layers of NbTi per saddle coil were wet-wound in a racetrack shape. They were then installed on a cylindrical support tube and epoxyed to prevent them from moving when the

coils are energized. As expected from our model calculation, a set of two saddle coils produced 0.36 T in the middle of the coils with a 25-A current at 4 K, which is 63% of the critical current of the wire. The measured homogeneity of the field over the target volume has a maximum variation from the average value of 0.6% [Seo10].

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[Seo10] P.-N. Seo *et al.*, Nucl. Instrum. Methods, **A618**, 43 (2010).



## 9.2 Detector Development and Characterization

### 9.2.1 A Detector Array for Photoneutron Studies

J.R. TOMPKINS, M.W. AHMED, N. BROWN, B. DAVIS, M. EMAMIAN, J.M. MUELLER, S. STAVE, H.R. WELLER, *TUNL*; C. SMITH, *George Washington University, Washington, DC*;

**A new detector array for photoneutron studies consists of 18 TUNL Bicorn-type neutron detectors oriented parallel and perpendicular to the plane of  $\gamma$ -ray polarization. Two frames have been designed to be the backbone of this array, facilitating detector placements at distances of 1 m and 0.5 m from the target.**

The capability of HI $\gamma$ S to produce 100% linearly-polarized  $\gamma$ -ray beams has made it possible to study photoneutron polarization asymmetries. Recent experiments to study photofission and ( $\gamma, n$ ) reactions (see Sect. 7.1.1) have required the ability to place up to 18 TUNL Bicorn-type neutron detectors [Tro08] both in and out of the plane of polarization, which is parallel to the floor. To accommodate the experimental requirements, two new frames have been designed for positioning the detectors at distances  $\sim 0.5$  and  $\sim 1.0$  m from the target.

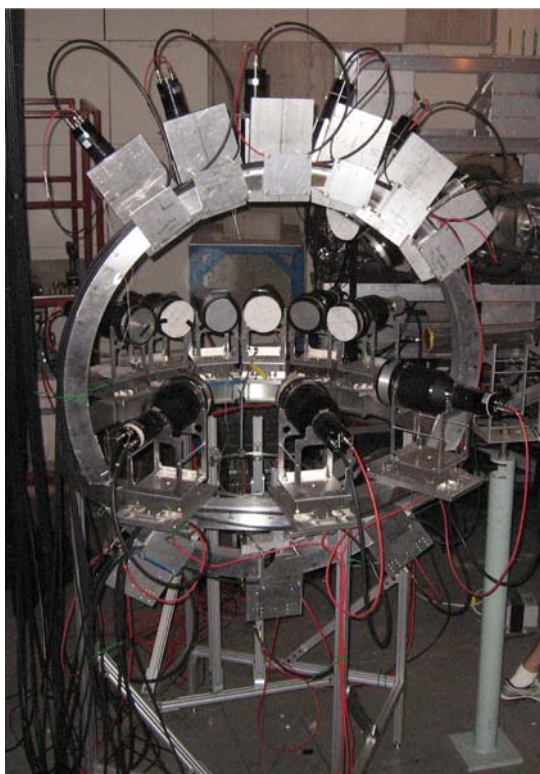


Figure 9.7: (Color online) The 0.5 m frame.

The array was designed to create a free flight path for neutrons traveling from a target to detectors mounted parallel and perpendicular to the plane of polarization. Further design principles were portability and the ease and flexibility of detector placement. These were accomplished with a modular design in which detectors are held in adjustable cradles that clamp to a sturdy aluminum frame.

Each frame was constructed by attaching two rings with equal diameters at a right angle (see Fig. 9.7). The rings join so that each is offset from the beam by about 30 cm to allow room for the detectors. Each of the rings is constructed from rectangular aluminum tubing. These were bent to half circles of 1.22 m and 0.71 m outer radii and then joined together to form the complete rings. The vertical ring on the 1 m frame contains two straight sections to account for the fact that it mounts to either end of a chord across the horizontal ring (see Fig. 9.8). The 0.5 m frame does not contain this feature due to an improved design. Both frames are supported by extruded aluminum legs.

**Table 9.1: Technical comparison of the 1 m and 0.5 m setups. Nominal values are given for the packing angles and capacities.**

| Specifications             | Frame         |               |
|----------------------------|---------------|---------------|
|                            | 1 m           | 0.5 m         |
| Flight path (m)            | $1.0 \pm 0.1$ | $0.5 \pm 0.1$ |
| Packing angle ( $^\circ$ ) | 9             | 17            |
| Capacity (# dets)          | $\approx 36$  | $\approx 22$  |
| Footprint ( $\text{m}^2$ ) | 4.7           | 1.6           |

The use of extruded aluminum increases the versatility of the detector array because it is commercially available and can easily be appended

to without custom machining. Beyond the dimensions of the frames, there are no differences between the two setups. For technical comparisons of the two setups, refer to Table 9.1.

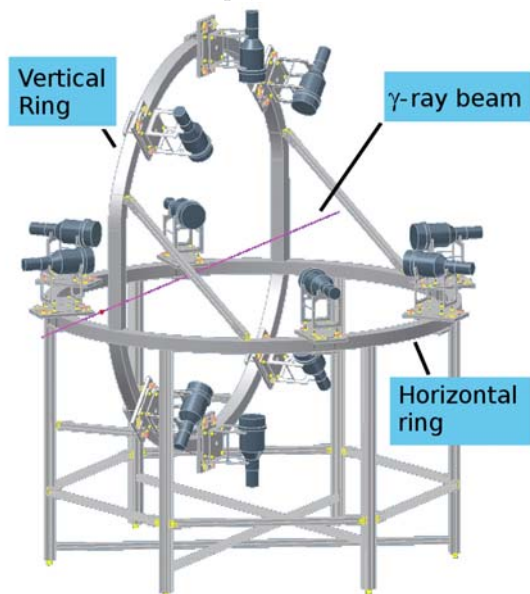


**Figure 9.8:** (Color online) The 1 m frame.

The detector cradles that clamp to the stand are designed to provide the adjustment necessary for aligning the detectors. There are three adjustments, fore-aft, up-down, and yaw. Twenty four cradles have been assembled for the 18 detectors already existent and in anticipation of 6 more.

The only material that intrudes upon the neutron flight paths is the target stand. Because of this, the stand was designed to be lightweight. It

is composed of three sections: a horizontal target ring, a target arm, and interchangeable target holders that attach to the arm. The 45.7 cm diameter target ring shares the same symmetry axis as the horizontal ring of the frame and is held in place by three vertical extruded aluminum bars that provide vertical adjustment. The target arm is clamped to the target ring. It is a vertical 5/16 inch (0.79 cm) threaded rod with a lightweight aluminum joint that holds a 0.64 cm diameter aluminum rod at 45°. The aluminum rod can be extended, and various adaptors can be screwed into the end to hold targets. This is essential, because target shapes are non-uniform, and modifications to them are not always permitted. The orientation of the target is determined using the joint in the arm and the positioning of the arm on the ring.

The array is designed to hold the TUNL Bicorn-type detectors. The cradles fit these detectors and their corresponding photomultiplier tubes. Six new detectors intended for use in the array have been constructed and have been characterized with a  $^{137}\text{Cs}$  and Am-Be neutron source. The identification numbers 18 through 23 have also been assigned to them.

The array has successfully been commissioned in different experiments with both frames. During the next year, it is likely that small improvements to the array will be made and that more detectors will be added.

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[Tro08] D. Trotter *et al.*, Nucl. Instrum. Methods A, **522**, 234 (2008).

### 9.2.2 BrillanCe Detector Energy Resolution Characterization at HI $\gamma$ S

N.J. BROWN, M.W. AHMED, S. STAVE, S.S. HENSHAW, B.A. PERDUE, P.-N. SEO, H.R. WELLER, C. SUN, Y.K. WU, *TUNL*; P.P. MARTEL, A. TEYMURAZYAN, *University of Massachusetts, Amherst, MA*; A. OWENS, F. QUARATI, *European Space Research and Technology Centre, Noordwijk, The Netherlands*

Lanthanum halide crystals represent a major step in finding a room temperature photon detector having high efficiency plus good timing and energy resolution over a wide range of energies. We have studied the performance of these detectors between 2.5 and 15.5 MeV using  $\gamma$ -ray beams produced by the HI $\gamma$ S facility. Gaussian fits to the BrillanCe<sup>TM</sup> detector spectra were corrected for the beam energy spread to obtain the detector resolution. A 10.16 cm (diameter) x 15.24 cm (long) LaCl<sub>3</sub>(Ce) detector and a 7.62 cm x 7.62 cm LaBr<sub>3</sub>(Ce) detector were characterized in the present study. The energy resolution of each detector is reported as a function of incident  $\gamma$ -ray energy from 2.5 to 15.5 MeV. In addition, the response of these detectors to thermal neutrons is described.

The recent discovery [vL00, vL01] of lanthanum halide (LaX<sub>3</sub>:Ce) crystals represents a major step towards finding a photon detector that has high efficiency, good energy and timing resolution, operates at room temperature, and can be used over a wide range of energies. These detectors are presently being marketed under the trademark names of BrillanCe 350<sup>TM</sup>(LaCl<sub>3</sub>(Ce)) and BriLanCe 380<sup>TM</sup>(LaBr<sub>3</sub>(Ce)).

The energy resolution of the  $\gamma$ -ray beam at HI $\gamma$ S [Wel09] depends on the diameter of the collimator in place during experimental operation. The 12 mm collimator used during this experiment yields an energy spread ranging from 50 to 250 keV for  $\gamma$ -ray energies from 2.5 to 15.5 MeV. The maximum delivered intensity of the HI $\gamma$ S facility in the energy range of 2-16 MeV is over 10<sup>7</sup>  $\gamma$  rays per second, so attenuators were used to moderate the beam for the measurements of the present work.

The full-energy peak response of the B350 and B380 detectors were fit with a Gaussian line-shape. The fit yields a full width at half maximum for the full-energy peak with contributions from both the detector and the beam. The energy resolution of the beam was determined using a 120% HPGe detector. The resolution of the detectors was then obtained by correcting the measured spectra for the beam energy spread. The B350 (LaCl<sub>3</sub>Ce) and B380 (LaBr<sub>3</sub>Ce) results are similar, as seen in Figs. 9.9 and 9.10. Also included in the figures are dotted lines representing

an  $\frac{A}{\sqrt{E}} + B$  curve. The coefficients for the curves are A=76.3 and B=1.04 in Fig. 9.10, and A=76.3 and B=0.49 in Fig. 9.10.

The presence of thermal neutrons leads to <sup>35</sup>Cl(n, $\gamma$ ) and <sup>79</sup>Br(n, $\gamma$ ) reaction products in the case of the B350 and B380 detectors, respectively, as well as the <sup>140</sup>La(n, $\gamma$ ) products for both detectors. We placed a 200 mC Americium-Beryllium fast neutron and gamma-ray source in a 50.80 cm wide paraffin cube, in order to thermalize the fast neutrons. One meter away, at the same height as the source, a <sup>6</sup>Li-Glass detector stood behind 10.16 cm of lead shielding. The lead is required to suppress the  $\gamma$ -rays from the source by a factor of about 100. The <sup>6</sup>Li-Glass detector, which detects (thermal) neutrons by means of the <sup>6</sup>Li(n, $\alpha$ )<sup>3</sup>H reaction, has an efficiency of essentially 100% for thermal neutron detection. The measured count rate indicated that there were 8.5 $\pm$ 0.5 neutrons per second impinging on the 5.08 cm diameter, 0.9 cm thick Li-glass detector. This serves to define our thermal neutron environment, which was identical for the <sup>6</sup>Li-Glass, the B350 and the B380 detectors.

The <sup>35</sup>Cl (n, $\gamma$ ) transition intensities reported in ENSDF are shown in Fig. 9.11. Both the full energy peak and first escape peak for each relevant transition are shown. They are normalized to the 6.1 MeV peak, the strongest intensity peak in the reported work [End98], having 77 out of 100 units. Using this scale, all the intensities of the included transitions are depicted by the heights of the vertical dashed lines. It can be

seen that the observed peaks are well correlated with the  $\gamma$ -ray lines, as expected.

The highest energy  $\gamma$ -ray for the  $^{79}\text{Br}(n,\gamma)$  reaction at 7.9 MeV is also labeled [Sin05]. The transitions from the  $^{139}\text{La}(n,\gamma)$  reaction are visible in Fig. 9.11 and are more pronounced in Fig. 9.12 because of the smaller background from the  $^{79}\text{Br}(n,\gamma)$  reaction as compared to the  $^{35}\text{Cl}(n,\gamma)$  background in Fig. 9.11.

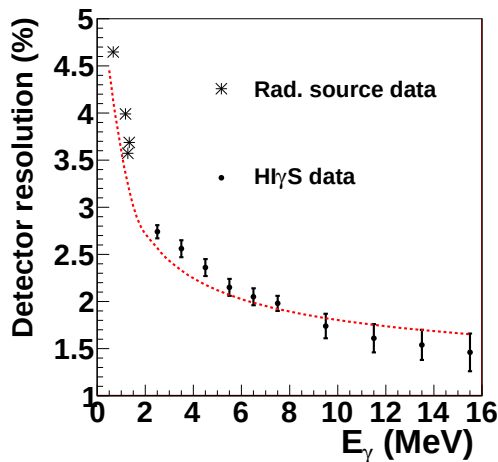


Figure 9.9: (Color online) The 10.16 x 15.24 cm B350 detector resolution vs. incident  $\gamma$ -ray energy after correcting for the beam energy spreads. The additional low energy points are from radioactive source data, and the dotted line is described in the text.

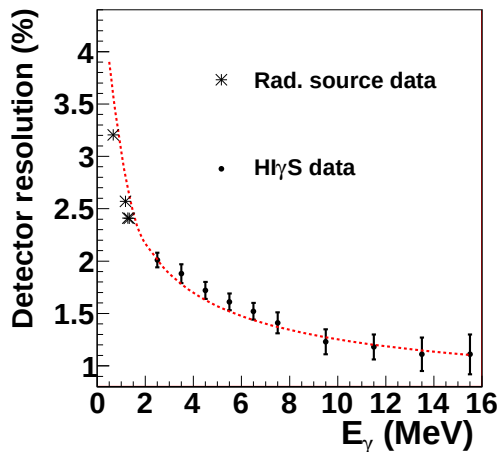


Figure 9.10: (Color online) The 7.62 x 7.62 cm B380 detector resolution vs. incident  $\gamma$ -ray energy after correcting for the beam energy spreads. The additional low energy points are from radioactive source data, and the dotted line is described in the text.

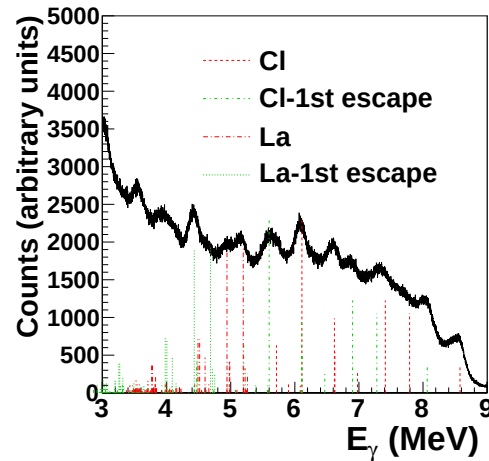


Figure 9.11: (Color online) The B350 detector response from the  $^{35}\text{Cl}(n,\gamma)$  reaction.

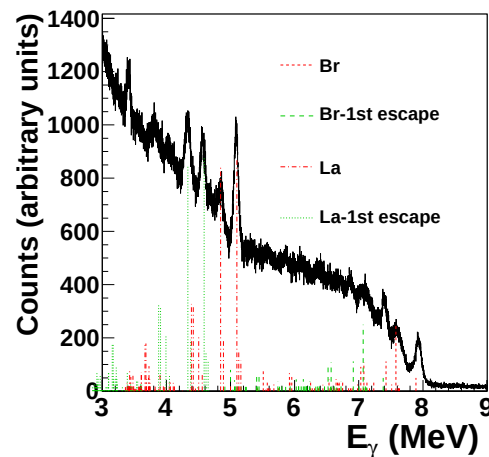


Figure 9.12: (Color online) The B380 detector response from the  $^{79}\text{Br}(n,\gamma)$  reaction.

[End98] P. M. Endt and R. B. Firestone, Nucl. Phys., **A633**, 1 (1998).

[Sin05] B. Singh, Nucl. Data Sheets, **105**, 223 (2005).

[vL00] E. V. D. van Loef *et al.*, Appl. Phys. Lett., **77**, 1467 (2000).

[vL01] E. V. D. van Loef *et al.*, Appl. Phys. Lett., **79**, 1573 (2001).

[Wel09] H. R. Weller *et al.*, Prog. Part. Nucl. Phys., **62**, 257 (2009).

### 9.2.3 Characterization of a Neutron Counter for High-Precision $(\gamma, n)$ Cross-Section Measurements

C.W. ARNOLD, T.B. CLEGG, C.R. HOWELL, H.J. KARWOWSKI, G.C. RICH, J.R. TOMPKINS  
TUNL

**The detection efficiency of an INVS counter has been characterized using four well-understood neutron sources. Both monoenergetic and broad spectrum neutron sources were employed. Measured efficiencies agree with mcnp simulations and improve the accuracy of the absolute detection efficiency to  $\pm 3\%$  for neutrons of energy  $\leq 1.0$  MeV.**

The model IV inventory sample counter (INVS) developed at Los Alamos National Laboratory [SJ93] was designed for fast, non-destructive assay of radioactive materials. Simple adaptations make it an invaluable tool for measuring  $(\gamma, n)$  cross sections using TUNL's HI $\gamma$ S facility. For such measurements, it is critical that the energy-dependent, absolute neutron-detection efficiency be known. Efficiency here is generally defined as

$$\epsilon \equiv \frac{N_{\text{detected}}}{N_{\text{emitted}}}. \quad (9.7)$$

Four different sources, each able to emit a known number of neutrons, were used. First, a NIST-calibrated  $^{252}\text{Cf}$  source provided a broad spectrum of neutron energies with a neutron flux known to  $\pm 4.4\%$  [Tho09]. Second, a coincidence experiment using the  $^2\text{H}(d, n)^3\text{He}$  reaction provided a monoenergetic source of 2.26 MeV neutrons with a flux known to  $\pm 10\%$ . A third inves-

tigation using the  $^7\text{Li}(p, n)^7\text{Be}$  reaction produced  $\sim 1$  MeV neutrons with fluxes known to  $\pm 6.6\%$ . Finally, the  $^2\text{H}(\gamma, n)\text{H}$  reaction used the high resolution HI $\gamma$ S beam to produce tunable sources of monoenergetic neutrons ( $0.1 \leq E_n \leq 1.0$  MeV) with  $\pm 3\%$  accuracy. A comparison of all experimental data with Monte Carlo models demonstrates agreement to within the  $\pm 6\%$  uncertainty imposed by modeling. However, data from  $^2\text{H}(\gamma, n)\text{H}$  improved the accuracy of the absolute efficiency to  $\pm 3\%$  for neutrons with energy  $\leq 1.0$  MeV.

A detailed report of these results will be published in the near future.

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[SJ93] J. K. Sprinkle Jr. *et al.*, Los Alamos National Lab Report No. LA-12496-MS, page 11 (1993).

[Tho09] A. K. Thompson, private communication, 2009.



Figure 9.13: Photograph of the INVS counter. A large cylindrical polyethylene body envelops 18  $^3\text{He}$  proportional-counting tubes, each containing 6 atm of  $^3\text{He}$ . Maximum detection efficiency for this detector is  $\sim 64\%$ .

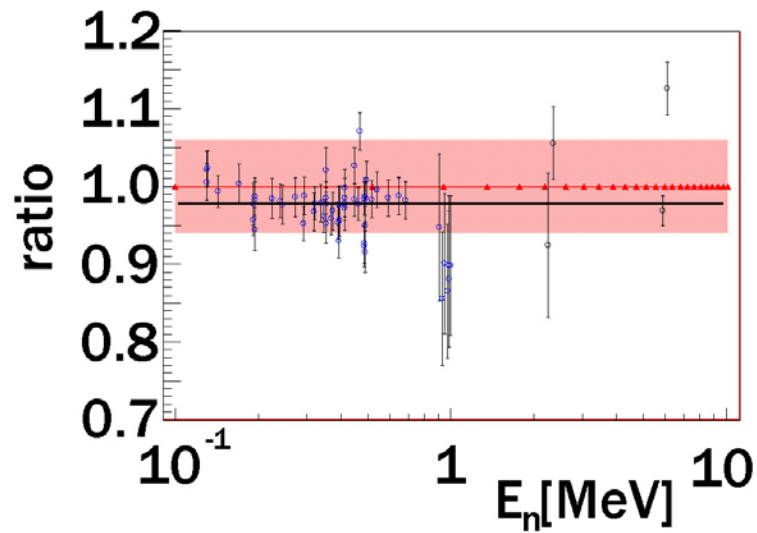


Figure 9.14: (Color Online) Ratio of measured efficiency to modeled efficiency vs.  $E_n$ . The red line at a ratio of unity with a  $\pm 6\%$  error band displays the modeling uncertainty. The black line fits the majority of the data points, which are systematically lower than the modeled efficiency by approximately 2%.

### 9.2.4 Determination of the Absolute $\gamma$ -ray Detection Efficiency of the *Molly* detector.

C.W. ARNOLD, A. ADEKOLA, T.B. CLEGG, H.J. KARWOWSKI, G.C. RICH, J.R. TOMPKINS  
TUNL

The 340 keV resonance of the  $^{19}\text{F}(p,\alpha\gamma)$  reaction was accessed using the mini-tandem accelerator at TUNL. The  $\gamma$  rays from this reaction are known to be emitted isotropically, and lead shielding was employed to collimate them into a 2.54 cm diameter distribution centered on the face of TUNL's large NaI detector known as *Molly*. The total efficiency of *Molly* is consistent with  $\sim 100\%$  for a beam of 6.130 MeV  $\gamma$ -rays. Any loss of efficiency from threshold settings may be accurately discerned from modeling in geant4.

For many experiments performed at TUNL's HI $\gamma$ S facility, an absolute measure of the efficiency of the large NaI crystal detector known as *Molly* is needed in order to understand the limits of precision for experiments requiring knowledge of the incident  $\gamma$ -ray flux. Models predict that *Molly* has a total-efficiency of  $\sim 100\%$  for  $\gamma$ -ray beams incident on its face with energies between 1.5 and 15 MeV. This total efficiency may be affected by electronic threshold settings, light collection efficiency, and variables for which ascribing uncertainties may be difficult. The  $^{19}\text{F}(p,\alpha\gamma)$  reaction, which provides a monoenergetic  $\gamma$ -ray coincident with an associated  $\alpha$  particle, was chosen to measure *Molly's* absolute  $\gamma$ -ray efficiency experimentally.

The  $^{19}\text{F}(p,\alpha)$  reaction creates an excited state of  $^{20}\text{Ne}$  that then decays to one of four available excited states or the ground state in  $^{16}\text{O}$ . Of the four excited states, three may decay to the ground state of  $^{16}\text{O}$  via  $\gamma$ -ray emission. The three  $\gamma$ -ray-associated  $\alpha$  particles will have different energies, corresponding to the different excited states in  $^{16}\text{O}^*$  to which the  $^{20}\text{Ne}^*$  decays. Figure 9.15 shows a typical silicon detector spectrum, with three clearly defined  $\alpha$ -particle peaks, corresponding to the three states in  $^{16}\text{O}^*$ . The resonance for 340 keV incident protons favors the  $3^-$  state of  $^{16}\text{O}^*$ , which decays by emission of a 6.13 MeV  $\gamma$  ray. These  $\gamma$  rays are emitted isotropically [Hel72]. To produce beam-like conditions, more than 20 cm of lead shielding was arranged to collimate the  $\gamma$  rays down to a 2.54 cm diameter circle centered on the front face of *Molly*. The solid angle opening defined by this lead shielding determines the fraction of the  $\alpha$ -particle-associated  $\gamma$  rays incident on the face of

*Molly*.

Figure 9.16 shows the experimental setup. A small scattering chamber designed with very thin windows was set on the beam line following TUNL's mini-tandem accelerator. Six silicon detectors were placed at backward angles to detect outgoing  $\alpha$  particles. Incident protons with energies  $\geq 340$  keV were collimated by a double-slit collimator located 6.35 cm away from the target. The targets were thin films of LiF approximately  $50 \mu\text{g}/\text{cm}^2$  in thickness evaporated onto  $\sim 10 \mu\text{g}/\text{cm}^2$  carbon backings.

The presence of a peak in the TAC spectrum confirmed  $\alpha$ - $\gamma$  coincidences. Software gates isolated events that were both in the resonant  $\alpha$ -particle peak of each silicon detector and in the peak of the TAC spectrum, thus generating a spectrum of coincident events in the NaI detector (see Fig. 9.15). Coincident counts that fell within the full energy peak were ideal for the present analysis for two reasons. First, natural backgrounds at 6.13 MeV are low. Second, confusion between  $\gamma$  rays that scattered before entering the detector and those that Compton scatter within the detector is eliminated by choosing only  $\gamma$  rays in the full energy peak.

The measured peak efficiency of *Molly* is

$$\epsilon_{\text{peak}} = \frac{N_{\gamma}^{\text{peak}}}{\frac{d\Omega}{4\pi} \times N_{\alpha}} \quad (9.8)$$

where  $N_{\gamma}^{\text{peak}}$  is the number of detected  $\gamma$  rays in the full energy peak,  $\frac{d\Omega}{4\pi}$  is the fractional solid angle defined by the lead shielding, and  $N_{\alpha}$  is the number of  $\alpha$ -particles detected for the resonant reaction.

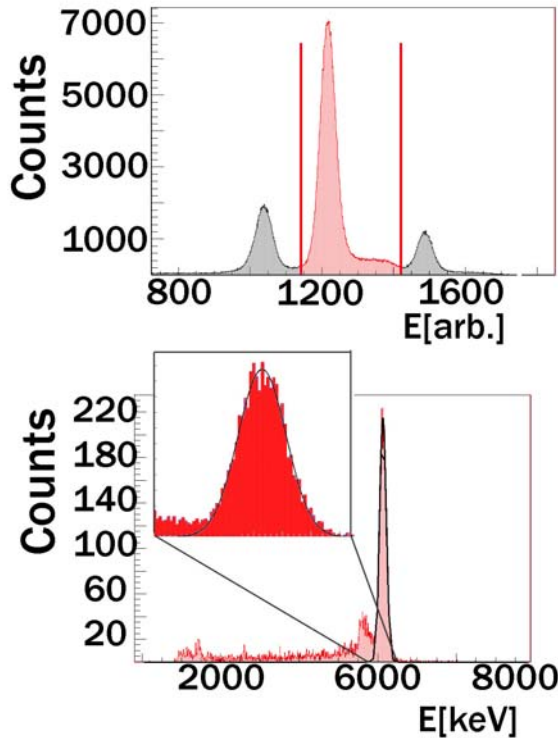


Figure 9.15: (Color Online) (Top) Three  $\alpha$ -particle peaks from a typical silicon detector spectrum. Gates have been drawn around the resonant peak. (Bottom) The summed spectrum of all coincident  $\gamma$  rays from all runs. A Gaussian fit to the full energy peak at 6.13 MeV (inset) determines  $N_{\gamma}^{peak}$ .

Over 6000 total  $\alpha$ - $\gamma$  coincidences resulted from  $1.3 \times 10^7$  total  $\alpha$  particles counted over the course of 50 hours of data collection. The fractional solid angle defined by the lead shielding was calculated to be  $(4.87 \pm 0.12) \times 10^{-4}$ . Precision was limited by uncertainties in the measurements of the distance between the target and the

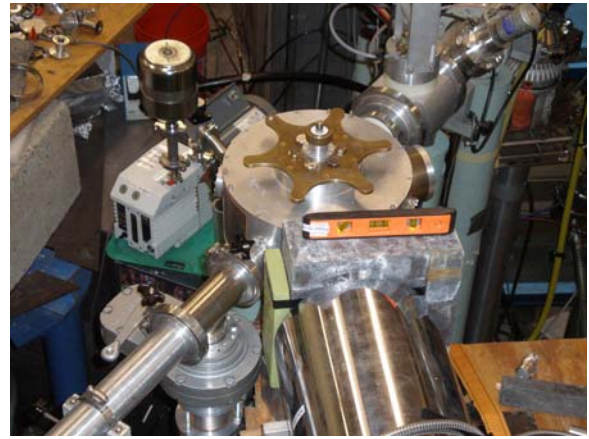


Figure 9.16: (Color Online) Photograph of the experimental setup. *Molly* (bottom) sits behind a collimating wall of lead. Additional lead shielding was placed inside the scattering chamber (center).

end of the collimator, and of the collimator diameter. Simulations of the solid angle were performed using the Monte Carlo code MCNPX to account for the effects of finite beam size and known geometrical constraints in the experiment. A fractional solid angle of  $(4.91 \pm 0.12) \times 10^{-4}$  was adopted, yielding a peak efficiency of  $69.5 \pm 1.9\%$ . This peak efficiency is consistent with GEANT4 models of *Molly*, which predict a peak efficiency of 69.7% and a corresponding total efficiency of 98.9% for an incident beam of 6.13 MeV  $\gamma$ -rays. From these results we infer that experiment-dependent losses of efficiency caused by electronic threshold settings can be modeled very accurately.

We would like to acknowledge M. Ahmed, S. Stave, P. Martel, S. Henshaw, A. Couture, D. Ticehurst and the Duke Machine Shop for their help in making this experiment successful.

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[Hel72] R. Hellborg and L. Ask, *Physica Scripta*, **6**, 47 (1972).

### 9.2.5 Characterization of a Gd-Loaded Neutron Detector

D.R. TICEHURST, M.W. AHMED, C.R. HOWELL, H.J. KARWOWSKI, J.R. TOMPKINS, W. TORNOW, TUNL

**A neutron detector filled with BC-521 Gd-loaded liquid scintillator has been characterized. The efficiency, energy resolution, and pulse shape discrimination (PSD) properties were measured. The detector was developed to assess the possibility of using BC-521 for  $(\gamma, n)$  cross section measurements or measurements of delayed neutrons from fission.**

Direct measurements of total cross sections for  $(\gamma, n)$  reactions and delayed neutrons from fission require neutron detectors that cover a large solid angle. Detectors with fast time resolution ( $<100$  ns) and that measure energy without TOF will enable a number of new experiments that require detection of low energy neutrons in the exit channel. A prototype gadolinium-loaded detector (Gadet) was constructed two years ago and characterized this past year using both measurements and simulations.

Gadet, shown in Fig. 9.17, consists of a can that is 20 cm long and 13 cm in diameter, filled with BC-521. It has a borosilicate glass window attached to a 13 cm PMT. Like most organic scintillators, BC-521 exhibits a fast response (rise/decay times on the order of 10 ns) and PSD capabilities, allowing neutrons to be distinguished from  $\gamma$  rays.

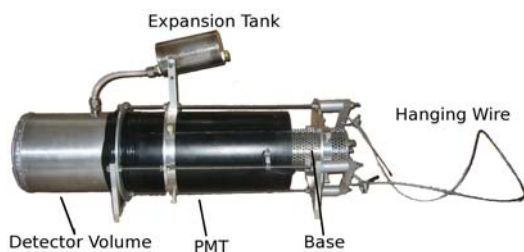


**Figure 9.17: (Color Online) A photo of Gadet. The detector has a total length of about 65 cm and a mass of about 12 kg.**

One way to quantify the PSD capabilities of a scintillator is with a figure of merit,  $M$ , calculated from a 1-dimensional PSD histogram:

$$M = \frac{\Delta}{\delta\gamma + \delta n}$$

where  $\Delta$  is separation of the peaks' centroids and  $\delta\gamma$  ( $\delta n$ ) is the FWHM of the  $\gamma$ -ray ( $n$ ) peak

[Ban07]. Using a  $^{241}\text{Am-Be}$  source,  $M = 0.59$  for Gadet (see Fig. 9.18 compared with  $M = 1.24$  for a 5 cm long  $\times$  13 cm diameter scintillator detector filled with BC-501A.

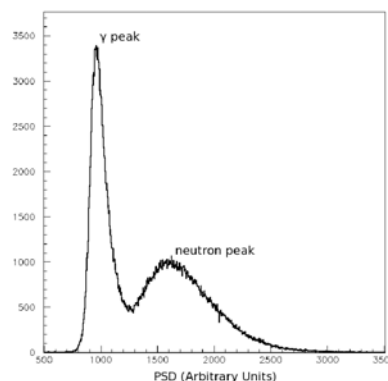


**Figure 9.18: A PSD spectrum from Gadet using a  $^{241}\text{Am-Be}$  source**

Neutron energies are generally measured using TOF. The addition of  $^{nat}\text{Gd}$  to liquid scintillator permits another method of measuring neutron energy, due to gadolinium's 49 kb thermal neutron capture cross section. When a neutron is captured by Gd, energy is released, typically as three  $\gamma$  rays with a total energy of  $\sim 8$  MeV [Ban07]. These  $\gamma$  rays may produce a signal in the detector. However for a neutron to capture on Gd, it must thermalize. The full thermalization process takes several  $\mu\text{s}$  but produces a prompt signal (ns wide) proportional to the initial neutron energy. Thus, after a prompt signal from a neutron ( $\gamma$  rays excluded by PSD), the next signal will be from either neutron capture or an uncorrelated random event. At counting rates of a few kHz, the spectrum from random events within 40  $\mu\text{s}$  (the TAC range) of the prompt signal is flat and thus only translates the overall spectrum up. The characteristic neutron thermalization time can be measured with a time

distribution (TD) spectrum: a histogram of the times between the prompt signal and the very next signal. For neutrons, the histogram consists of a flat background and a peak centered at the average moderation time, about  $6 \mu\text{s}$ . Applying both PSD and TD gates (for neutrons and moderated neutrons, respectively) to the pulse height (PH) data gives a PH spectrum of the neutron energies (a technique called “capture gating” [Kno00]). Thus a detector such as Gadet can measure neutron energy without TOF.

Capture gating was used to make neutron energy spectra for monoenergetic neutrons produced by the  $^2\text{H}(d,n)^3\text{He}$  reaction (see Fig. 9.19). The width of the peaks characterizes Gadet’s energy resolution, is poor due to the low light output characteristic of neutrons, but improves with increasing energy.

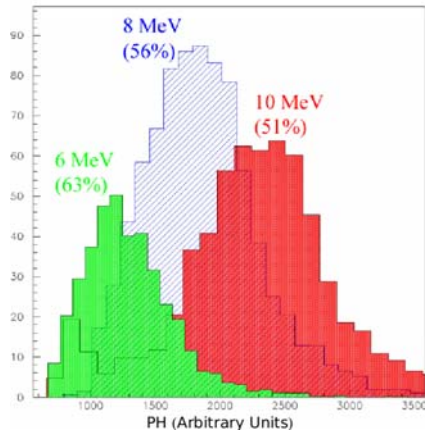


Figure 9.19: (Color Online) Three capture-gated PH spectra (with their energy resolutions) from 6, 8, and 10 MeV neutrons.

The neutron detection efficiency of Gadet was calculated with GEANT4 and measured using monoenergetic neutrons at several energies. The GEANT4 simulation used the “QGSP BIC HP” physics library and light output functions from the Monte-Carlo efficiency code NEFF7 [Die82]. These functions were measured for BC-501A but were used here since light output functions for BC-521 have not been measured. The light output per event was scaled down according to the percent anthracene light output published in the manufacturer’s data sheets.

The efficiency measurement was conducted with a pulsed monoenergetic neutron beam at 6, 8, and 10 MeV. The pulsed beam permitted TOF measurements and a plastic scintillator paddle provided relative flux normalization. Gadet and a  $5 \text{ cm} \times 13 \text{ cm}$  BC-501A detector with a well-known efficiency were placed in the beam separately at each energy. Gadet’s absolute efficiency was calculated as

$$\epsilon_{\text{Gd}} = \frac{Y_{\text{Gd}}}{Y_0} \times \frac{r_0^2}{r_{\text{Gd}}^2} \times \epsilon_0$$

where  $Y$  is the flux-normalized neutron yield and  $r$  is the detector radius. The subscripts Gd and 0 denote Gadet and the reference detector, respectively.

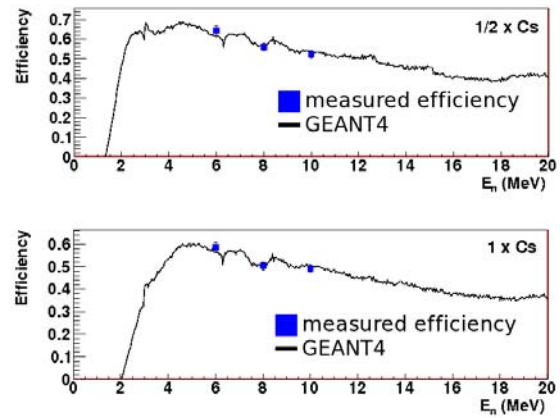


Figure 9.20: (Color Online) Gadet’s neutron efficiency for 6, 8, and 10 MeV neutrons at  $1 \times Cs$  and  $1/2 \times Cs$  thresholds.

The advantage of a liquid scintillator neutron detector loaded with Gd or some other element with a high thermal-neutron-capture cross section is the ability to measure neutron energy without TOF while retaining PSD capabilities. The trade off is poor energy resolution and worse PSD than with a standard liquid scintillator. Since neutrons take several  $\mu\text{s}$  to moderate, the ADC gate must be long, limiting the counting rate. The low count rate combined with the fact that only about 3% of the incident neutrons end up producing a detected capture signal leads to long counting times. However, such a detector might have an application where neutron energy information and large solid angle-coverage are simultaneously desirable.

When Gadet was disassembled after completion of the characterization, a breakdown of the grease junction between the light guide and the PMT tube was noticed. This likely caused a systematic decrease in the amount of light reaching the PMT, and thus our characterization measurements may be considered lower limits.

[Ban07] K. Banerjee *et al.*, Nucl. Instrum. Methods A, **580**, 1383 (2007).

[Die82] G. Dietze and H. Klein, Technical Report PTB-ND-22, Physikalisch-Technische Bundesanstalt, Braunschweig, Germany, 1982.

[Kno00] G. F. Knoll, *Radiation Detection and Measurement*, Wiley and Sons, 3rd edition, 2000.

### 9.2.6 Ratio of Ge Detector Peak Efficiencies at Energies of 4.4 and 11.7 MeV

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**Full-energy peak efficiencies of Ge detectors are frequently investigated at energies below 4 MeV using calibrated radioactive sources, while very accurate peak efficiencies for higher photon energies are essentially nonexistent. Peak efficiencies in the energy range of  $E = 4 - 12$  MeV are crucial for a number of applications, including nuclear astrophysics measurements of fusion reactions and resonance fluorescence experiments. We report on a novel method of accurately measuring the ratio of full-energy peak efficiencies at 4.44 and 11.66 MeV using the 163 keV resonance in the  $^{11}\text{B}(p,\gamma)^{12}\text{C}$  reaction. Our values have a precision of 1.4 – 1.6%.**

The determination of full-energy peak efficiencies for Ge detectors has been the subject of numerous studies. Below an energy of 3.5 MeV, radioactive sources are conveniently used for such calibrations. Computer simulations, using Monte-Carlo procedures, are also routinely performed by many groups. Frequently, only relative peak efficiencies are computed and the simulated results are normalized to the data in order to aid in the interpolation of efficiencies between measured energies.

For the measurement of peak efficiencies at higher energies—say, between 4 and 12 MeV—a number of different strategies are employed, depending on the technical capabilities of the laboratory. For example, the low-energy peak efficiency data from the radioactive source measurements are used for normalizing simulated peak efficiencies obtained from Monte-Carlo calculations. The normalized simulation results are then adopted for extrapolating peak efficiencies to high energies. Such an extrapolation is not without dangers, since the energy dependence of the peak efficiency may differ at low and high energies. Furthermore, it is difficult to assign uncertainties to a peak efficiency that has been extrapolated over many MeV. The present work was motivated by the scarce data on accurate full-energy peak efficiencies of Ge detectors at high photon energies ( $E = 4 - 12$  MeV).

Here we discuss the use of the  $E_r^{lab} = 163$  keV resonance in  $^{11}\text{B}(p,\gamma)^{12}\text{C}$ . It gives rise to a strong cascade with photon energies of 4.44 and 11.66 MeV. For such a cascade, the ratio of peak efficiencies for the first (RprimaryS) transition and

second (RsecondaryS) transition is determined only by the corresponding ratio of measured net peak intensities. One goal of our study was to determine how accurately the full-energy peak-efficiency ratio at these two energies can be determined when using this particular resonance. We address all of the important effects that may influence this ratio: side-feeding  $\gamma$ -ray branchings, angular correlations and coincidence summing. A second goal of our study was to find out how well the Monte Carlo codes GEANT3 and GEANT4 are able to reproduce the measured peak-efficiency ratio at high  $\gamma$ -ray energy.

In brief, the experiment was carried out at the Laboratory for Experimental Nuclear Astrophysics (LENA). A 1 MV JN Van de Graaff accelerator supplied proton beams of up to  $10\ \mu\text{A}$  on target in the bombarding energy range of  $E_p^{lab} = 150 - 180$  keV. The target was fabricated by evaporating boron, enriched in  $^{11}\text{B}$ , onto a 0.05 mm thick tantalum backing. The beam was focused into a profile of  $\approx 10$  mm diameter on target. The counter consisted of a p-type, closed end, bulletized high-purity germanium (HPGe) detector. It was purchased from EG&G Ortec (Oak Ridge, TN, USA) in 1995 and was originally specified as having a 140% relative efficiency. Signals from the detector were processed using standard VME electronics and analyzed with the data acquisition system JAM. The detector was positioned at an angle of  $67^\circ$  with respect to the incident proton beam direction in order to minimize angular correlation effects. Three distances between the target midpoint and the center of the outer surface of the detector end cap were chosen

in the measurement: 3.05, 11.91 and 26.36 cm.

The main results can be summarized as follows. First, the precision of the peak-efficiency ratio achieved in our experiment amounts to 1.4 – 1.6%. A longer measurement time in order to accumulate more statistics would be of limited use since the uncertainty arising from the angular correlation correction alone amounts to 1.0%. Clearly, a significantly improved precision would require a dedicated remeasurement of the angular correlations in the decay of the  $E_r^{lab} = 163$  keV resonance. Second, the peak-efficiency ratios for different distances are consistent within uncertainties, despite the fact that the measurement at the shortest distance (3.05 cm) is expected to suffer from significant coincidence summing effects.

As a next step, we determined the detector crystal geometry independently from the dimensions supplied by the manufacturer. Images from both radiographs and computed tomography were obtained by scanning our detector at UNC hospitals. Based on the derived crystal di-

mensions, computer simulations using GEANT3 and GEANT4 were performed. We can draw the following conclusions by comparing measured and simulated peak-efficiency ratios at  $\gamma$ -ray energies of  $E = 4.44$  MeV and 11.66 MeV: (i) the measured and all of the simulated peak-efficiency ratios show the same dependence on distance; (ii) the GEANT4 simulation results agree with the measured peak-efficiency ratios within an uncertainty of 1.6%; (iii) the code GEANT3 underpredicts the measured peak-efficiency ratios by 2.6%. The results presented here allow for an estimation of uncertainties when peak efficiencies are extrapolated from low energy data to high energies based only on simulations. More experimental work is called for in the future in order to compare measured and simulated absolute full-energy peak efficiencies.

This work has now been published. For detailed results, see Ref. [Car10].

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[Car10] S. Carson *et al.*, Nucl. Instrum. Methods, **A618**, 190 (2010).

### 9.2.7 Initial Studies of HPGe Detectors for Nuclear Astrophysics

G. RICH, A.E. CHAMPAGNE, C. ILIADIS, *TUNL*

**We have begun simulation studies aimed at a conceptual design for an HPGe detector optimized for nuclear-astrophysics measurements. This work will be the starting point for a project for the Deep Underground Scientific and Engineering Laboratory (DUSEL) to design a detector for a future underground accelerator laboratory.**

A significant amount of effort has been devoted to designing and constructing HPGe detectors for nuclear-structure and double- $\beta$ -decay studies, and some of these design concepts could be adapted to the needs of nuclear astrophysics. For example, although the usual close target-detector geometry limits the usefulness of tracking, some degree of segmentation could be used to suppress external backgrounds. Event localization provided by point-contact detectors may also prove effective in reducing backgrounds. To explore some of these ideas, we have begun some simple simulation studies of HPGe detectors. To begin, we looked at the ideal dimensions for a cylindrical, point-contact detector. The mass was fixed at 2.7 kg, which is similar to that of a commercial, large-volume detector. For  $\gamma$  rays with energies of 1–10 MeV, the ideal dimensions (as predicted by GEANT4) are approximately 9 cm in diameter by 7.9 cm long, and these dimensions were fixed for subsequent calculations.

Pulses from a point-contact detector carry information about the location of an event, which will be investigated in detail in future studies. For now, we have explored two simple background cuts based on the number of interactions for a fully absorbed  $\gamma$  ray and on the longitudinal distribution of energy. We used an isotropic circular plane source of 1 MeV  $\gamma$  rays, 2.54 cm in diameter, parallel to the “front” face of the detector and at a distance of 1.6 cm to represent  $\gamma$  rays produced in a typical accelerator target. Two background sources ( $^{40}\text{K}$  and  $^{208}\text{Tl}$ ) were emulated as isotropic point sources located 6 cm directly above the midline of the detector volume. The number of 1 MeV  $\gamma$  rays interacting versus distance along the detector is shown in Fig. 9.21.

Although the geometry used here was rather artificial, it does appear that a cut on energy deposited versus distance along the detector would be helpful, and this will be explored in more detail in future studies. We also found that photo-

peak events undergo about 10 interactions, on average, so that requiring some minimum number of events would have the effect of suppressing a portion of the Compton continuum. In Fig. 9.22, we have applied cuts requiring  $z > 0$  and more than six interactions to the  $^{208}\text{Tl}$  events, thus reducing them by a factor of three to five. However, these cuts have a much smaller effect on 1-MeV-photo-peak events from target  $\gamma$  rays (see Fig. 9.23), which are reduced by only  $\sim 30\%$ . At the same time, there is a significant reduction in Compton events, which could be useful for situations where a weak line of interest is obscured by Compton events from a stronger line.

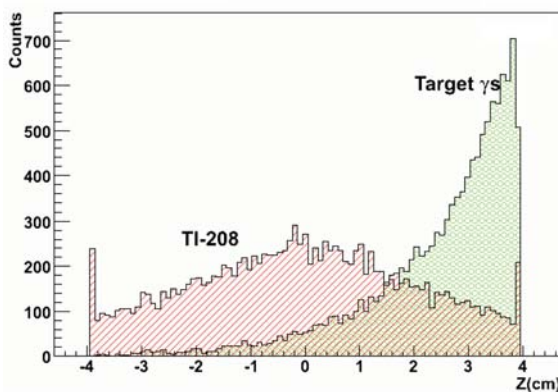


**Figure 9.21:** (Color online) Counts (or energy deposited) versus detector depth. The front face of the detector is located at  $z = 4$  cm and a  $^{208}\text{Tl}$  source was suspended above  $z = 0$

The results described here are intended to guide more comprehensive calculations that are planned for later this year. This work will be part of a funded Solicitation-4 DUSEL project aimed at defining a conceptual HPGe detector for a future underground accelerator. However, it should be noted that such a detector would also be useful above ground and may be considered for future work at LENA.

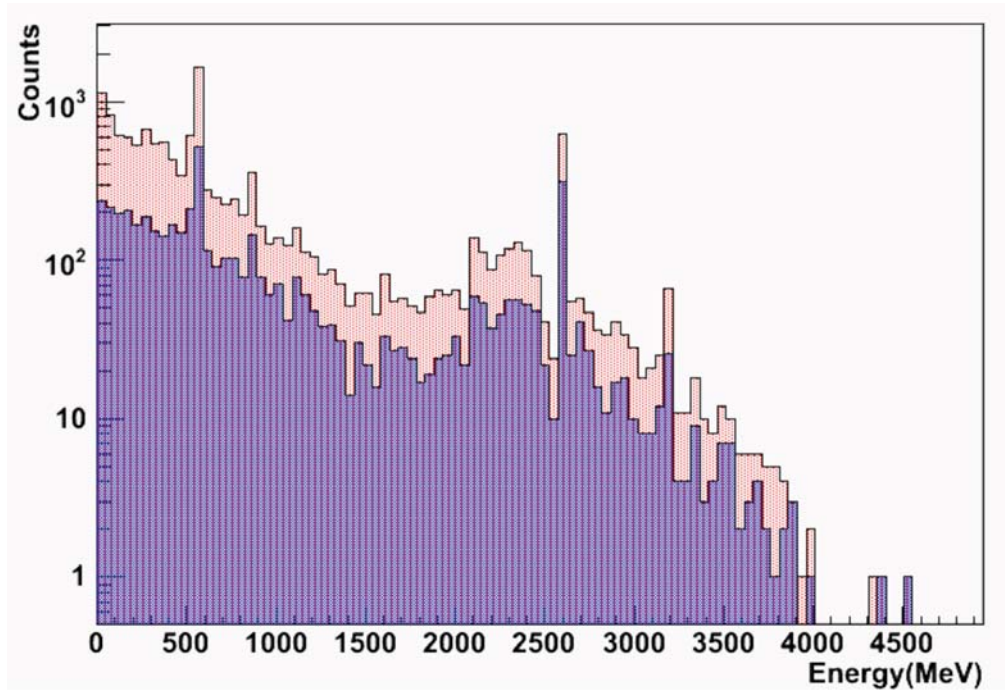


Figure 9.22: (Color online) Spectra of  $^{208}\text{Tl}$  events. The lighter color shows the raw  $^{208}\text{Tl}$  spectrum, while the darker spectrum results from the requirements that  $z > 0$  and that there be more than six interactions.

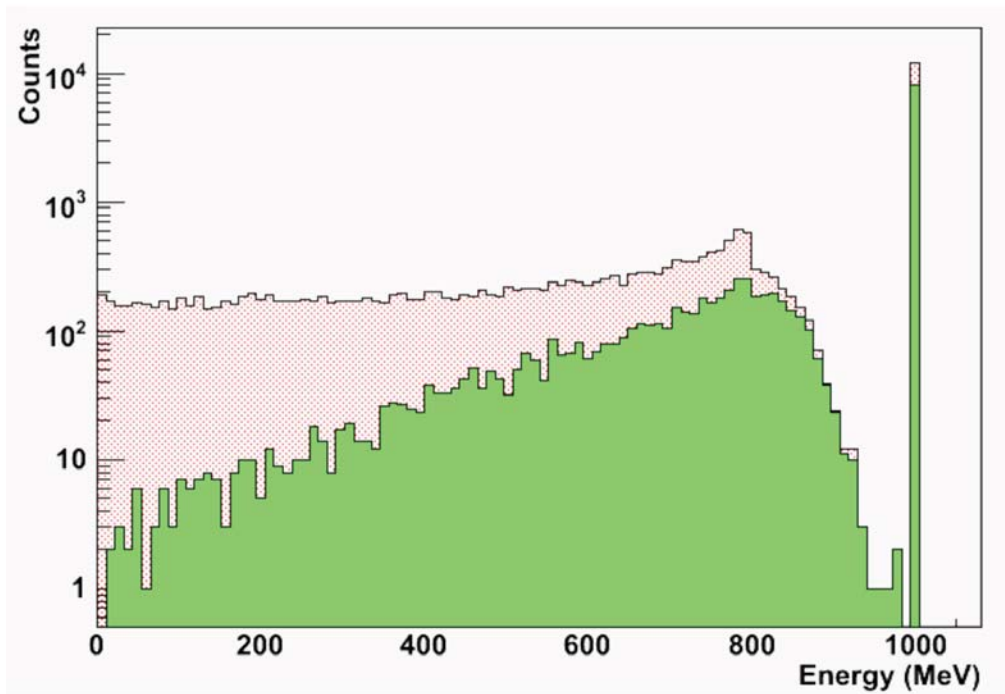


Figure 9.23: (Color online) Spectra of 1 MeV “target” events. The lighter color is again the raw spectrum, while the darker spectrum results from the requirements that  $z > 0$  and that there be more than six interactions.

### 9.2.8 Upgrade and Assembly of the APEX Trigger Detector

S. DAIGLE, A.E. CHAMPAGNE, *TUNL*

The APEX trigger detector was assembled, and its original 48 PMTs were upgraded with 32 Hamamatsu R580 tubes and 16 Photonis XP2012B tubes. A radial collimator was designed and constructed to facilitate simultaneous position calibrations of the 24 NaI(Tl) segments. A new CAEN V862 charge-to-digital converter is currently being tested for use in data acquisition, to eliminate the integration of noise in the PMT output signals.

The 24-element NaI(Tl) scintillator array originally built for the APEX experiment [Kal93] has been upgraded and assembled for use in low-energy nuclear experiments at LENA. The original 48 PMTs have been replaced with 32 Hamamatsu R580 tubes and 16 Photonis XP2012B tubes in new aluminum mounts. The new PMT housings have eliminated light leaks, while the upgraded tubes provide improved position and energy resolution [Dai09]. Figure 9.24 is a photograph of the fully assembled NaI(Tl) array located in the detector setup area of LENA.



**Figure 9.24:** (Color online) Photograph of the fully constructed APEX detector outfitted with 48 new PMTs and aluminum mounts.

Before assembly, all detector segments were thoroughly cleaned, photographed, and documented to catalog the current condition of the NaI(Tl) crystals. A few crystals showed signs of damage in the form of streaking and fogging around the quartz windows. These minor defects most likely occurred during transportation but also may be a result of their age. This information is kept on file for future reference in the event we suspect a scintillator bar is behaving poorly. During assembly, a dime-size amount of Saint-Gobain BC-630 silicone optical grease was placed on the PMT glass surface and then methodically pressed against the quartz window using constant pressure. Positive pressure is maintained by rubber o-rings within the PMT housing. Once assembled, the optical grease and quartz window provide a transparent interface between the PMT and the scintillator crystal, while the o-rings also shield the tube from light leaks.

A radial collimator was constructed to precisely control the physical position of a  $\gamma$ -ray disk source along the position-sensitive axis of the detector. Figure 9.25 is an Autodesk Inventor image of the radial collimator, which is seated on Thomson rails to allow for unrestricted movement and quick calibration while the detector is in position on the beam line at LENA. The collimator is constructed of a 11.43 cm diameter aluminum pipe that houses a delrin container attached to the end of a 1.07 m aluminum rod. The aluminum rod has been etched in 0.5 cm increments to allow for precise positioning of the source. Inside the delrin container are two cylinders of lead (5.08 cm thick and 10.16 cm in diameter) that radially collimate the  $\gamma$ -ray source. The dimensions of the lead collimators were chosen so that the size of the  $\gamma$ -ray image on the detectors would be smaller than their intrinsic position resolution. The delrin container can slip

freely throughout the aluminum pipe, allowing the collimator base to be locked in position while the source is inserted into the detector using the rod-and-container assembly.



**Figure 9.25:** (Color online) Autodesk Inventor graphic of radial collimator on Thomson rails (three-quarter section view). The collimator allows for precise measurements along the position-sensitive axis of each scintillator bar in 0.5 cm increments.

We have simulated the response of the APEX detector to the collimated source using the GEANT4 simulation package [Ago03]. Figure 9.26 is the result of a simulation of 1332 keV  $\gamma$  rays emitted from a  $^{60}\text{Co}$  disk source placed inside the radial collimator. The simulated FWHM of those events detected is 2.5 cm, which is less than the position resolution of the detector (approximately 3.5 cm).

A CAEN SY2527 multichannel HV power supply was recently purchased to bias all 48 PMTs to their operating voltages (approximately -1500 V). Gain-matching each PMT can be easily performed by adjusting the voltages on the power

supply that bias the tubes on either end of a detector segment. Progress is being made on developing an optimal electronics setup for data acquisition. Currently, we are investigating the advantages of using an individual gate charge-to-digital converter (QDC) (V862) available from CAEN electronics over our existing setup using a CAEN ADC (V785). There is evidence that the QDC will greatly reduce the steep slope of low-energy counts in our spectra that arise from integrating noise in the output signals of the PMTs. In order to complete the proposed electronics setup, two V862 QDCs must be purchased to replace the V785 ADCs.

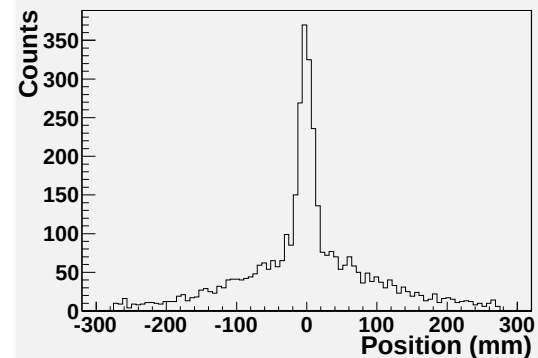


**Figure 9.26:** geant4 simulation of  $\gamma$ -rays emitted from a  $^{60}\text{Co}$  source inside the radial collimator. The FWHM of simulated 1332 keV  $\gamma$ -rays is 2.5 cm.

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- [Ago03] S. Agostinelli *et al.*, Nucl. Instrum. Methods, **A506**, 250 (2003).
- [Dai09] S. Daigle and A. E. Champagne, TUNL Progress Report, **XLVIII**, 166 (2009).
- [Kal93] N. I. Kaloskakis *et al.*, Nucl. Instrum. Methods, **A330**, 447 (1993).

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### 9.2.9 Rutherford-Backscattering Analysis of Polymer Membranes Used for Water Purification

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The concentration of ionizable functional groups in reverse-osmosis and nanofiltration polymer membranes, as well as the concentration of contaminants partitioned into the membranes, can be determined by Rutherford backscattering of He ions from virgin and treated membranes, respectively. In preparation for such experiments, we have constructed a sample holder to mount inside an existing scattering chamber and hold multiple membranes. The position of each membrane can be rastered across the beam by stepper motors controlled via LabVIEW.

#### 9.2.9.1 The Experiment

The concentration and distribution of ionizable functional groups in the active layer of reverse-osmosis (RO) and nanofiltration (NF) membranes will be studied using Rutherford backscattering spectrometry (RBS) [COR08, COR09]. Such RO and NF membranes are increasingly attractive technologies for the drinking-water and water-reuse industries, because they are able to remove a broad range of water contaminants in one treatment step without the addition of chemicals to the water. The structure of RO and NF membranes usually consists of an ultra-thin ( $\approx 100$  nm), fully aromatic polyamide layer on top of a polysulfone support ( $\approx 50$   $\mu\text{m}$ ) backed by a layer of polyester fibers ( $\approx 300$   $\mu\text{m}$ ), with the polyamide layer representing the main barrier to the permeation of water and contaminants [BMI06]. The polyamide layer, usually referred to as the active layer, contains ionizable functional groups that provide charges to the membrane and affect the rejection of ionic contaminants [COR08]. The ionizable functional groups are broken links in the polymer structure and thus are directly related to the free volume of the active layer and its permeability to water and contaminants. Accordingly, achieving a thorough understanding of the concentration and distribution of ionizable functional groups in active layers is important to both (i) understand the mechanisms of transport of water and contaminants and (ii) identify the improvements needed in commercial membranes in order to develop new membranes with enhanced performance.

The experiments will consist of saturating ionized functional groups with heavy ion probes,

and determining the ion probe concentration by RBS [COR08, COR09]. Negative and positive functional groups will be saturated with silver ( $\text{Ag}^+$ ) and tungstate ( $\text{WO}_4^{2-}$ ), respectively. A beam of 2 MeV He<sup>+</sup> will be used for analysis by backscattering. Currents of 40–100 nA will be used, with beams having a diameter of 2–3 mm. The He<sup>+</sup> ion fluence on membrane samples will be maintained below threshold values for degrading the integrity of the polymers [BMI07]. Membrane samples will be prepared using ion-probe solutions in the pH of interest for membrane analysis (2–11), with emphasis on the pH range of interest for water treatment (6–10). Divalent barium ( $\text{Ba}^{2+}$ ) will also be used to probe negative functional groups. By comparing the results obtained for  $\text{Ag}^+$  and  $\text{Ba}^{2+}$ , the average distance between ionizable functional groups will be calculated [COR09]. The results from this study will advance the understanding of the physico-chemical structure of the active layer of RO and NF membranes.

#### 9.2.9.2 The Sample Holder

The sample holder accommodates multiple targets, each of which scans through the beam in contiguous arcs. Samples are mounted on an aluminum wheel which moves vertically and rotates azimuthally within the scattering chamber. The whole assembly also rotates around an axis perpendicular to the scattering plane to set the incident angle of the He ion beam on the samples. The vertical and azimuthal motions of the sample wheel are achieved with small stepper motors, while the rotation of the whole assembly is manual. Absolute encoders are mounted onto the rear

shafts of the stepper motors to register their exact position. Both stepper motors are controlled by a single driver located outside of the scattering chamber.



**Figure 9.27: Sample Holder Assembly**

The sample wheel is detachable from the assembly, allowing the user to load the sample wheel easily for RBS analysis. The wheel is electrically insulated from the rest of the assembly and connected externally via a graphite brush and wire to facilitate beam current integration.

National Instruments software LabVIEW is used to locate the samples on the wheel and determine the rastering pattern for each sample. A photograph taken of the loaded sample wheel is uploaded to LabVIEW, and the picture is cali-

brated with user input to convert Cartesian coordinates in pixels into polar coordinates in millimeters. The user then inputs the number of samples on the wheel and outlines each sample. Finally, the LabVIEW code determines raster arcs that will fit within each sample for a particular beam spot size.

A separate LabVIEW program is used to control the stepper-motor driver and to read the signal from the absolute encoders mounted on the stepper motors. The design of the sample holder along with the absolute encoders allows LabVIEW to know the exact position of the beam on the sample wheel. The LabVIEW program controls the stepper motors to raster each sample in the predetermined arcs. LabVIEW also controls external hardware to allow (inhibit) data collection from the detectors in the chamber when the beam is (is not) hitting a sample.

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- [BMI06] B. Mi *et al.*, J. Mem. Sci., **282**, 71 (2006).
  - [BMI07] B. Mi, D. Cahill, and B. Marinas, J. Mem. Sci., **291**, 77 (2007).
  - [COR08] O. Coronell *et al.*, Environ. Sci. Technol., **42**, 5260 (2008).
  - [COR09] O. Coronell, B. Marinas, and D. Cahill, Environ. Sci. Technol., **43**, 5042 (2009).

## 9.3 Facilities

### 9.3.1 Development of an Ultracold Neutron Source at the NC State PULSTAR Reactor Facility

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**We are in the final stages of constructing a next-generation ultracold neutron source at the PULSTAR reactor facility on the campus of NC State University. We envision using the source for performing neutron  $\beta$ -decay measurements as well as systematic studies for the neutron electric dipole moment experiment.**

Ultracold neutrons (UCNs) play an important role in nuclear-physics investigations that seek to test the Standard Model of particle physics and characterize the weak interaction. UCN-source technology is advancing rapidly, and the numerous techniques presently being implemented should permit several orders of magnitude gain in useful UCN densities. Such higher densities of UCNs will not only permit improved measurements of quantities such as the neutron electric dipole moment (EDM) and neutron  $\beta$ -decay lifetime, where measurements utilizing UCNs already provide the most precise experimental values, but will also play a role in neutron-angular-correlation measurements, neutron-antineutron-oscillation searches, spectroscopic studies of neutron decay, fundamental tests of quantum mechanics, and, potentially, cutting-edge neutron-scattering applications.

The PULSTAR ultracold neutron (UCN) source is designed to be a next generation UCN source that utilizes solid deuterium ( $\text{SD}_2$ ) at a temperature of 5 K to moderate thermal neutrons to UCN energies. The high leakage of fast/thermal neutrons from the reactor core makes it possible to couple efficiently the neutron flux to the  $\text{D}_2\text{O}$  thermal moderator and the solid methane  $\text{CH}_4$  cold moderator that surround the deuterium.

The concept for our facility is to place the UCN source in a tank of  $\text{D}_2\text{O}$  positioned in the former thermal column of the PULSTAR reactor. Neutrons leaving the face of the reactor core are channeled into the  $\text{D}_2\text{O}$  tank by a 45 cm  $\times$  45 cm  $\times$  70 cm long void in a graphite assembly called the nose port. The source consists of a UCN converter of solid ortho deuterium,

17 cm diameter  $\times$  4.5 cm thick, held at a temperature of  $< 5$  K. The converter is surrounded by a 1 cm thick, cup-shaped cold source of solid methane held at a temperature of  $\approx 25$  K. This configuration was optimized for maximum cold-neutron flux using detailed MCNP calculations. Upcoming measurements of the thermal neutron flux inside the  $\text{D}_2\text{O}$  volume will be used to benchmark these calculations and to predict the useful experimental UCN population using a Monte Carlo transport code developed at NCSU. The basic geometry of the source is shown in Fig. 9.28, with a closer view of the cryogenic components shown in Fig. 9.29. An assembled view of the source and guide housing is shown in Fig. 9.30.

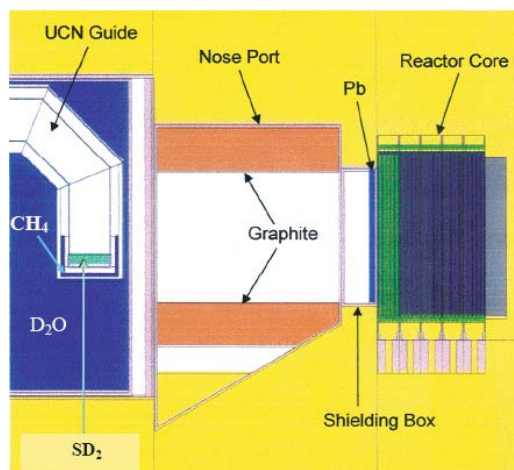


**Figure 9.28:** (Color online) MCNP geometry plot showing the general layout of the UCN source and guide, nose port, and reactor core.

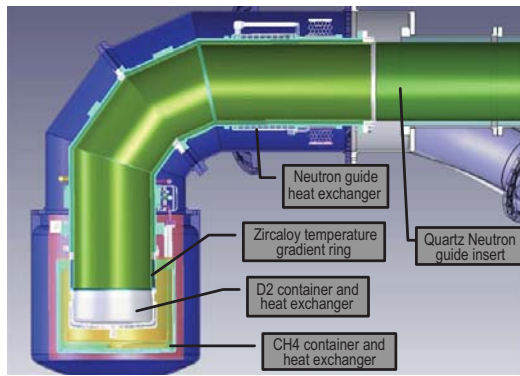


**Figure 9.29:** (Color online) UCN source and guide system.

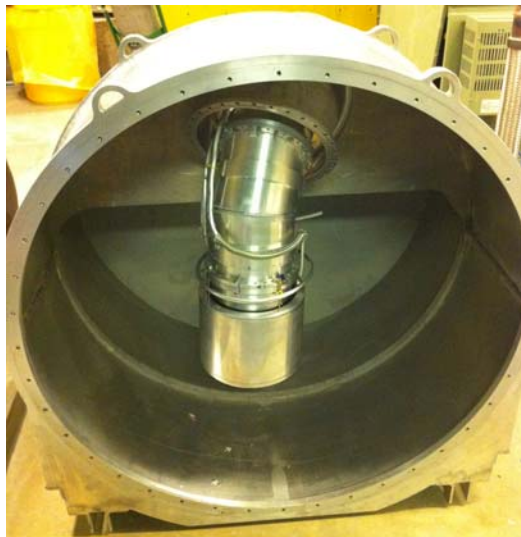


**Figure 9.30:** (Color online) Photograph of the assembled UCN source. The large Al container houses the  $D_2O$  thermal moderator that surrounds the UCN source assembly.

Through a separate NSF grant, we have funding to complete the commissioning and to lay the foundation for a research program at PULSTAR. We will submit separate proposals to operate individual experiments at the PULSTAR source. As an example, funding is being sought for work to support the neutron EDM effort based at Oak Ridge National Laboratory. A brief outline of the proposed research program is given below.

One area of activity focuses on tailoring the cold neutron energy spectrum to optimize UCN production. Previously we were involved in measurements of UCN production as a function of cold neutron energy at Paul Scherrer Institut in Switzerland, together with C.-Y. Liu. Subsequently there have been very complete mea-

surements of the cold-neutron-scattering law for solid deuterium by the Munich group. These new scattering kernels, together with our experimental program, should permit us to produce an extremely detailed evaluation of the performance of the PULSTAR solid-deuterium source, permitting us to optimize our UCN production rate.

The program at PULSTAR will provide us with unprecedented access to measurements of our thermal, cold, and ultracold neutron fluxes and to measure and control properties of the solid deuterium, such as the physical properties of the crystal and the para-deuterium contamination. This will permit us to understand and maximize the output of both the PULSTAR and Los Alamos solid-deuterium sources.

Because of the complexity and long cooling cycle ( $\sim 6$  to 8 weeks turn-around time) of the planned large-scale neutron electric dipole moment (nEDM) apparatus, the collaboration is baselining into the project plan a smaller test apparatus that will be operated at the PULSTAR UCN source. The smaller apparatus will enable the study of different techniques needed for the nEDM measurement. The primary goals for these measurements are: (1) Determination of the UCN storage time,  $^3\text{He}$  depolarization time, and UV-scintillation-detection efficiency of nEDM measurement cells before installation in the main apparatus at ORNL. (2) Studies and development of operating procedures related to optimizing the techniques for observing double-resonance effects in the  $^3\text{He}$ -UCN system. These will include studies to optimize the procedures for critical spin dressing and techniques for minimizing and measuring the “false EDM” systematic error. (3) Studies of the trajectory correlation functions important for the geometric-phase systematic errors and the influence of surface roughness. The apparatus will be based on our existing dilution refrigerator and cryostat and will be flexible enough to allow meaningful studies in a reasonable time. The basic idea will be to reproduce a single full size measuring cell containing all the features of the final experiment except for the electric field.

There is also the exciting possibility of operating the Los Alamos neutron lifetime experiment at PULSTAR. This relatively compact experiment utilizes a 45 cm deep,  $0.6 \text{ m}^3$  trap formed by a Hallbach array of NdFeB permanent magnets ( $B_{\text{max}} \approx 1.3 \text{ T}$ ). Given that the LANSCE facility will be operating for five or six months per year, sharing the experiment will provide a genuine opportunity to refine the approach and realize the physics potential of this project.

### 9.3.2 Systematic Studies for the nEDM Experiment at the PULSTAR UCN Facility

R. GOLUB, H. GAO, D.G. HAASE, P.R. HUFFMAN, A. MERIZALDE, C.M. SWANK, Q. YE, TUNL; A. HAWARI, E. KOROBKINA, *North Carolina State University, Nuclear Engineering Department, Raleigh, NC*; S.K. LAMOREAUX, *Yale University, New Haven, CT*; THE NEDM COLLABORATION

**We are developing an apparatus, based on our existing dilution refrigerator and cryostat, that will allow tests using a single full-size measurement cell (without an  $E$  field) of key systematic effects for the neutron-EDM experiment. The tests will focus on demonstrating and quantifying the double-magnetic-resonance technique using polarized  $^3\text{He}$  and ultracold neutrons.**

A program at TUNL is being developed with the primary goal of significantly exploring key systematic effects for the neutron-electric-dipole-moment (nEDM) experiment. In addition, measurements performed during the commissioning of the main apparatus will be costly and time-consuming, so this apparatus can be used to perform characterization tests on a single full-size measuring cell containing all the features of the final experiment except for the electric field. The design of the apparatus will be based on our existing dilution refrigerator and cryostat.

The primary objectives of the design of the apparatus are as follows:

- A standing set-up to measure ultracold-neutron (UCN) storage time,  $^3\text{He}$  depolarization time, and ultraviolet scintillation detection efficiency of the nEDM measurement cells prior to installation in the main apparatus at ORNL.
- Studies and development of the operating procedures to optimize the observation of double-resonance effects in the  $^3\text{He}$ -UCN system. These will include studies aimed at optimizing the procedures for critical spin dressing and techniques for minimizing and measuring the “false edm” systematic error.
- The system will also serve as a stand-by test bed for studies of systematic errors that may be proposed as the full nEDM experiment is underway.

A general schematic showing the key components of the apparatus is shown in Fig. 9.31.

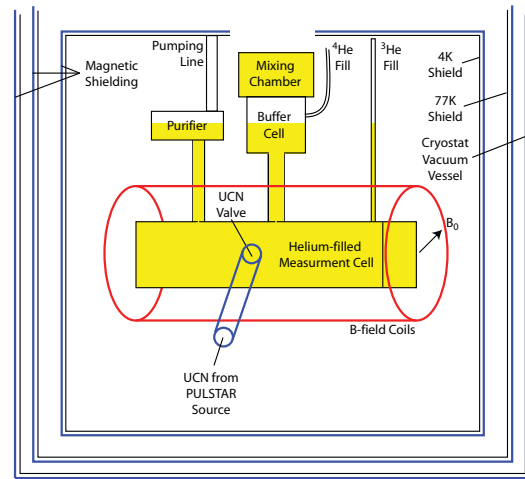


**Figure 9.31: (Color online) Schematic of the proposed apparatus showing the key components.**

The measurement cell will be suspended from the bottom of a buffer cell connected to the mixing chamber of the dilution refrigerator. The long axis of the measurement cell will be horizontal and enclosed in a set of cylinders containing the magnetic field coils and a ferromagnetic (Met-glass) shield. Additional magnetic shielding will be mounted on the 4 K and 77 K cryostat heat shields and the vacuum vessel itself. These are all coaxial cylinders with horizontal axes. The cell will be cooled by a combination of gold plated copper wires and  $^4\text{He}$ -filled acrylic tubes. The nEDM cells have only one opening used to admit polarized  $^3\text{He}$ . In our setup this opening will be used for filling the cell with UCNs. The cell

will be filled with  $^4\text{He}$  and sealed by a thin foil window that will transmit UCNs from the PULSTAR UCN source. The  $^4\text{He}$  and polarized  $^3\text{He}$  will enter the measurement cell through a small hole on top of the cell.

The  $^3\text{He}$  will be polarized using the same apparatus previously used in the studies of  $^3\text{He}$  wall depolarization and geometric phase effects. As the turn-around time for measurements using  $^3\text{He}$  is limited by the polarization time, we will have several hours to remove the depolarized  $^3\text{He}$ . For the more detailed studies of the  $^3\text{He}$ -UCN spin dynamics, the  $^3\text{He}$  will enter and leave by means of a dedicated 1 mm hole. This will not impact the UCN storage time. There will be a small evaporating chamber connected to the hole so that the depolarized  $^3\text{He}$  can be pumped away. The UCNs will enter through a thin window to confine the  $^4\text{He}$  liquid and then through a UCN valve.

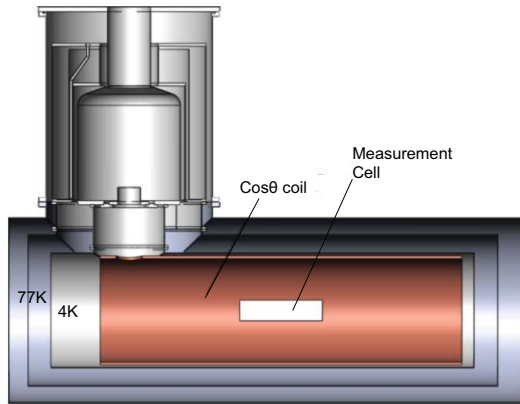


**Figure 9.32:** (Color online) Model of the cryostat for the systematic effects apparatus. The length of the apparatus is approximately 2 m.

Two quantities set the size of the apparatus: the measurement cell and the magnetic field coils. The measurement cell has been specified by the collaboration to be rectangular with inner dimensions of  $7 \times 10 \times 30 \text{ cm}^3$ . The measurements require a uniform magnetic field across the cell region, so the diameter of the magnetic field coil must be large enough to accommodate the uniform field region. Our initial estimate, based on field calculations using a  $\cos\theta$  winding geometry, suggests that the diameter of the coil will need

to be approximately 50 cm and the length about 1.5 m. Based on these dimensions, a preliminary design for the cryostat has been developed and is shown in Fig. 9.32.

The physics program will begin with the commissioning of the  $^3\text{He}$  transport features and the measurement of wall relaxation rates for the  $^3\text{He}$ . This work could be done “off-line,” before the apparatus is installed at the PULSTAR source. The work would continue with studies of the  $^3\text{He}$  trajectory correlation functions.

The same program would then be carried out with UCNs alone. Finally, we would introduce UCNs and  $^3\text{He}$  into the cell together and start to use the scintillation detection to study the critical dressing and its behavior as a function of the operating parameters. Experiments to study the pseudomagnetic-field interaction and possible new schemes for double resonance will then be undertaken.

The primary issues we envision addressing with this apparatus are as follows:

- UCN storage and depolarization studies to optimize cell materials and fabrication techniques.
- New cell designs and trouble-shooting cells that don’t work in the main apparatus.
- Measurement of scintillations due to relative  $^3\text{He}$ -UCN precession.
- Demonstration of the concept of critical dressing through the observation of a constant scintillation rate.
- Detection of the  $^3\text{He}$  pseudomagnetic field.
- Techniques for reversing the  $^3\text{He}$  and UCN spins,  $\sigma(^3\text{He})$  and  $\sigma(\text{UCN})$ , and the magnetic field  $B_0$ .
- Measurement of the “trajectory correlation function” for systematic error characterization.
- Techniques for NMR imaging of  $^3\text{He}$ .

This program of studies will occur in parallel with the construction and commissioning of the nEDM apparatus. We estimate that the entire program will last 4-5 years.

### 9.3.3 Development of the Fundamental Neutron Physics Beamline at the SNS

P.R. HUFFMAN, C.R. GOULD, *TUNL*; R. ALLEN, N. FOMIN, V. CIANCIOLO, G.L. GREENE, *Oak Ridge National Laboratory, Oak Ridge, TN*

**The construction of the polychromatic cold and 0.89 nm beamlines at the Fundamental Neutron Physics Beamline (FNPB) facility at the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory is complete. The neutron spectrum for each line has been characterized and benchmarked with simulations. The project has achieved CD-4 approval.**

TUNL played a major supporting role in the design and construction of the Fundamental Neutron Physics Beamline (FNPB) facility at the SNS. In collaboration with the University of Tennessee/ORNL team, led by G. L. Greene, we have participated in all aspects of the design, construction, and commissioning.

The FNPB includes two beamlines: a polychromatic cold beam and a 0.89 nm monochromatic beam used primarily for experiments that produce ultracold neutrons (UCNs) using the superthermal process in helium. The FNPB will be operated as a user facility, with experiment selection based on a peer-reviewed proposal process. An initial program of five experiments in neutron decay, hadronic weak interaction, and time reversal symmetry violation (nEDM) has been proposed. The  $np \rightarrow d\gamma$  experiment will be the first experiment to collect data on the cold beamline.

The FNPB has come online and completed commissioning at the SNS facility. Initial commissioning runs were aimed at measuring the neutron flux in order to demonstrate the DOE CD-4 project deliverables. Additional issues identified as important to the success of research carried out at this facility are being characterized. These include the optimization of the neutron flux and measurement of the phase space of the flux (energy, position, and angle), the time distribution of neutrons of a given energy relative to the time the proton pulse hits the spallation target, and the number and time distribution of  $\beta$ -delayed neutrons.

The first neutron fluence measurements were taken at the FNPB while the accelerator operated at 1 kW. These data are shown in last year's progress report [Huf09]. Monte Carlo simulations were part of an earlier project at TUNL to design, specify, and procure the neutron optics components for the FNPB. The performance of the

cold beamline is within about 20% of the initial estimates, which were based on the crude physics model for the SNS moderator performance.

Recently we have focused on the installation and characterization of the 0.89 nm monochromator and the  $\lambda/2$ - and  $\lambda/3$ -filter systems for the 0.89 nm beamline. A 0.89 nm monochromatic beam is reflected out of the polychromatic beam and directed to an external facility for UCN experiments. The monochromatic beamline consists of a stage-1, potassium-intercalated graphite monochromator and a second stage-1, rubidium-intercalated graphite monochromator configured in a double-crystal design, along with two highly oriented, pyrolytic graphite (HOPG) monochromators to remove the higher-order ( $\lambda/2$  and  $\lambda/3$ ) Bragg reflections from the beam. A secondary shutter for the beamline is also present.

NC State University, Oak Ridge National Laboratory, and the Institut Laue Langevin (ILL) in Grenoble, France worked cooperatively to construct the intercalated monochromators used in the FNPB. A recent photograph of the rubidium intercalated graphite monochromator is shown in Fig. 9.33.

The monochromators, filters, and shutter were assembled externally and installed into the monochromator housing in the beamline. The assembled components can be seen in Fig. 9.34 prior to installation. The beam enters from the rear-facing side of the K-intercalated monochromator, is reflected to the left towards the Rb-intercalated crystals and emerges in the forward direction.

Beam optimization and flux measurements were performed at the end of the 8 m ballistic horn using two methods. In the first method, an aperture of known area masking a fast detector with known efficiency was used to tune the angles of the monochromators so that the approximate

center of the beam was at 0.89 nm. Next, using the same aperture, the fast detector was replaced with a neutron image plate and the identical measurement was performed. This step transfers the calibration of the detector to the image plate. Lastly, the entire beam was covered with image plate and the flux distribution was determined across the beam.



Figure 9.33: (Color online) A photograph of the rubidium intercalated graphite monochromator assembly prior to installation.



Figure 9.34: (Color online) A photograph of the complete monochromator and filter assembly prior to installation.

The second method utilized a large format CCD imaging detector borrowed from the NIST fundamental-neutron-physics group. A profile of the neutron intensity taken with the image plate is shown in Fig. 9.35.

The FNPB 413.3 Technical Specification required for satisfying the DOE CD-4 requirements is specified to be  $2.1 \times 10^8 \text{ n s}^{-1} \text{ \AA}^{-1} (\text{MW})^{-1}$ ,

defined in terms of the maximum of the 0.89 nm flux distribution integrated over the entire output of the guide scaled to accelerator power. The initial measurement yielded a value of  $6.7 \times 10^8 \text{ n s}^{-1} \text{ \AA}^{-1} (\text{MW})^{-1}$ . Additional optimizations are planned, but the result easily satisfies the project requirements.

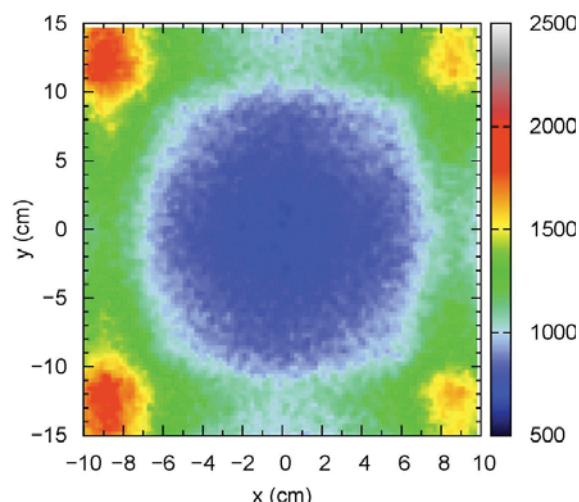


Figure 9.35: (Color online) The 0.89 nm neutron flux distribution at the end of the monochromatic beam guide.

TUNL also continues to play an active role in the development of two key experiments that are envisioned to collect data using the Fundamental Neutron Physics Beamline facility at the SNS: a high-precision search for the neutron EDM and a measurement of the neutron lifetime using magnetically trapped UCNs. These are discussed in detail in other sections of this report. The executive committee for the instrument development team consists of project manager G. L. Greene (Oak Ridge National Laboratory and University of Tennessee, Knoxville) and committee members W. M. Snow, chair, (Indiana University), V. Cianciolo (ORNL), J. D. Bowman (ORNL), J. Doyle (Harvard), C. R. Gould, and P. R. Huffman.

[Huf09] R. R. Huffman *et al.*, TUNL Progress Report, **XLVIII**, 24 (2009).

### 9.3.4 Status of the KURF Low-Background Counting Facility

J. STRAIN, H.O. BACK, P. FINNERTY, R. HENNING, S. MACMULLIN, J.F. WILKERSON, *TUNL*; R.B. VOGELAAR, *Virginia Polytechnic Institute and State University, Blacksburg, VA*; R. LINDSTROM, *National Institute of Standard and Technology, Gaithersburg, MD*

**The Kimballton Underground Research Facility houses a  $\gamma$ -ray counting facility consisting of two HPGe detectors specifically designed for low-background assay work. Counting techniques and sample preparation for  $\gamma$ -ray assay at this facility are discussed.**

#### 9.3.4.1 Introduction to the Facility

The Kimballton Underground Research Facility (KURF) is located about 25 miles from the campus of Virginia Polytechnic and State University in the Chemical Lime Company's Kimballton Mine. The experimental area is located on the 14th level at a depth of 520 m, or approximately 1450 meters of water equivalent shielding. A trailer owned by NRL and operated by UNC/TUNL houses the low-background counting facility.

The facility consists of two HPGe detectors specifically designed for low-background assay work. One detector, "Melissa", is a 1.1 kg, 50% RE (relative efficiency compared to NaI) Canberra LB (low-background) detector. Melissa is oriented vertically and is cooled using a dipstick cryostat. Melissa's shield consists of 15 cm of Doe-run lead and 2.54 cm OFHC (oxygen-free high conductivity) copper. The fwhm at 1.33 MeV is 1.70 keV, and the threshold is  $\sim 20$  keV. The other detector, "VT-1", is a 0.956 kg, 35% RE ORTEC LLB Series detector in a J-type configuration. VT-1's shield consists of a 10.1 cm ORTEC commercial lead shield and 0.3 cm of OFHC copper. VT-1 has a fwhm of 1.80 keV at 1.33 MeV, and the threshold is  $\sim 20$  keV.

The inner cavity of both detectors is continuously purged with dry liquid nitrogen boil-off from a dedicated 30 L dewar, resulting in a reduction in  $^{222}\text{Rn}$  by a factor of approximately 3.5. See Refs. [Mac09] and [Fin10] for a more detailed explanation of background reduction techniques.

#### 9.3.4.2 Sample Preparation

Low-background assay work requires that samples are clean so that unwanted radionuclides are not measured. Therefore samples are prepared beforehand in a cleanroom and properly bagged

for transport to the low-background counting facility in KURF. Depending on the material and the required detection limit, different preparation procedures may be used, including leaching plastics with acid, etching metals with acid, or cleaning with ultra-pure solvents. Samples are then bagged in clean-room nylon that has a low permeability to radon.

Past samples have been prepared in a clean laboratory environment at TUNL that is equipped with a snorkel hood. A cleanroom at UNC is currently under construction (see Fig. 9.36) and is expected to be class 1000 or better. This cleanroom is equipped with a hood, proper air filtration, cleanroom furniture, ultrasonic cleaners, and a high-purity water source producing  $18.2 \text{ M}\Omega\cdot\text{cm}$  water [Str09].



**Figure 9.36:** (Color online) Cleanroom at UNC.

#### 9.3.4.3 Assay Analysis

In May 2010 an object-oriented software program, ORCA, was installed as the data acquisition system for the low-background counting facility at KURF (see Sect. 9.4.4).

A Monte Carlo simulation for each assayed sample is done using MAGE, a GEANT4-based simulation package maintained and developed by a joint group of the MAJORANA and GERDA collaborations [Bau06]. In a simulation, each sample is

uniformly doped with an isotope, particularly isotopes from the  $^{238}\text{U}$ ,  $^{232}\text{Th}$ ,  $^{40}\text{K}$ , and  $^{60}\text{Co}$  decay chains. The  $\gamma$ -rays from these decays are tracked from their emission in the sample to the detector. Figure 9.37 displays a simulation geometry of lead bricks that were assayed.

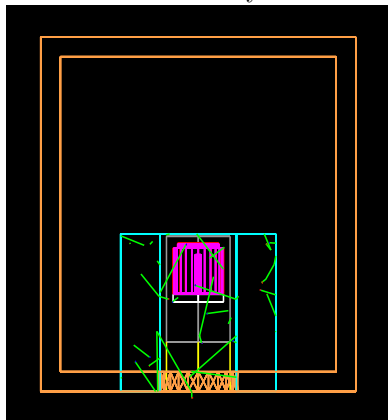


**Figure 9.37:** (Color online) Image of simulation of lead bricks in Melissa.

Using a locally developed ROOT analysis package and Monte Carlo simulations, the absolute peak efficiency for an isotope can be found. The activity of an isotope can then be determined using the equation

$$A_{\gamma} = \frac{N}{\epsilon_{\gamma} m} \quad (9.9)$$

where  $N$  is the net peak area, in units of counts per day, determined by subtracting a background spectrum from the sample spectrum;  $\epsilon_{\gamma}$  is the efficiency; and  $m$  is the mass of the assayed sample. A typical counting time for a sample is two to four weeks. If no statistically significant peak is present for an isotope, an upper limit can be placed on the activity of a sample.

To determine the detectors' sensitivities, a Marinelli beaker, often used for  $\gamma$ -ray assay, was counted in Melissa and VT-1. A MAGE/GEANT4 simulation was done to determine peak efficiencies, and an upper limit was placed on the peaks as previously described. Table 9.2 displays the best detection limits for  $^{40}\text{K}$ ,  $^{238}\text{U}$  and  $^{232}\text{Th}$ . See Ref. [Fin10] for a complete table of the detection limits for  $^{238}\text{U}$  and  $^{232}\text{Th}$ , as well as for a more detailed explanation of the analysis techniques and Monte Carlo validation for KURF's

low-background counting facility.

**Table 9.2: Detector Sensitivities**

| Isotope<br>(Chain)                      | Energy<br>[keV] | Detection Limits [mBq/kg] |      |
|-----------------------------------------|-----------------|---------------------------|------|
|                                         |                 | Melissa                   | VT-1 |
| $^{40}\text{K}$ ( $^{40}\text{K}$ )     | 1461            | 30                        | 90   |
| $^{214}\text{Bi}$ ( $^{238}\text{U}$ )  | 609             | 10                        | 15   |
| $^{212}\text{Pb}$ ( $^{232}\text{Th}$ ) | 238             | 6                         | 10   |

### 9.3.4.4 Conclusions

KURF's low-background counting facility has been in operation and doing assay work for over two years. Assay work done in the last year includes:

- Axon Picocoax®, a possible candidate for making low-background signal cables for the MAJORANA project and other low background experiments.
- Sullivan Lead Bricks, low-background lead bricks that could be possibly used for shielding for the MAJORANA project.
- University of Washington Lead Bricks, low-background lead bricks that could possibly be used for shielding for the MAJORANA project.
- PEEK Plastic, low-background plastic that could possibly be used in the MAJORANA project.

For a complete list of all assay work done and the results see Ref. [Fin10].

Future work, beyond assaying more samples, includes continuous radon monitoring and measuring the total muon, neutron, and  $\gamma$ -ray flux at KURF.

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- [Bau06] M. Bauer *et al.*, J. Phys. Conf. Ser., **39**, 362 (2006).
- [Fin10] P. Finnerty *et al.*, arXiv:nucl-ex/1007.0015, (2010).
- [Mac09] S. MacMullin *et al.*, TUNL Progress Report, **XLVIII**, 155 (2009).
- [Str09] J. Strain *et al.*, TUNL Progress Report, **XLVIII**, 159 (2009).

### 9.3.5 Unfolding Full-Energy Peaks in $\gamma$ -ray Spectra

A.D. HILL, *TUNL*

**A method is developed for spectral unfolding for generic  $\gamma$ -ray detectors in order to determine the energy distribution of 2-15 MeV  $\gamma$ -ray beams, using germanium detectors as an example. It is assumed that the distribution is approximately Gaussian.**

In the analysis of nuclear spectra, it is often critical to determine the energy profile of the incident beam. For example, when calculating reaction cross sections, one must first know the flux of incident  $\gamma$  rays at the resonance energy. Such a beam profile may be generated via spectral unfolding, which involves processing a detected spectrum to find the incident energy distribution. While more complicated, more accurate methods exist, we present a very simple, rough method for the approximation of this incident  $\gamma$ -ray energy profile. This method relies solely on processing the full-energy peaks from zero-degree measurements of  $\gamma$ -ray beams, without respect to beam parameters.

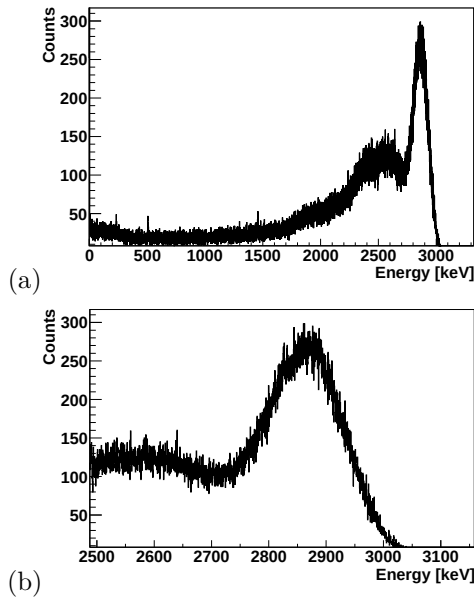


Figure 9.38: (a) Zero-degree  $\gamma$ -ray beam profile observed in the Ge detector, (b) FEP in detail

Due to electronic noise, quantum mechanical effects, and the original beam energy distribution, the full-energy-peak (FEP) energy spectrum will have a nonzero width. Typically, the

fwhm of an incident  $\gamma$ -ray-beam energy distribution, like the beams produced at HI $\gamma$ S, is dominated by the incident distribution. We may therefore assume that the half of the beam-induced FEP above the energy centroid is a reasonable approximation to the upper half of the incident-beam energy distribution; the lower half of the FEP is distorted by the presence of Compton-scattering events (see Fig. 9.38).

In the present method, first the centroid of the FEP is found and all counts below the centroid are removed. Then the remaining counts are mirrored across the centroid, which results in an approximately Gaussian beam profile. This symmetric peak distribution  $I(E)$  may then be adjusted for the detector's response function  $\varepsilon(E)$  to approximate the incident beam flux and energy distribution:

$$\Phi(E) = \frac{I(E)}{\varepsilon(E)}$$

where  $\Phi(E)$  is the beam flux as a function of energy (see Fig. 9.39).

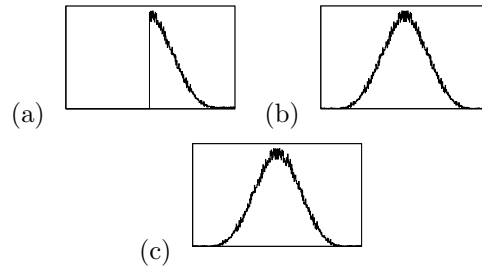


Figure 9.39: Illustration of the unfolding process. (a) The FEP with counts below the centroid removed. (b) The "chopped" FEP mirrored across the centroid. (c) The approximate beam energy distribution after accounting for detector efficiency.

The detector efficiencies were simulated using GEANT4. For this example, efficiency simulations assumed a mono-energetic, infinitely thin beam

striking a virtual detector 2 cm off the detector axis. The generated table of simulated detector efficiencies was queried to obtain the needed values for  $\varepsilon(E)$ . Because it is computationally cumbersome to generate efficiencies for each energy binning scheme one might encounter in a typical data set, energies are rounded to the nearest value given in the data file before querying. In the examples shown, efficiencies were simulated in 100 keV intervals, which ensured that any discrepancies between true efficiencies and their rounded approximations were negligible.

This process produces a spectrum qualitatively similar to a Gaussian distribution, although the resulting isolated peak may be fit with any appropriate function. Figure 9.40 presents a fit composed of two Gaussian distributions, summed and weighted by polynomial factors,

$$f(E) = \frac{ae^{-(\frac{E-E_0}{c})^2}}{\varepsilon(E)} + \frac{b(E-E_0)^2}{\varepsilon(E)}e^{-(\frac{E-E_0}{d})^2},$$

where  $E_0$  represents the centroid energy, and  $\varepsilon(E)$  represents a fit to the calculated or measured detector efficiency. This function raises the tails of the Gaussian distribution, thus more accurately fitting the FEP.

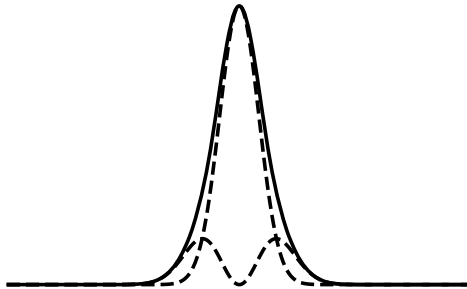


Figure 9.40: Polynomial-weighted Gaussian distributions summed to form a more accurate fitting function.

Using the ROOT data-analysis package, we fit this function to our example data (see Fig. 9.41).

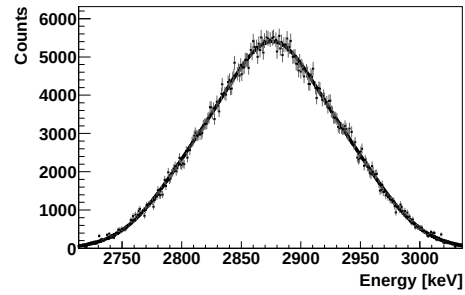


Figure 9.41: A fit of the summed-Gaussian function.

Because the upper and lower halves of the generated FEP are almost symmetric, the fit was only applied to the upper half of the spectrum. The fit shown in Fig. 9.41 has a reduced  $\chi^2_{\text{red}}$  of 0.96. For comparison, a simple Gaussian fit results in a reduced goodness-of-fit statistic of  $\chi^2_{\text{red}} = 1.77$ , indicating that the proposed modification is reasonable for the given data and binning scheme. Major discrepancies between the unfolded spectrum and the fitting function are likely due to misestimations of the error of the unaltered data. For this example, we found the fit parameters to be  $a = 1972 \pm 12$ ,  $b = 0.52 \pm 0.02$ ,  $c = 46.2 \pm 0.8$  keV, and  $d = 64.2 \pm 0.3$  keV, with  $E_0 = 2876.1 \pm 0.2$  keV. Note that these errors correspond to the fitting parameters alone, and the centroid energy may have a higher error carried over from the initial peak-finding routine. (We estimate that the total centroid uncertainty is approximately 25 keV for this example.) Despite this error estimate, there is good agreement between the fitting function and the unfolded incident beam profile.

A program which employs this method of unfolding is freely available upon request.

## 9.4 Data Acquisition Hardware and Software Development

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### 9.4.1 Status of the ORCA Data Acquisition System

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M.A. HOWE, J.F. WILKERSON, *TUNL*; M.G. MARINO, J. KASPER, *University of Washington, Seattle, WA*

**We describe additions and improvements to ORCA, an object-oriented real-time control and acquisition system. ORCA is currently in use in the development of several experiments in the US, Canada, and Germany and is under continuous development. Support for a number of new VME, USB, and serial devices was added, an improved driver for the VME bridge chip on the VME controller single-board computer (SBC) was developed, and the SBC readout software was rewritten in C++.**

The ORCA (Object-oriented Real-time Control and Acquisition) software system [How09] is designed for dynamically building flexible and robust data acquisition systems. ORCA was first used as the data acquisition system for the Sudbury Neutrino Observatory (SNO) Neutral Current Detector (NCD) experiment and successfully took production data continuously for three years until Nov 2006. After the NCD experiment was decommissioned, ORCA was used in an alpha counter to study “hot spots” on the removed NCD tubes, and during the last few months of the SNO experiment it was used in the SNO muon-tracking system. Since then the world-wide base of ORCA systems has continued to grow.

The University of Washington’s (UW) Center for Experimental Nuclear Physics and Astrophysics is using ORCA in several test stands for the development of the pre-spectrometer for KATRIN (the Karlsruhe Tritium Neutrino experiment), the commissioning of the KATRIN main focal-plane detector, the development of the KATRIN veto system, validation of the electronics for the MAJORANA experiment, and some SNO+ development work. The UW radiology department has been using it for several years in the characterization of detectors for a small animal PET scanner.

In Germany, the Karlsruhe Institute of Technology (KIT) is running ORCA in many KATRIN-related hardware development test stands, a tritium source development system, and the KATRIN pre-spectrometer.

UNC has several ORCA test stands running, both on campus and at KURF. Recently two systems have been setup at TUNL.

At SNOlab, the SNO+ and HALO experiments have chosen ORCA as their production

DAQ system and are currently running several development test stands.

There are also ORCA systems running at LANL, LBNL, and MIT.

The catalog of objects supported by ORCA continues to grow. In the last year a number of new VME cards were added.

- CAEN V965/965A 16/8-channel charge-to-digital converter.
- CAEN V775/775N 32/16-channel TDC.
- CAEN V260 Scaler with 16 independent 24-bit counting channels at the maximum input frequency of 100 MHz.
- CAEN V785/785N 32/16-channel peak sensing 12-bit ADC.
- SIS 3800 32-channel 32-bit scaler with a maximum counting frequency of 200 MHz (ECL and NIM) or 100 MHz (TTL), respectively.
- SIS 3820 32-channel 32-bit scaler with a maximum counting frequency of 250 MHz counting rate (ECL and NIM) or 100 MHz (TTL). Only the generic scaler functions are supported at this time.
- SIS 3302 eight-channel digitizer. The version implemented is the Gamma firmware, specifically version 0x1407, which supports a finite-response filter-based triggering, asynchronous readout of raw and/or computed (i.e. energy) digitizer information. It is of particular interest for detector studies with  $\gamma$ -ray tracking and strip detectors.

- SIS 3320 eight-channel 12-bit 250 MHz digitizer (currently in advanced state of development).
- SIS 3350 four-channel 12-bit digitizer, which can sample at up to 500 MSamples/sec.
- VHQ224LHV two-channel 4 kV high voltage supply.
- VHQ4030HV four-channel 3 kV high voltage supply.

The list of newly supported serial devices includes:

- AMRel HV. Both one and two channel versions are supported.
- A Varian turbo-pump system controller.
- iTrans Modbus Oxygen Sensor.
- KJL Ion Gauge Controller.
- CC4189 Temperature/Humidity Sensor.
- MKS PDR2000 controller for reading out two Baratron pressure sensors.
- Ami 286 cryogenic level controller. This device has been supported for more than a year, but a number of improvements and alarm handling functions were recently added.
- A variant of the MIT custom pulser, with a different range, was added.

For the KATRIN experiment, the version 4 first- and second-level-trigger (FLT and SLT) electronics were finished and delivered to UNC for testing. After ORCA support for the SLT and FLT cards was completed and verified, the electronics were shipped to UW to be used in the final commissioning of the KATRIN detector. Recently an additional four FLTs and one SLT, along with a mini-crate were sent from KIT to UNC for further software testing and verification. ORCA support of the KATRIN version 4 hardware is now considered essentially complete, pending any new issues discovered at UW.

For the SNO+ experiment, support for a totally new SNO crate controller/readout card

was added to ORCA. This card, the XL3, replaces the XL2 crate controllers used in the original SNO experiment. These field-programmable, gate array-based controllers communicate directly with ORCA over sockets using TPC/IP. The XL3 cards read out of each of the SNO crates and stream all data back to ORCA for storage, monitoring, and re-broadcast to an event builder.

Major experiments such as KATRIN, MAJORANA, and HALO need specially developed high-level dialogs to ease the burden on the experiment's operators. New dialogs were added for HALO and MAJORANA. These dialogs collect and display information, such as channel-by-channel rates and total rate over time, in one place so that the state of an experiment can be monitored from one dialog. They also provide an interface for mapping detector channels to electronics channels. The existing dialog for the KATRIN experiment was also improved to include system pre-amp and crate-level views.

ORCA supports the use of LINUX-based single board computers (SBCs) as crate controllers for VME, cPCI, and IPE crates. The code that executes on these boards is managed by ORCA, thus providing the transparent use of SBCs for data read-out. This read-out code was originally written completely in C. In 2009 it was completely rewritten in C++ to be fully object oriented. It was also refactored to put each of the device-read-out functions into separate files and thus into separate objects. It is now much easier to extend the code and to add support for new objects.

The SBCs use a Universe II VME bridge chip to provide access to VME address space. The original driver was somewhat limited, in that it did not support DMA access. This driver was completely rewritten and now supports DMA and block-level transfers. The original software programming interface was retained.

A secondary application to ORCA, called ORCAROOT, provides a tool kit to build analysis programs that can decode raw ORCA data streams. As new objects are added to ORCA, new decoders are also added to ORCAROOT to fully support ROOT analysis of data from the new objects.

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[How09] Howe, M. A. *et al.*, TUNL Progress Report, **XLVIII**, 179 (2009).

### 9.4.2 IORCA, An iPad-based DAQ monitoring Tool

M.A. HOWE, J.F. WILKERSON, *TUNL*

**IORCA is a mobile data-acquisition monitoring tool hosted on the iPad platform. Information that is to be monitored is placed into an SQL (structured query language) database by participating DAQ applications such as ORCA. It can then be retrieved using web-based URL queries. Each query triggers a PHP script that returns the result in XML (extensible markup language) format. IORCA stores the result and displays it as needed. Multiple data-acquisition systems can be monitored by multiple IORCA applications simultaneously.**

With the introduction of highly mobile computing and display devices, such as Apple's iPhone and iPad, hand-held remote data acquisition monitoring and control tools have suddenly become practical. One such application, IORCA (iPad-ORCA), has been developed at UNC for the iPad. IORCA is designed as a mobile link between remote users and ORCA data-acquisition systems (described in Sect. 9.4.1). It is written in Objective-C for the iOS operating system using the Cocoa and iTouch software frameworks. The application design is object-oriented and highly modular, making the addition of new features relatively simple. IORCA is currently available only for the iPad, although it will probably be possible to provide a stripped-down version for the iPhone. IORCA is only available direct from the UNC developers on an iPad-by-iPad basis using Apple's ad hoc distribution system. For security reasons, there are no plans for distribution via the Apple Store.

IORCA is designed around web-based access to a central data repository in the form of a MySQL database that is populated by ORCA systems. Each iPad running IORCA can monitor many ORCAs but each ORCA must individually opt-in to be monitored. This is done by including a special SQL object into the ORCA configuration. If it is present and configured with the proper database location, username, and password, then the monitored parameters are collected, organized into groups, and inserted into the proper database tables. There is one table for the list of all running ORCA systems, one for 1D histograms, one for run status, etc. Each table is predefined when the database is set up, and the format is known to the ORCA SQL object. For example, the table holding run status holds all information associated with the current run state. A partial listing of that table is:

| Field      | Type        |
|------------|-------------|
| run_id     | int(11)     |
| machine_id | int(11)     |
| runNumber  | int(11)     |
| state      | int(11)     |
| experiment | varchar(64) |
| started    | varchar(64) |
| ...        | ...         |
| timeLimit  | int(11)     |
| repeatRun  | tinyint(1)  |

The key that links all the tables is a machine identifier, which is, in turn, linked to the MAC ethernet address of each computer running ORCA. By using a particular MAC address, the identifier key for that system can be retrieved from the main table holding all machines, and an SQL query can be constructed to extract data from any table or combination of tables.

Queries to the database are done via a web-site PHP hypertext-preprocessor script that takes an SQL select command and a tag as a parameter. For example, a URL to retrieve data from the run status table would be something like:

```
http://.../queryXML ? tag=runstatus &
query = select * from runs where
machine_id = 12
```

where the ellipsis is replaced with a path to the web site holding the query XML script. The query script can process only one generic 'select'-type query at a time, and any attempt to execute multiple commands or other types of commands is rejected, in order to help prevent SQL injection attacks. Valid queries are sent to the SQL server, and the response is formatted into XML and returned to IORCA. The final XML packet from the

above query example would look something like the following:

```
<?xml version="1.0"?>
<runstatus>
  <run_id> 8 </run_id>
  <machine_id> 12 </machine_id>
  <run> 2413 </run>
  <subrun> 0 </subrun>
  <state> 1 </state>
  <experiment> Katrin </experiment>
  <started> 72010 11:48:15 </started>
  .. truncated for brevity ..
  <timeLimit>0</timeLimit>
  <repeatRun>0</repeatRun>
</runstatus>
```

IORCA does not use the XML directly but converts it into standard iOS dictionary objects, where each data item is stored locally with a key that is the same as the tag associated with the data field. Knowing the tag value and the data keys, each display in IORCA can extract whatever data are needed for a particular page. Each display page is refreshed whenever a query is returned from the database. The query rate is variable but typically on the order of once every two seconds. The round trip time for a query depends on the network but is generally a few tens of milliseconds. The total bandwidth required is limited by having IORCA request only the data that are needed for a particular display.

The user interface in IORCA is arranged around a series of display pages. The pages that are currently defined include the following:

- Database Setup: Here the user sets the access path for the database and the PHP query script.
- System Statistics: Displays a query-and-response timing histogram and total access counts. Useful for debugging.
- System List: A list of all participating ORCA systems connected to a database.

Once a system is selected on this page, it is the working system for all other displays.

- Summary Page: Shows a summary of run status and a list of all ORCA alarms. Also provides links to the data list, control pages, and the experiment-specific page.
- Data List: Shows a list of all available histogram data being accumulated. Also provides a link to the plot page.
- Plot Page: Displays a particular histogram.
- Run Control: Provides access to ORCA's run control functions. Password protected.
- Command Center: Allows execution of an arbitrary command via ORCA's command center. Password protected.
- Experiment Specific: Different for each experiment. For example, the KATRIN display shows information associated with the main focal plane detector.

In addition to displaying information, IORCA has some control functions. This is accomplished via a direct socket connection into ORCA's command center. The socket is opened only when a page that uses this facility is visible; otherwise it is closed. The control pages are protected with each IORCA's expert function password. The most extensive use of the control functionality is on the run-control page, where users can remotely operate all of ORCA's run control functions. There is also a generic command page that allows the input of Objective-C commands into the ORCA command center. A user with knowledge of Objective-C and ORCA's internals can execute almost any method in the ORCA code base.

IORCA has so far been a test of what kind of functionality would be desirable in a mobile monitoring and control application. As it is refined and new functionality is added, it is anticipated that it could find a place in monitoring major experiments such as KATRIN and MAJORANA.

### 9.4.3 Validation and Characterization of the KATRIN DAQ Electronics System

D.G. PHILLIPS II, T.J. CORONA, M.A. HOWE, J.F. WILKERSON, *TUNL*; T. BERGMANN, A. KOPMANN, *Karlsruhe Institute of Technology - Institute for Data Processing and Electronics, Karlsruhe, Germany*

**This report describes characterization and validation studies performed on the hardware and software data acquisition (DAQ) systems of the KATRIN experiment. It also describes script development for the characterization and validation studies, which has been made possible using ORCA's scripting language known as ORCAScript.**

A next generation tritium  $\beta$ -decay experiment known as the Karlsruhe TRitium Neutrino (KATRIN) experiment is currently under construction at the Forschungszentrum Karlsruhe campus of the Karlsruhe Institute of Technology (KIT). Electronics systems developed at KIT's Institute of Data Processing and Electronics (IPE) [Kop08] will serve as readout for the 148-pixel detector and the 32-channel veto system. The data acquisition software utilized by the KATRIN experiment is a Mac OS X application called ORCA (Object-oriented Real-time Control and Acquisition) [How08]. A block diagram of the data flow in the KATRIN experiment is given in Fig. 1.

A wide range of event rates will be expected in the KATRIN experiment, where the normal background rate will be as low as 10 mHz and the calibration rate will be as high as 1 MHz. One key point of validation is to verify that the KATRIN DAQ system can handle this wide range of data rates. With production data taking set to begin in 2012, a thorough characterization and validation of the KATRIN DAQ system is needed. This task will be completed by the TUNL group. A brief list of the hardware and software that is undergoing tests includes the following:

- **DAQ Hardware:** The field-programmable-gate-array (FPGA)-based electronics systems are each divided into a second level trigger (SLT) card and a group of first level trigger (FLT) cards. The SLT card serves as the controller and module for readout of the FLT cards. In the earlier Mark 3 (Mk3) version, the FLT cards had an ADC sample rate of 10 MHz with a precision of 12 bits [Wil09]. The FPGAs on

the current Mark 4 (Mk4) FLT card version that will be used in the experiment have a larger memory than their Mk3 counterparts. This allows for all DAQ modes to be available without reprogramming the card. Each Mk4 FLT cards has 24 channels (ADCs), which is two more ADCs than the Mk3 FLT card. Data can be acquired from the Mk4 FLT cards in single-event mode (energy and time stamp), waveform mode (digitized signal) or histogramming mode (energy histograms for each channel). The ADCs in the Mk4 FLT cards can sample at 20 MHz (14 bits), and the histograms in histogram mode have increased from 512 bins to 2048 bins, where each bin is 32 bits (vs. the Mk3 value of 24 bits). The Mk4 SLT cards have been upgraded to contain a single-board computer running LINUX (OpenSUSE version 10.3).

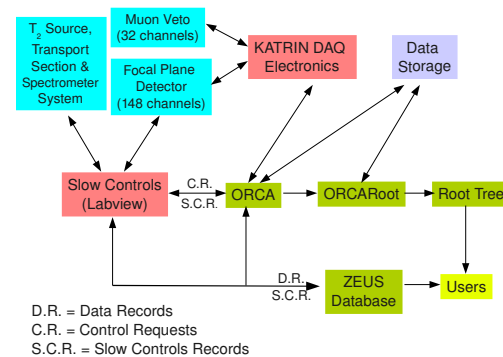


**Figure 9.42: (Color online) KATRIN data flow.**

- **DAQ Software:** ORCA software is used to control and acquire data from the IPE's FPGA-based electronics. ORCA uses

software-bus concepts to encapsulate hardware objects and data-acquisition concepts into software objects that have user-friendly graphical interfaces. In addition to the hardware used in the KATRIN validation and characterization tests, ORCA provides control to a large number of other hardware devices. An experimental setup is assembled in ORCA's interface and dynamically configured at runtime, without any re-compilation of ORCA required. Extensive software validation of all KATRIN's required objects is on-going.

- *DAQ Scripting Languages:* ORCA contains two C-like scripting languages [How09]. The first is a C-like language with ObjectiveC extensions called ORCAScript. The ORCAScript language can access any software method in the ORCA code base, thus allowing for full automation of any object within ORCA. The other C-like scripting language, FilterScript, can be used to construct data-filtering and event-building routines within ORCA.
- *Mk4 Linearity Testing:* A characterization of the linearity of the Mk4 ADCs has been performed to determine whether they meet the accuracy needed by the KATRIN experiment for energy measurements. Encouraging results from linearity testing reveal a low integral non-linearity ranging from 0.01% to 0.04% across a sample of 110 Mk4 ADCs. ORCAScript was used to automate all of the validation and characterization studies, which in itself constitutes a rigorous test of the scripting languages.
- *Mk4 Stability Testing:* The long-term single-channel stability of the Mk4 DAQ system has been measured over a period of six days. By pulsing individual channels with KATRIN-signal-like pin-diode waveforms, the Gaussian mean of the resultant energy spectrum has been shown to vary by only  $\pm 2\%$ . This result is well within KATRIN's requirements. Long-term tests using multiple channels under realistic conditions are presently being performed.
- *Mk4 Efficiency Testing:* Characterization of the dead time in each DAQ measurement mode must be made in order to deduce the event rate at which counting efficiency of the Mk4 electronics drops below nominal. Tests carried out on single Mk4 FLT channels using random pin-diode pulses with a decay time of  $8\ \mu\text{s}$  have shown that the counting efficiency drops below 100% at 375 Hz for waveform mode. A similar test performed in single-event mode showed that the counting efficiency drops below 100% at 68 KHz using random pin-diode pulses with a decay time of  $2\ \mu\text{s}$ . A more thorough study using multiple channels and KATRIN-like pin-diode pulses with a decay time of  $400\ \mu\text{s}$  is currently underway.
- *Future Testing:* Many tests will be performed in the coming months to complete the validation and characterization of the Mk4 DAQ system. Evaluation of correct functionality between the Mk4 histogramming-mode software and hardware will be completed to ensure that histogramming is fully functional and available for periods of high data rates. A comparison of the Mk4 hardware trapezoidal filter algorithm (TFA) with a software filter will be made to determine whether the TFA is functioning as expected. Cross-talk between FLT channels will also be evaluated.

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[How08] M. Howe, M. Marino, and J. F. Wilkerson, IEEE Nucl. Sci. Symp. Conf. Rec., **NSS '08**, 3562 (2008).

[How09] M. Howe *et al.*, TUNL Progress Report, **XLVIII**, 178 (2009).

[Kop08] A. Kopmann *et al.*, IEEE Nucl. Sci. Symp. Conf. Rec., **NSS '08**, 3186 (2008).

[Wil09] J. Wilkerson *et al.*, TUNL Progress Report, **XLVIII**, 38 (2009).

#### 9.4.4 Installation and Commissioning of the MALBEK Low-Background BEGe Detector Data Acquisition System

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**We describe the current status of the data-acquisition system for the MAJORANA low-background BEGe detector at the Kimballton Underground Research Facility, as well as the progress we have made in evaluating waveform digitizers for use with the MAJORANA DEMONSTRATOR.**

As part of the research and development efforts of the MAJORANA collaboration (see Sect. 2.1.1), we have deployed a prototype 450g broad-energy germanium (BEGe) detector at the Kimballton Underground Research Facility (KURF) in Ripplemeade, VA. The MAJORANA low-background broad-energy germanium detector at KURF (MALBEK) will investigate point-contact, modified BEGe detector performance, explore the sub-keV energy spectrum in a search for light weakly interacting massive particles (WIMPs), and serve as a test-bed for electronics, software, and data analysis techniques for the MAJORANA DEMONSTRATOR (see Sects. 2.1.5 and 2.1.6).

After initial detector characterization and testing, we installed the MALBEK detector and data acquisition system underground at KURF in January 2010. The MALBEK data acquisition system uses the Object-oriented Real-time Control and Acquisition (ORCA) system, an object-oriented data-acquisition application that provides an easy-to-use, graphical interface for manipulation of experimental hardware and data streams (see Sect. 9.4.1). The ORCA-managed slow control system is used to control the detector and to monitor the detector environment. The high voltage bias for MALBEK is provided by a VME based iseg VHQ224L module allowing remote voltage and current monitoring and control. Another iseg VME bias supply, the 12 channel VHSC020, will be used for the active muon-veto photomultiplier tubes. Liquid nitrogen levels in the MALBEK detector dewar and the radon purge system's nitrogen boil-off dewar are monitored and controlled remotely using an American Magnetics 286 multi-channel liquid level controller. Seismic monitoring to veto microphonic induced signals in the detector is done using a GLI Interactive motion node. Seis-

mic data from vibrations exceeding a user-defined value are inserted into the data stream for off-line analysis. Oxygen levels in the trailer housing the MALBEK detector and the trailer housing the DAQ electronics and computer are monitored by iTrans gas monitors. Excursions from atmospheric concentrations of oxygen sound a local audible alarm and an email notification. All of these systems have been running stably since installation.

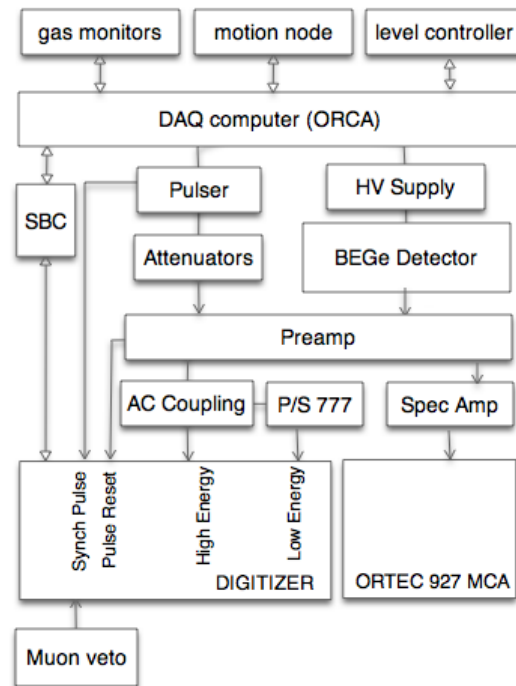


Figure 9.43: Block diagram of the MALBEK DAQ

For fast DAQ, two different VME-based digitizers have been used to collect the analog signals from the MALBEK low-noise, pulse-reset, charge-sensitive preamplifier and the active muon

veto. Both are candidates for use with the MAJORANA DEMONSTRATOR. The Struck Innovative Systeme 3302 ADC is a VME-based, 8 channel, 16-bit digitizer capable of digitization rates up to 100 MHz. The SIS3302 incorporates both a fast finite impulse response (FIR) trapezoidal triggering filter capable of triggering on low amplitude signals and a slow FIR trapezoidal filter for determining signal height. The SIS3302 supports data readout in parallel with acquisition and signal decimation. The Gretina Mark IV is a 10 channel, 14 bit digitizer and digital signal processing board developed for the Gamma Ray Energy Tracking In-Beam Nuclear Array (GRETINA) [And07]. The Mark IV uses a leading-edge-discriminator trigger and has a built-in trapezoidal energy filter. An analog spectroscopy amplifier and an Ortec 927 MCA are used to collect energy spectra.

ORCA provides a catalog of fully encapsulated objects representing hardware, data-readout tasks, data analysis modules, and control modules. The ORCA data stream can be monitored in real time using ORCA's data monitoring object. In addition, by using ORCAScript (a small interpreted programming language) operators can implement data-stream filtering and real-time event building and data plotting. ORCAScript also allows for the automation of run control and run-time experimental parameters. ORCA is self-monitoring, sending email notification and alarms to operators based on user-configurable preferences.

During a run, data readout from the VME bus is performed by a Concurrent Technologies single board computer that interfaces directly with the data acquisition computer. Digitized waveforms are filtered in real time using ORCAScript to eliminate noise events related to preamplifier resets, thus reducing the size of data files saved to disk. Another ORCAScript continuously polls the liquid nitrogen levels of the detector dewar and the status of the other slow control systems so as to safely unbiased the detector in the event of a prolonged power failure or an increase in detector temperature.

In order to periodically test the trigger efficiency of the digitizers and the gain stability of the DAQ, an Agilent 33220A arbitrary waveform generator coupled to a set of step attenuators is used to generate test signals of varying amplitude and shape at the input of the preamplifier. This is patterned on a system implemented by the University of Washington at the Soudan Underground Laboratory. The waveform generator interfaces with the data acquisition computer via USB-2.0. The step attenuators can be controlled via an Acromag IP408 I/O module, a 32-channel digital input/output module mounted on an Acromag AVME 9630 Carrier Board that transfers signals between the IP408 and the SBC controlled VME bus. An ORCAScript automates this process, varying test pulse sizes and rise times to determine the trigger efficiency of the digitizers down to sub-keV energies and for event rise times as fast as 350 ns. These trigger-efficiency studies are used to determine the ability of the digitizers to meet the DEMONSTRATOR low-energy physics goals.

The MALBEK DAQ was installed in January 2010 and has been taking data with the SIS3302 since March. After initial data runs with the card, we recognized several bugs in ORCA related to data readout and card triggering, as well as a limitation in the length of the pre-trigger waveform the card can digitize. This hindered the performance of offline energy calculations. We have now fixed these ORCA problems and are working with engineers at Struck Innovative Systeme to increase the length of the SIS3302 pre-trigger delay. We are also in contact with the Gretina engineers, requesting that they implement a fast trapezoidal filter to improve the Gretina digitizer's low-energy triggering. The MALBEK DAQ is currently taking data at KURF where we continue our evaluation of the SIS3302 and the Gretina Mark IV digitizer.

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[And07] J. T. Anderson *et al.*, In *Nuclear Science Symposium Conference Record, NSS '07. IEEE*, p. 1751, 2007.

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### 9.4.5 Characterization of DAQ Hardware for the HALO Experiment

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T.J. CORONA, M. HOWE, N. MYKINS, J.F. WILKERSON, *TUNL*

**The Helium and Lead Observatory is a supernova neutrino detector in development at SNO-LAB, a deep-underground laboratory located near Sudbury, Ontario. Signals will be read out using  $^3\text{He}$  detectors previously developed for the SNO neutral-current detectors. The modules include custom VME shaping-discriminating-ADC boards used in tandem with a custom VME trigger board. Configuration and characterization of these boards has been completed.**

The signal readout system for the Helium And Lead Observatory (HALO) consists of custom-built 8-channel shaper/ADC boards and custom-built trigger boards, designed for use in a standard 6U VME crate. The shaper/ADC boards will read out signals sent from the  $^3\text{He}$  proportional detectors. A custom-built trigger card will be used to attach a time-stamp to events and to lock and unlock channels for data taking.

The shaper/ADC boards were originally designed and built at the University of Washington (UW) for use in the emiT, SNO and KATRIN experiments. Each channel has its own gain and level discriminator and has a sample-and-hold ADC allowing the energy of input pulses to be determined. The boards are designed for data readout and parameter switching via Object-oriented Real-time Control and Acquisition (ORCA), a data acquisition program (see Sect. 9.4.1).

The shaper/ADC boards can be configured to operate in two modes: continuous and multi-board. During continuous mode, each channel

reads in and digitizes a signal independent of the other channels on the board. In multi-board mode, once a single channel reads in a signal, it locks out the other channels until the data is released from the card by the ORCA system. When used with the custom-built trigger card, multiple shaper/ADC boards can operate in multi-board mode as though all of the channels were on one board; a lock-out signal from a single channel will prevent all of the channels from all of the boards from acquiring data until the lock-out signal is released by ORCA. This allows unique time stamping of each event.

Characterization and testing of the shaper/ADC boards in both continuous and multi-board mode has been completed. The linearity and gain testing on each channel of every card has been performed, the sensitivity of the individual cards to pulses with different rise-times has been determined, and general testing of each card's inhibit logic has been accomplished.





# Appendices

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- Graduate Degrees Awarded
- Publications
- Invited Talks, Seminars, and Colloquia
- Professional Service Activities

## A.1 Graduate Degrees Awarded

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### Ph.D. Degrees

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1. Changchun Sun, *Characterizations and Diagnostics of Compton Light Source*, Duke University, November 2009,  
*Supervisor*: Y.K. Wu.
2. Andrii Chyzh, *Neutron Capture Measurements on  $^{157}\text{Gd}$  and  $^{89}\text{Y}$  at DANCE*, North Carolina State University, December 2009,  
*Supervisor*: G.E. Mitchell.
3. Peter F. Bertone, *Indirect Approaches to Constraining the Best Estimate of the Astrophysical  $S$ -factor for Proton Radiative Capture on  $^{14}\text{N}$* , University of North Carolina at Chapel Hill, December 2009,  
*Supervisor*: A.E. Champagne.
4. Joe Newton, *Hydrogen Burning of  $^{17}\text{O}$* , University of North Carolina at Chapel Hill, December 2009,  
*Supervisor*: C. Iliadis.
5. Jianfeng Zhang, *Study on Beam Polarization and its Applications on Electron Storage Ring*, University of Science and Technology of China, December 2009,  
*Supervisors*: Y.K. Wu (Duke), H. Xu (USTC), A.W. Chao (SLAC).
6. Michelle L. Leber, *Monte Carlo Calculations of the Intrinsic Detector Backgrounds for the Karlsruhe Tritium Neutrino Experiment*, University of Washington, December 2009,  
*Supervisor*: J.F. Wilkerson.
7. Wei Chen, *A Measurement of the Differential Cross Section for the Reaction  $\gamma n \rightarrow \pi^- p$  from Deuterium*, Duke University, February 2010,  
*Supervisor*: H. Gao.
8. Xing Zong, *First Study of Three-body Photodisintegration of  $^3\text{He}$  with Double Polarizations at HI $\gamma$ S*, Duke University, February 2010,  
*Supervisor*: H. Gao.
9. Mary F. Kidd, *Double-Beta Decay of  $^{150}\text{Nd}$  to Excited Final States*, Duke University, March 2010,  
*Supervisor*: W. Tornow.
10. Christopher O'Shaughnessy, *Development of a Precision Neutron Lifetime Measurement: Magnetic Trapping of Ultracold Neutrons*, North Carolina State University, April 2010,  
*Supervisor*: P. Huffman.
11. Bayarbadrakh Baramsai, *Neutron Capture Reactions on Gadolinium Isotopes*, North Carolina State University, May 2010,  
*Supervisors*: G.E. Mitchell and U. Agvaanluvsan.
12. Richard Longland, *Investigation of  $s$ -process Neutron Source  $^{22}\text{Ne}^{+\alpha}$* , University of North Carolina at Chapel Hill, May 2010,  
*Supervisor*: C. Iliadis.

13. Brent A. Perdue, *Measurements of the Absolute Cross Section of the Three-Body Photodisintegration of  $^3\text{He}$  Between  $E_\gamma=11.4$  MeV and 14.7 MeV at HI $\gamma$ S*,  
Duke University, July 2010,  
*Supervisor:* H.R. Weller.
14. Xin Qian, *Measurement of Single Spin Asymmetry in  $n^\uparrow(e, e'\pi^\pm)X$  on Transversely Polarized  $^3\text{He}$* ,  
Duke University, September 2010,  
*Supervisor:* H. Gao.

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### M.S. and M.A. Degrees

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1. Sean Patrick MacMullin, *Background Reduction and Detector Characterization at the KURF Low-Background Counting Facility*,  
University of North Carolina at Chapel Hill, August 2009,  
*Supervisor:* R. Henning.
2. David Ticehurst, *Development of a Gd-loaded Neutron Detector*,  
University of North Carolina at Chapel Hill, December 2009,  
*Supervisor:* H.J. Karwowski.
3. Chris Cottrell, *Deuterium Source Development at the PULSTAR Reactor*,  
North Carolina State University, December 2009,  
*Supervisor:* A. R. Young.

## A.2 Publications

The publications co-authored by members of TUNL research groups between September 2009 and August 2010 are tabulated in Table A.1. The papers in refereed journals by TUNL research groups are listed below in chronological order.

| Type                         | No. |
|------------------------------|-----|
| Refereed Journal Papers      | 47  |
| Conference Proceeding Papers | 18  |

**Table A.1: Summary of TUNL publications from September 2009 through August 2010. Among 47 refereed journal papers, 5 were letters.**

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### Journal Articles Published

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1. *Chiral Dynamics in Photo-Pion Physics: Theory, Experiment, and Future Studies at the HI $\gamma$ S Facility*, A. M. Bernstein, M. W. Ahmed, S. Stave, Y. K. Wu, *Annu. Rev. Nucl. Part. Sci.*, **59**, 115-144 (2009).
2. *Competition Between Excited Core States and  $1\hbar\omega$  Single-Particle Excitations at Comparable Energies in  $^{207}\text{Pb}$  from Photon Scattering*, N. Pietralla, T. C. Li, M. Fritzsche, M. W. Ahmed, T. Ahn, A. Costin, J. Enders, J. Li, S. Müller, P. von Neumann-Cosel, I. V. Pinayev, V. Yu. Ponomarev, D. Savran, A. P. Tonchev, W. Tornow, H. R. Weller, V. Werner, Y. K. Wu, and A. Zilges, *Phys. Lett. B*, **681**, 134-138 (2009).
3. *Direct Measurements of  $(p, \gamma)$  Cross-Sections at Astrophysical Energies Using Radioactive Beams and the Daresbury Recoil Separator*, D. W. Bardayan, K. A. Chipps, R. P. Fitzgerald, J. C. Blackmon, K. Y. Chae, A. E. Champagne, U. Greife, R. Hatarik, R. L. Kozub, C. Matei, B. H. Moazen, C. D. Nesaraja, S. D. Pain, W. A. Peters, S. T. Pittman, J. F. Shriner, Jr., and M. S. Smith, *Eur. Phys. J. A*, **42**, 457, (2009).
4. *Investigation of Solid D-2, O-2, and CD $_4$  for Ultracold Neutron Production*, F. Atchison, B. Blau, K. Bodek, B. van den Brandt, T. Brys, M. Daum, P. Fierlinger, A. Frei, P. Geltenbort, P. Hautle, R. Henneck, S. Heule, A. Holley, M. Kasprzak, K. Kirch, A. Knecht, J. A. Konter, M. Kuzniak, C.-Y. Liu, C. L. Morris, A. Pichlmeaier, C. Plonka, Y. Pokotilovski, A. Saunders, Y. Shin, D. Tortorella, M. Wohlmuther, A. R. Young, J. Zejma, G. Zsigmond, *Nucl. Instrum. and Methods in Phys. Res. A*, **611**, 252-255 (2009).
5. *Measurement of the Cosmic Ray and Neutrino-induced Muon Flux at the Sudbury Neutrino Observatory*, B. Aharmim *et al.* [SNO Collaboration including M.A. Howe and J.F. Wilkerson], *Phys. Rev. D*, **80**, 012001, (2009).
6. *Measurement of the Neutrino-spin Correlation Parameter  $\gamma$  in Neutron Decay Using Ultracold Neutrons*, W. S. Wilburn, V. Cirigliano, A. Klein, M. F. Makela, P. L. McGaughey, C. L. Morris, J. Ramsey, A. Salas-Bacci, A. Saunders, L. J. Broussard, and A. R. Young, *Revista Mexicana de Física Suplemento* 55, 119 (2009).
7. *Measurement of the Solar Neutrino Capture Rate with Gallium Metal. III. Results for the 2002/2007 Data-taking Period*, J. N. Abdurashitov *et al.* [SAGE Collaboration including J.F. Wilkerson], *Phys. Rev. C*, **80**, 015807, (2009).
8. *Nab: Measurement Principles, Apparatus and Uncertainties*, D. Pocanic, R. Alarcon, L. P. Alonzi, S. Baessler, S. Balascula, J. D. Bowman, M. A. Bychkov, J. Byrne, J. R. Calarco, V. Cianciolo, C. Crawford, E. Friez, M. T. Gericke, G. L. Greene, R. K. Grzywacz, V. Gudkov, F. W. Hersman, A. Klein, J. Martin, S. A. Page, A. Palladino, S. I. Pentilla, K. P. Rykaczewski, W. S. Wilburn, A. R. Young, G. R. Young, *Nucl. Instrum. and Meth. in Phys. Res. A*, **611**, 211-215 (2009).

9. *New Measurements of the European Muon Collaboration Effect in Very Light Nuclei*, J. Seely *et al.* (including D. Dutta, H. Gao, X. Qian, S. Tajima, and X. Zheng, Phys. Rev. Lett. **103**, 202301, (2009).
10. *Photoexcitation of Astrophysically Important States in  $^{26}\text{Mg}$* , R. Longland, C. Iliadis, G. Rusev, A. P. Tonchev, R. J. deBoer, J. Görres, and M. Wiescher, Phys. Rev. C, **80**, 055803 (2009).
11. *Reconstruction of a Radiation Point Sources Radial Location Using Goodness-of-Fit Test on Spectra Obtained from an HPGe Detector*, L. T. Evans, K. Andre, R. De, R. Henning, and E. D. Morgan, Nucl. Instrum. Methods B, **267**, 3688, (2009).
12. *The BLAST Experiment*, D. Hasell, *et al.* (including D. Dutta, and H. Gao), Nucl. Instrum. Methods A, **603**, 247-262, (2009).
13. *The Extraction of  $\phi - N$  Total Cross Section from  $d(\gamma, pK^+K^-)n$* , X. Qian, W. Chen, H. Gao, *et al.*, Phys. Lett. B, **680**, 417, (2009).
14. *The KamLAND Full-Volume Calibration System*, B. E. Berger *et al.* (KamLAND Collaboration including W. Tornow, H. J. Karwowski, and D. M. Markoff), JINST, **4**, P04017 (2009).
15. *Transmission-based Detection of Nuclides with Nuclear Resonance Fluorescence Using a Quasi-monoenergetic Photon Source*, C. A. Hagmann, J. M. Hall, M. S. Johnson, D. P. McNabb, J. H. Kelley, C. Huibregtse, E. Kwan, G. Rusev, and A. P. Tonchev, J. Appl. Phys., **106**, 084901 (2009).
16. *Water Cooled, In-cavity Apertures for High Power Operation of FEL Oscillators*, S. Huang, J. Li, Y. K. Wu, Nucl. Instrum. Methods A, **606**, 762-769, (2009).
17. *Measuring the Neutron Lifetime Using Magnetically Trapped Neutrons*, C.M. O'Shaughnessy, R. Golub, K.W. Schelhammer, P.R. Huffman *et al.*, Nucl. Instrum. Methods A, **611**, 171-175 (2009).
18. *Experimental Searches for the Neutron Electric Dipole Moment*, S.K. Lamoreaux and R. Golub, J. Phys. G **36**, 104002 (2009).
19. *A High Pressure Polarized  $^3\text{He}$  Gas Target for the High Intensity Gamma Source Facility at the Duke Free Electron Laser Laboratory*, Q. Ye, G. Laskaris, W. Chen, H. Gao, W. Zheng, X. Zong, T. Averett, G. D. Cates, W. A. Tobias, Eur. Phys. J. A, **44**, 55, (2010).
20. *Charged-particle Thermonuclear Reaction Rates: I. Monte Carlo Method and Statistical Distributions*, R. Longland, C. Iliadis, A. E. Champagne, J. R. Newton, C. Ugalde, A. Coc, and R. Fitzgerald, Nucl. Phys. A, **841**, 1-30, (2010).
21. *Charged-particle Thermonuclear Reaction Rates: II. Tables and Graphs of Reaction Rates and Probability Density Functions*, C. Iliadis, R. Longland, A. E. Champagne, A. Coc, and R. Fitzgerald, Nucl. Phys. A, **841**, 31-250, (2010).
22. *Charged-particle Thermonuclear Reaction Rates: III. Nuclear Physics Input*, C. Iliadis, R. Longland, A. E. Champagne, and A. Coc, Nucl. Phys. A, **841**, 251-322, (2010).
23. *Charged-particle Thermonuclear Reaction Rates: IV. Comparison to Previous Work*, C. Iliadis, R. Longland, A. E. Champagne, and A. Coc, Nucl. Phys. A, **841**, 323-388, (2010).
24. *Corrections for the Polarization Dependent Efficiency and New Neutron-proton Analyzing Power Data at 7.6 MeV*, G. J. Weisel, R. T. Braun, and W. Tornow, Phys. Rev. C, **82**, 027001 (2010).
25. *Determination of the E1 Component of the Low-Energy  $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$  Cross Section*, X. D. Tang, K. E. Rehm, C. R. Ahamd, C. Brune, A. E. Champagne, J. P. Greene, A. Hecht, D. J. Henderson, R. V. F. Janssens, C. L. Jiang, L. Jisonna, D. Kahl, E. F. Moore, M. Notani, R. C. Pardo, N. Patel, M. Paul, G. Savard, J. P. Schiffer, R. E. Segel, S. Sinha, and A. H. Wuosmaa, Phys. Rev. C, **81**, 045809, (2010).

26. *Differential Cross Section for Neutron Scattering from  $^{209}\text{Bi}$  at 37 MeV and the Weak Particle-core Coupling*, Z. Zhou, X. Ruan, Y. Du, B. Qi, H. Tang, H. Xia, R. L. Walter, R. L. Braun, C. R. Howell, W. Tornow, G. J. Weisel, M. Dupuis, J. P. Delaroache, Z. Chen, Z. Chen, Y. Chen, Phys. Rev. C, **82**, 024601, (2010).
27. *Dipole Strength in  $^{139}\text{La}$  Below the Neutron-separation Energy*, A. Makinaga, R. Schwengner, G. Rusev, F. Döna, D. Bremmerer, R. Beyer, P. Crespo, M. Erhard, A. R. Junghans, J. Klug, K. Kosev, C. Nair, K. D. Schilling, and A. Wagner, Phys. Rev. C, **82**, 024314, (2010).
28. *Dipole strength in  $^{144}\text{Sm}$  Studied via  $(\gamma, n)$ ,  $(\gamma, p)$ , and  $(\gamma, \alpha)$  Reactions*, C. Nair, A. R. Junghans, M. Erhard, D. Bemmerer, R. Beyer, E. Grosse, K. Kosev, M. Marta, G. Rusev, K. D. Schilling, R. Schwengner, and A. Wagner, Phys. Rev. C, **81**, 055806, (2010).
29. *E1 strength in  $^{208}\text{Pb}$  Within the Shell Model*, R. Schwengner, R. Massarczyk, B. A. Brown, R. Beyer, F. Döna, M. Erhard, E. Grosse, A. R. Junghans, K. Kosev, C. Nair, G. Rusev, K. D. Schilling, and A. Wagner, Phys. Rev. C, **81**, 054315, (2010).
30. *Experimental Study of the  $A(e, e'\pi^+)$  Reaction on  $^1\text{H}$ ,  $^2\text{H}$ ,  $^{12}\text{C}$ ,  $^{27}\text{Al}$ ,  $^{63}\text{Cu}$  and  $^{197}\text{Au}$* , Q. Xin, et al. (including D. Dutta, and H. Gao), Phys. Rev. C, **81**, 055209, (2010).
31. *g-factor Measurements at RISING: The Cases of  $^{127}\text{Sn}$  and  $^{128}\text{Sn}$* , L. Atanasova, et al. (including G. Rusev), Europhys. Lett. **91**, 42001, (2010).
32. *Improved Results for the  $^2\text{H}(d, n)^3\text{He}$  Transverse Vector Polarization-Transfer Coefficient  $K_y'(0^\circ)$  at Low Energies*, C. D. Roper, T. B. Clegg, J. D. Dunham, A. J. Mendez, W. Tornow, R. L. Walter, Few-Body Syst., **47**, 177-184, (2010).
33. *Level Densities and  $\gamma$ -ray Strength Functions in Sn Isotopes*, H. K. Toft, A. C. Larsen, U. Agvaanluvsan, A. Burger, M. Guttormsen, G. E. Mitchell, H. T. Nyhus, A. Schiller, S. Siem, N. U. H. Syed, and A. Voinov, Phys. Rev. C, **81**, 064311, (2010).
34. *Measurement of  $^{17}\text{O}(p, \gamma)^{18}\text{F}$  Between the Narrow Resonances at  $E_r=193$  and 519 keV*, J. R. Newton, C. Iliadis, A. E. Champagne, J. M. Cesaratto, S. Daigle, and R. Longland, Phys. Rev. C, **81**, 045801, (2010).
35.  *$(n, 2n)$  and  $(n, 3n)$  Cross Sections of Neutron-Induced Reactions on  $^{150}\text{Sm}$  for  $E_n$  from Threshold to 35 MeV*, D. Dashdorj, G. E. Mitchell, T. Kawano, J. A. Becker, M. Devlin, N. Fotiades, R. O. Nelson, and S. Kunieda, Nucl. Instrum. Meth. in Phys. B, **268**, 114, (2010).
36. *Neutron-deuteron Analyzing Power Data at 19.0 MeV*, G. J. Weisel, W. Tornow, B. J. Crowe III, A. S. Crowell, J. H. Esterline, C. R. Howell, J. H. Kelley, R. A. Macri, R. S. Pedroni, R. L. Walter, and H. Witała, Phys. Rev. C, **81**, 024003, (2010).
37. *Photoexcitation of Astrophysically Important States in  $^{26}\text{Mg}$* , R. J. deBoer, M. Wiescher, J. Görres, R. Longland, C. Iliadis, G. Rusev, and A. P. Tonchev, Submitted to Phys. Rev. C, **82**, 025802 (2010).
38. *Production of Radioactive Isotopes Through Cosmic Muon Spallation in KamLAND*, (The KamLAND Collaboration, including H. J. Karwowski, D. M. Markoff, W. Tornow), Phys. Rev. C, **81**, 025807, (2010).
39. *Ratio of Germanium Detector Peak Efficiencies at Photon Energies of 4.4 and 11.7 MeV: Experiment Versus Simulation*, S. Carson, C. Iliadis, J. Cesaratto, A. Champagne, L. Downen, M. Ivanovic, J. Kelley, R. Longland, J. R. Newton, G. Rusev, and A. P. Tonchev, Nucl. Instrum. Methods A, **618**, 190, (2010).
40. *Re-analysis of Recent Neutron Diffusion and Transmission Measurements in Nuclear Graphite*, C. R. Gould, A. I. Hawari, and E. I. Sharapov, Nucl. Sci. Eng., **165**, 200-209, (2010).
41. *Resonance Strength in  $^{22}\text{Ne}(p, g)^{23}\text{Na}$  From Depth Profiling in Aluminum*, R. Longland, C. Iliadis, J. M. Cesaratto, A. E. Champagne, S. Daigle, J. R. Newton, R. Fitzgerald, Phys. Rev. C, **81**, 055804, (2010).

42. *Spectral Structure of the Pygmy Dipole Resonance*, A. P. Tonchev, S. Hammond, J. H. Kelley, H. Lenske, W. Tornow, and N. Tsoneva, Phys. Rev. Lett., **104**, 072501 (2010).
43. *Substantial Increase in Acceleration Potential of Pyroelectric Crystals*, W. Tornow, S. M. Lynam, and S. M. Shafroth, J. Appl. Phys., **107**, 063302, (2010).
44. *Search for a Bosonic Component in the Neutrino Wave Function*, W. Tornow, Nucl. Phys. A, **844**, 57C, (2010).
45. *A Feasibility Study Using Radiochromic Films for Fast Neutron 2D Passive Dosimetry*, S.L. Brady, R. Gunasingha, T.T. Yoshizumi, C.R. Howell, A.S. Crowell, B. Fallin, A.P. Tonchev, and M. Dewhirst, Phys. Med. Biol., **55**, 4977 (2010).
46. *Development of a Superconducting Transverse Holding Magnet for the HIγS Frozen Spin Target*, P.-N. Seo, D.G. Crabb, R. Miskimen, M. Seely, H.R. Weller, Nucl. Instrum. Methods A, **618**, 43, (2010).
47. *Measurement of the  $^{241}\text{Am}(\gamma, n)^{240}\text{Am}$  reaction in the giant dipole resonance region*, A. P. Tonchev, S. Hammond, C. R. Howell, A. Hutcheson, T. Kawano, J. H. Kelley, E. Kwan, G. Rusev, W. Tornow, D. Vieira, and J. B. Wilhelmy, Phys. Rev. C, **82**, 054620 (2010).

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**Journal Articles Accepted**

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1. *Electron Beam Energy Spread Measurements Using Optical Klystron Radiation*, B. Jia, J. Li, S. Huang, Scott C. Schmidler, and Y. K. Wu, accepted to be published in Phys. Rev. ST Accel. Beams (2010).
2. *GEMStar: The Alternative Reactor Technology Comprising Graphite*, C. D. Bowman, E. G. Bilpuch, D. C. Bowman, A. S. Crowell, C. R. Howell, K. McCabe, G. A. Smith, A. P. Tonchev, W. Tornow, V. Violet, R. B. Vogelaar, R. L. Walter, and J. Yingling, Chapter prepared for the new International Handbook of Nuclear Engineering, Ed. Dan Gabriel Cacuci.
3. *Hydrodynamic Models of Type I x-ray Bursts: Metallicity Effects*, J. Jose, F. Moreno, A. Parikh, and C. Iliadis, Astrophys. J., submitted (2010).
4. *Neutron Production With a Pyroelectric Double-crystal Assembly Without Nano-tip*, W. Tornow, W. Corse, S. Crimi, and J. Fox, submitted to Nucl. Instrum. Methods A, (2010).
5. *Random Matrices and Chaos in Nuclear Physics: Nuclear Reactions*, G. E. Mitchell, A. Richter, and H. A. Weidenmüller, to be published in Rev. Mod. Phys.
6. *Energy Levels of Light Nuclei,  $A=3$* , J.E. Purcell, J.H. Kelley, E. Kwan, C.G. Sheu, and H.R. Weller, accepted for publication in Nucl. Phys. A.
7. *Production and Characterization of Intercalated Graphite Crystals for Cold Neutron Monochromators*, P. Courtois *et al.* (including P.R. Huffman), Nucl. Instrum. Methods A, in press (2010).

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**Journal Articles Submitted**


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1. *A General Solution to the Diffusion Induced Transverse and Longitudinal Relaxation in a Non-uniform Magnetic Field with Constant Field Gradients*, W. Zheng, H. Gao *et al.*, submitted to Phys. Rev. A, (2010).
2. *BrillLanCe<sup>TM</sup> Detector Characterization Below 15.5 MeV*, N. Brown, M. W. Ahmed, S. S. Henshaw, B. A. Perdue, P. -N. Seo, S. Stave, H. R. Weller, C. Sun, Y. K. Wu, P. P. Martel, A. Teymurazyan, A. Owens, and F. Quarati, submitted to Nucl. Instr. Methods A, (2010).
3. *Determination of the Proton and Alpha-particle Light-response Function for the KamLAND, BC-501A and BC-517H Liquid Scintillators*, B. Braizinha, J. H. Esterline, H. J. Karwowski, and W. Tornow, submitted to Nucl. Instr. Methods A, (2010).
4. *Low-background Gamma Counting at the Kimballton Underground Research Facility*, P. Finnerty, S. MacMullin, H. O. Back, R. Henning, K. T. Macon, J. Strain, R. M. Lindstrom, and R. B. Vogelaar, submitted to Nucl. Instrum. Methods A, (2010).
5. *Nuclear Astrophysics Studies at LENA: The Accelerators*, J. M. Cesaratto, A. E. Champagne, T. B. Clegg, M. Q. Buckner, R. C. Runkle, and A. Stefan, to be published in Nuclear Instruments and Methods in Physics Research, A, (2010).
6. *Spin-Correlation Coefficients and Phase-Shift Analysis for  $p+^3\text{He}$  Elastic Scattering*, T. V. Daniels, C. W. Arnold, J. M. Cesaratto, T. B. Clegg, A. H. Couture, H. J. Karwowski, and T. Katabuchi, submitted to Phys. Rev. C, March 30, 2010.
7. *Understanding the  $^{11}\text{B}(p,\alpha)\alpha\alpha$  Reaction at the 0.675 MeV Resonance*, S.S. Stave, M.W. Ahmed, R.H. France III, S.S. Henshaw, B. Müller, B.A. Perdue, R.M. Prior, M.C. Spraker, and H.R. Weller, submitted to Phys. Lett., (2010).
8. *An Optical Readout TPC (O-TPC) for Studies in Nuclear Astrophysics with Gamma-ray Beams at HIγS*, M. Gai *et al.*, submitted to JINST, (2010).
9. *Dipole States in  $^{235}\text{U}$* , E. Kwan, G. Rusev, A. S. Adecola, S. L. Hammond, C. R. Howell, H. J. Karwowski, J. H. Kelley, R. S. Pedroni, R. Raut, A. P. Tonchev, and W. Tornow, submitted to Phys. Rev. C, (2010).

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**Special Reports and Books**

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1. *Missing Level Corrections using Neutron Spacings*, G. E. Mitchell and J. F. Shriners, Jr., INDC(NDS)-0561 International Atomic Energy Agency, Vienna, (2009).
2. *Proceedings of the First International Conference Ulaanbaatar Conference on Nuclear Physics and Applications*, ed. D. Dashdorj, U. Agvaanluvsan, and G. E. Mitchell, AIP Volume 1109, Melville, New York, (2009).
3. *Polarized Particle Sources: Protons and Heavy Ions*, T. B. Clegg and W. Haeberli, in Handbook of Accelerator Physics and Engineering, 2<sup>nd</sup> Edition, eds., A. Chao and M. Tigner, (to be published by World Scientific, Singapore).
4. *Neutron EDM Experiments*, Steve K. Lamoreaux and Robert Golub, in *Lepton Dipole Moments*, ed. B. Lee Roberts and William J. Marciano World Scientific Publishing Company, Singapore, 583-634, (2009).

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**Conference Reports and Articles in Conference Proceedings**


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1. *Complete Phenomenological Model for Projectile-breakup Reactions*, C. K. Walker, Report to the Second Research Coordination Meeting of the Fusion Energy Nuclear Data Library Coordinated Research Project (FENDL-3 CRP) of the International Atomic Energy Agency, Vienna, March (2010).
2. *Introduction to Nuclear Astrophysics*, C. Iliadis, Proceedings of the 5th European Summer School on Experimental Nuclear Astrophysics, Santa Tecla, Italy, AIP Conf. Proc., AIP, New York, in print (2009).
3. *New Results from the Bates Large Acceptance Spectrometer Toroid (BLAST)*, H. Gao, Conference Proceedings paper presented at the 7th International Conference on Nuclear Physics at Storage Rings STORI '08, Lanzhou, China, September 14 - 18, 2008, International Journal of Modern Physics E, **18**, No. 2, 209 - 219, (2009).
4. *Recent Few-Body Studies at TUNL - Experimental Results and Challenges*, T. B. Clegg, Invited contribution at 6th International Workshop on Chiral Dynamics, Univ. of Bern, July 6 - 10, (2009).
5. *Spin and Parity Assignments to Dipole Excitations of the Odd-Mass Nucleus  $^{207}\text{Pb}$  from Nuclear Resonance Fluorescence Experiments with Linearly-Polarized-Ray Beams*, N. Pietralla, T. C. Li, M. Fritzsche, M. W. Ahmed, D. Savran, A. P. Tonchev, W. Tornow, H. R. Weller, and V. Werner, Varna Summer School, Varna, Bulgaria (2009).
6. *Study of Semi-inclusive Deep-inelastic ( $e, e' \pi^\pm$ ) Production at 11 GeV in JLab With a Polarized  $^3\text{He}$  Target*, X. Qian, H. Gao, J. -P. Chen, and E. Chudakov, AIP Conf. Proc. **1149**, 457, (2009).
7. *The First Measurement of Neutron Transversity on a Transversely Polarized  $^3\text{He}$  Target*, Y. Qiang, proceedings of CIPANP 2009, (2009).
8. *The Majorana Project*, S. R. Elliott *et al.* (MAJORANA Collaboration), Carolina International Symposium on Neutrino Physics, Journal of Physics: Conference Series 173, 012007, (2009).
9. *A Pulsed ECR Source: Environmental and Beam Induced Background Suppression*, M. Q. Buckner, J. M. Cesaratto, T. B. Clegg, and C. Iliadis, Poster presentation at DOE Stewardship Science Annual Conference, Washington, DC, June 21-22, (2010).
10. *Cross Section Measurement on  $^{139}\text{La}$  ( $\gamma, \gamma'$ ) Below Neutron Separation Energy*, A. Makinaga, G. Rusev, R. Schwengner, F. Döna, R. Beyer, D. Bremmerer, P. Crespo, A. R. Junghans, J. Klug, C. Nair, K. D. Schilling, and A. Wagner, Tours Symposium on Nuclear Physics and Astrophysics - VII, Kobe, Japan, 2009, AIP Conf. Proc. **1238**, 228, (2010).
11. *Hydrodynamic Models of Classical Novae and Type I X-ray Bursts*, J. Jose, J. Casanova, F. Moreno, E. Garcia-Berro, A. Parikh, and C. Iliadis, Proceedings of the 7th Tours Symposium on Nuclear Physics and Astrophysics, Kobe, Japan, 2009, AIP Conf. Proc., AIP, New York, in print (2010).
12. *Monte Carlo Reaction Rate Evaluation for Astrophysics*, A. Coc, C. Iliadis, R. Longland, A. E. Champagne, and R. Fitzgerald, Proceedings of the 7th Tours Symposium on Nuclear Physics and Astrophysics, Kobe, Japan, 2009, AIP Conf. Proc., AIP, New York, in print (2010).
13. *New Developments in Experimental Thermonuclear Reactions*, C. Iliadis, Proceedings of the 7th Tours Symposium on Nuclear Physics and Astrophysics, Kobe, Japan, 2009, AIP Conf. Proc., AIP, New York, in print (2010).

14. *Photoactivation of the  $p$ -nucleus  $^{92}\text{Mo}$  with Bremsstrahlung at ELBE*, M. Erhard, E. Grosse, A. R. Junghans, J. Klug, C. Nair, G. Rusev, K. D. Schilling, R. Schwengner, and A. Wagner, Nuclear Physics in Astrophysics IV, Frascati, Italy, 2009, J. Phys. Conf. Ser. **202**, 012014, (2010).
15. *Photon Scattering Experiment on  $^{139}\text{La}$  below Neutron Separation Energy at ELBE*, A. Makinaga, G. Rusev, R. Schwengner, A. R. Junghans, and A. Wagner, Perspectives in Nuclear Physics, Tokai, Japan, 2008, AIP Conf. Proc. **1120**, 289, (2009).
16. *Properties of Warm Nuclei in the Quasicontinuum*, M. Guttormsen, U. Agvaanluvsan, A. C. Larsen, R. Chankova, G. E. Mitchell, A. Schiller, S. Siem, and A. Voinov, Proceedings of the Second International Workshop on Compound Nuclear Reactions and Related Topics, editors L. Bonneau, N. Dubray, F. Gunsing, B. Jurado, EDP Web of Conferences 2, 04001, (2010).
17. *Soft Structures of  $\gamma$ -ray Strength Functions Studied with the Oslo Method*, A. C. Larsen, U. Agvaanluvsan, S. Goriely, M. Guttormsen, E. Algin, L. A. Bernstein, R. Chankova, T. Lonnroth, G. E. Mitchell, J. Rekestad, H. K. Toft, A. Schiller, S. Siem, N. U. H. Syed, and A. Voinov, Proceedings of the Second International Workshop on Compound Nuclear Reactions and Related Topics, editors L. Bonneau, N. Dubray, F. Gunsing, B. Jurado, EDP Web of Conferences 2, 03001, (2010).
18. *The Majorana Project*, C. E. Aalseth *et al.* (MAJORANA Collaboration), Topics in Astroparticle and Underground Physics (TAUP 2009), Journal of Physics: Conference Series 203, 012057, (2010).

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### Abstracts to Meetings and Conferences

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1. *A New Measurement of the Total Cross Section for the Photodisintegration of  $^9\text{Be}$  Near Threshold*, C. W. Arnold, T. B. Clegg, H. J. Karwowski, G. C. Rich, J. R. Tompkins, C. R. Howell, <http://meetings.aps.org/link/BAPS.2010.APR.K7.7>
2. *An Overview of the Data Acquisition System in the KATRIN Experiment*, D. Phillips II, <http://meetings.aps.org/link/BAPS.2010.APR.G8.9>
3. *Astroparticle and Nuclear Physics with a Customized Low-Background Broad Energy Germanium Detector*, P. Finnerty, <http://meetings.aps.org/link/BAPS.2010.APR.Y10.4>
4. *Development of a Data Acquisition System for a Low-Background BEGe Detector*, G. K. Giovanetti, <http://meetings.aps.org/link/BAPS.2010.APR.G8.10>
5. *Calibration of the MiniCLEAN detector*, M. Akashi-Ronquest, <http://meetings.aps.org/link/BAPS.2010.APR.G9.3>
6. *Measurements of Dipole Excitations in  $^{48}\text{Ca}$  Between  $E_\gamma = 9.5$  and  $15.3$  MeV*, J. R. Tompkins, C. W. Arnold, H. J. Karwowski, G. C. Rich, C. R. Howell, L. G. Sobotka, <http://meetings.aps.org/link/BAPS.2010.APR.B7.2>
7. *Differential Cross Section Measurements of Elastic and Inelastic Scattering of Neutrons from Neon*, S. MacMullin *et al.*, <http://meetings.aps.org/link/BAPS.2010.APR.H7.3>
8. *Characterizing Electron Optics in the KATRIN Experiment*, T. Corona, <http://meetings.aps.org/link/BAPS.2010.APR.A8.1>
9. *Enabling Environmental Background Reduction for Nuclear Astrophysics Measurements with Pulsed Proton Beams*, M. Q. Buckner, J. Cesaratto, and T. B. Clegg, <http://meetings.aps.org/link/BAPS.2010.APR.H7.8>
10. *First Study of Three-body Photo-disintegration of  $^3\text{He}$ :  $^3\text{He}(\vec{\gamma}, n)pp$  with Double Polarizations*, W. Chen *et al.*, <http://meetings.aps.org/link/BAPS.2010.APR.K7.5>
11. *Sample Preparation and Gamma-Assay Measurements at the Low-Background Counting Facility at the Kimballton Underground Research Facility*, J. Strain *et al.*, <http://meetings.aps.org/link/BAPS.2010.APR.Y10.3>
12. *Astroparticle Physics with a Customized Low-Background Germanium Detector*, P. Finnerty, 2010 Symposium on Radiation Measurements and their Applications (SORMA XII), <http://rma-symposium.engin.umich.edu/index.php>
13. *Background Model for the MAJORANA DEMONSTRATOR*, R. Henning on behalf of the MAJORANA Collaboration, Poster Presentation at Neutrino 2010, Athens, Greece, 2010
14. *Fine Structure of the M1 Resonance in  $^{90}\text{Zr}$* , G. Rusev, A. S. Adekola, F. Dönau, S. Frauendorf, S. L. Hammond, C. Huibregtse, J. H. Kelley, E. Kwan, R. Schwengner, A. P. Tonchev, W. Tornow, and A. Wagner, <http://inpc2010.triumf.ca/>
15. *Asymmetry of Photo-fission Neutrons from  $^{238}\text{U}$* , J. R. Tompkins *et al.*, DNDO meeting, Alexandria, VA, April, (2010)
16. *Development of Gd-based Neutron Detector*, D. Ticehurst *et al.*, DNDO meeting, Alexandria, VA, April, (2010)

17. *Dipole Excitations in  $^{235}\text{U}$  ( $\gamma, \gamma'$ ) Scattering*, E. Kwan *et al.*, DNDO meeting, Alexandria, VA, April, (2010)
18. *Dipole States in  $^{238}\text{U}$* , S. L. Hammond *et al.*, DNDO meeting, Alexandria, VA, April, (2010)
19.  *$^{235}\text{U}$  Photofission Activation Measurement*, J.M. Mueller *et al.*, DNDO Meeting, Alexandria, VA, April, (2010)
20. *Determination of the  $^1\text{S}_0$  Neutron-neutron Scattering Length Using nd Breakup in Recoil Geometry at 19 MeV*, S. Tajima, A. S. Crowell, J. Deng, J. Esterline, C. R. Howell, M. R. Kiser, R. A. Macri, and W. Tornow, B. J. Crowe III, R. S. Pedroni, W. Von Witsch, H. Witala, <http://meetings.aps.org/link/BAPS.2009.SES.HC.2>
21. *Simulation Comparisons between Geant4 and MCNPX*, J. R. Tompkins, G. Rich and C. W. Arnold, <http://meetings.aps.org/link/BAPS.2009.SES.HC.3>
22. *Nuclear Resonance Fluorescence from Uranium above 2 MeV*, E. Kwan, C. R. Howell, R. Raut, G. Rusev, A. P. Tonchev, W. Tornow, A. Adekola, S. L. Hammond, H. J. Karwowski, J. R. Tompkins, C. Huibregtse, J. H. Kelley, B. Johnson, <http://meetings.aps.org/link/BAPS.2009.HAW.BK.6>
23. *Precision photo-induced cross-section measurements using the monoenergetic and polarized photon beams at HI $\gamma$ S*, A.P. Tonchev *et al.*, <http://meetings.aps.org/link/BAPS.2009.HAW.LC.3>
24. *Compton Scattering on  $^{209}\text{Bi}$  at HI $\gamma$ S from  $E_\gamma=11-30$  MeV*, S.S. Henshaw *et al.*, <http://meetings.aps.org/link/BAPS.2009.HAW.BH.11>
25. *Performance of the UConn-TUNL O-TPC with the Upgraded Optical Readout System*, W.R. Zimmerman *et al.*, <http://meetings.aps.org/link/BAPS.2009.HAW.LG.10>
26. *BrilLanCe detector energy resolution characterization at HI $\gamma$ S*, N. Brown *et al.*, <http://meetings.aps.org/link/BAPS.2009.HAW.ED.1>
27. *A New Method for Identifying Nuclear Isotopes Based Upon Polarized ( $\gamma, n$ ) Asymmetries*, S. Stave *et al.*, <http://meetings.aps.org/link/BAPS.2009.HAW.LC.1>
28. *The  $^{11}\text{B}(p, \alpha)\alpha\alpha$  Reaction at Low Energies*, R.M. Prior *et al.*, <http://meetings.aps.org/link/BAPS.2009.HAW.LG.8>
29. *Neutron-Neutron Scattering Length Determinations Using nd Breakup in Different Nucleon Detection Geometries*, C.R. Howell *et al.*, <http://meetings.aps.org/link/BAPS.2009.HAW.CH.7>
30. *High Precision Measurement of the  $^{19}\text{Ne}$  Lifetime*, L. Broussard *et al.*, <http://meetings.aps.org/link/BAPS.2009.HAW.KJ.11>
31. *Development of a Conversion Electron Source for Timing Measurements and the Determination of Angle Dependent Detector Response in the UCNA Experiment*, A.J. Cetnar, L. Broussard, R.W. Pattie, and A.R. Young, <http://meetings.aps.org/link/BAPS.2009.HAW.GB.24>
32. *Progress on the Construction of the PULSTAR Solid Deuterium Ultracold Neutron Source*, G. Palmquist *et al.*, <http://meetings.aps.org/link/BAPS.2009.HAW.KK.3>
33. *Precision UCN Polarimetry and the UCNA Experiment*, A.T. Holley, <http://meetings.aps.org/link/BAPS.2009.HAW.KK.8>
34. *Systematics of the UCNA Experiment*, R. Pattie, <http://meetings.aps.org/link/BAPS.2009.HAW.CK.7>

35. *Neutron Capture Measurements Using DANCE*, A. Chyzh *et al.*,  
<http://meetings.aps.org/link/BAPS.2009.HAW.DG.11>
36. *Updates on neutron induced measurements on Gadolinium isotopes at the DANCE array*, D. Dashdorj *et al.*,  
<http://meetings.aps.org/link/BAPS.2009.HAW.KC.11>
37. *Level Density and Radiative Strength of  $^{116,117}\text{Sn}$* , A. Schiller, U. Agvaanluvsan, A. C. Larsen, R. Chankova, M. Guttormsen, G. E. Mitchell, S. Siem, A. Voinov,  
<http://meetings.aps.org/link/BAPS.2009.HAW.DG.10>
38. *Ambient Neutron Flux Measurements at Kimballton Underground Research Facility (KURF)*, D. Kaleko, R. Henning, and W. Tornow,  
<http://meetings.aps.org/link/BAPS.2009.HAW.GB.61>
39. *Generation of Unprecedented high Electric Fields with Pyroelectric Crystals*, S. Crimi, W. Tornow, and Z. Corse,  
<http://meetings.aps.org/link/BAPS.2009.HAW.GB.29>
40. *Double-Beta Decay of  $^{150}\text{Nd}$  to Excited Final States*, M. Kidd, J.H. Esterline, and W. Tornow,  
<http://meetings.aps.org/link/BAPS.2009.HAW.DJ.6>

## A.3 Invited Talks, Seminars, and Colloquia

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### Invited Talks, Seminars, and Colloquia

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1. *Globular Clusters, Nuclear Physics and the Age of the Galaxy*, A. E. Champagne, Physics Colloquium, College of Charleston Charleston, SC, April, (2010).
2. *Stellar Reactions, Update, Status and Plans*, A.E. Champagne and C. Iliadis, Invited talk at the Workshop on Cosmic Chemical Evolution, St. Michaels, Md, June 2-4, (2010).
3. *Prospects in Neutron Transverse Spin Study with Polarized  $^3\text{He}$  at 12 GeV Jefferson Laboratory*, H. Gao, Invited talk at the 3rd Joint Meeting of the APS Division of Nuclear Physics and the Physical Society of Japan, Waikoloa, HI, Oct. 13 - 17, (2009).
4. *Prospects in Neutron Transverse Spin Study with Polarized  $^3\text{He}$  at 12 GeV Jefferson Laboratory*, H. Gao, Invited talk at the 76th Annual Meeting of the Southeastern Section of APS, Atlanta, GA, Nov. 11 - 14, (2009).
5.  *$\Phi$  Meson Photoproduction on Deuteron and Future Studies Using Heavier Nuclear Targets*, H. Gao, Invited talk at the High Energy Nuclear Physics and QCD, Florida International University, Miami, February 3 - 6, (2010).
6. *A New Search on the Neutron Electric Dipole Moment*, H. Gao, Colloquium, University of Minnesota, March 3, (2010).
7. *Workshop on Partonic Transverse Momentum in Hadrons (summary)*, H. Gao, Invited talk at the JLab Users Group annual meeting, Newport News, VA, June 7 - 9, (2010).
8. *Prospects/plans for TMD studies at the EIC*, H. Gao, Invited talk at the workshop on Transverse-Momentum-Dependent Distributions, Trento, Italy, June 21 - 25, (2010).
9. *Frontiers in Hadron Structure*, H. Gao, Special Lecture, 2010 US National Nuclear Physics Summer School (NNPSS) jointly with the TRIUMF Summer Institute (TSI), Vancouver, BC, Canada, June 21 - July 2, (2010).
10. *Recent Results on Structure Functions*, H. Gao, Plenary talk at the 35th International Conference on High Energy Physics, Paris, France, July 22 - 28, (2010).
11. *12 GeV Neutron  $^3\text{He}$  Transversity TMDs with SoLID*, H. Gao, Invited talk at the 2nd Workshop Hadron Physics in China and Opportunities with 12 GeV JLab, Beijing, China, July 28 - 31, (2010).
12. *Direct Detection of Dark Matter*, R. Henning, Southeastern Section of the APS 2009, Atlanta, GA, (2009).
13. *Overview of Current and Proposed Searches for Double-beta Decay*, R. Henning, Neutrinos and Dark Matter 2009, Madison, WI, (2009).
14. *Progresss Towards a beta-asymmetry Measurement with Ultracold neutrons*, A. T. Holley, 6th International Workshop on Cold and Ultracold Neutrons, St. Petersburg, Russia, June (2009).
15. *Nuclear Data Measurements on Actinides Using the High Intensity Gamma-ray Source*, C.R. Howell, ARI Grantees Conference, Alexandria, VA, April 2010.
16. *Simulations of TSSA from SIDIS at EIC*, M. Huang, Invited talk at the Workshop on Partonic Transverse Momentum in Hadrons: Quark Spin-Orbit Correlations and Quark-Gluon Interactions, Duke University, Durham, NC, March 13, (2010).
17. *Fundamental Neutron Physics Using in situ UCN Sources.*, P. R. Huffman, Research Opportunities with Ultracold Neutrons in the US, Santa Fe, NM, November, (2009).

18. *The Fundamental Neutron Physics Program at the Spallation Neutron Source*, P. R. Huffman, CAARI-2010, Fort Worth, TX, August (2010).
19. *New Developments in Experimental Thermonuclear Reactions*, C. Iliadis, Invited plenary talk at the 7th Tours Symposium on Nuclear Physics and Astrophysics, Kobe, Japan, November, (2009).
20. *Recent Measurements in Nuclear Astrophysics*, C. Iliadis, Talk at the Johann Wolfgang Goethe-Universität, Frankfurt am Main, Germany, June, (2010).
21. *Entfernungsmessung im Universum*, C. Iliadis, Talk at the Johann Wolfgang Goethe-Universität Frankfurt am Main, Germany, June, (2010).
22. *Introduction to Nuclear Astrophysics*, C. Iliadis, Lecture (2 hours) given at the Fifth European Summer School on Experimental Nuclear Astrophysics, Santa Tecla, Italy, September, (2009).
23. *Cross Sections and Reaction Rates in Nuclear Astrophysics*, C. Iliadis, One-week long course (5 hours) given at the ASA/ANITA Summer School in Stellar Nucleosynthesis, Monash University, Melbourne, Australia, January, (2010).
24. *Topics in Nuclear Astrophysics*, C. Iliadis, Lecture (3 hours) given at the Carpathian Summer School of Physics 2010 (Exotic Nuclei and Nuclear/Particle Astrophysics III), Sinaia, Romania, June, (2010).
25. *Methods to Detect SNM with Nuclear Resonance Fluorescence*, M. Johnson *et al.*, presented at International Conference Actinides 2009, Berkely, July, (2009).
26. *Nuclear Resonance Fluorescence on  $^{235,238}\text{U}$* , H.J. Karwowski, talk given at Workshop on Topics in Homeland Nuclear Security, Berkeley, July, (2009).
27. *Dipole States in  $^{232}\text{Th}$  and  $^{238}\text{U}$* , H.J. Karwowski, presented at the International Nuclear Physics Conf. Vancouver, July, (2010).
28. *Neutron Capture Reactions on Gadolinium Isotopes*, B. Baramsai, U. Agvaanluvsan, F. Becvar, T. Bredeweg, A. Chyzh, A. Couture, D. Dashdorj, R. Haight, M. Jandel, A. L. Keksis, M. Krticka, G. E. Mitchell, J. O'Donnell, R. Rundberg, J. Ullmann, D. Vieira, C. Walker, J. Wouters, LANSCE Users Group Meeting, Santa Fe, NM (2009).
29. *Neutron Capture Experiments at DANCE*, G. E. Mitchell, Forschungszentrum Dresden, Germany, November, (2009).
30. *Properties of Warm Nuclei in the Quasicontinuum*, M. Guttormsen, U. Agvaanluvsan, A. C. Larsen, R. Chankova, G. E. Mitchell, A. Schiller, S. Siem, and A. Voinov, Second International Workshop on Compound Nuclear Reactions and Related Topics, Bordeaux, France (2009).
31. *Soft Structures of  $\gamma$ -ray Strength Functions Studied with the Oslo Method*, A. C. Larsen, U. Agvaanluvsan, S. Goriely, M. Guttormsen, E. Algin, L. A. Bernstein, R. Chankova, T. Lonroth, G. E. Mitchell, J. Rekstad, H. K. Toft, A. Schiller, S. Siem, N. U. H. Syed, and A. Voinov, Second International Workshop on Compound Nuclear Reactions and Related Topics, Bordeaux, France (2009).
32. *Parity Violation in Compound Nuclear Resonances*, G. E. Mitchell, From Femtoscience to Nanoscience: Nuclei, Quantum Dots, and Nanostructures, Seattle, August, (2009).
33. *Cross Sections, Level Densities and Strength Functions*, G. E. Mitchell, Stockpile Stewardship Academic Alliance Symposium, Washington. D.C, January, (2010).
34. *Applications of Random Matrix Theory: Parity Violation and Missing Level Corrections*, G. E. Mitchell, Oak Ridge National Laboratory, Oak Ridge, May, (2010).
35. *Single-spin Asymmetry Measurement at Jefferson Lab Hall A with a Polarized  $^3\text{He}$  Target*, X. Qian, Nuclear Physics Seminar, Caltech, Oct. 9, (2009).

36. *Transverse Momentum-dependent Structure of the Nucleon*, Y. Qiang, Seminar at Rutgers University, New Brunswick, Oct. 28, (2009).
37. *Transverse Momentum-dependent Structure of the Nucleon*, Y. Qiang, Seminar at Jefferson Lab, Newport News, Oct. 30, (2009).
38. *Transverse Momentum-dependent Structure of the Nucleon*, Y. Qiang, Seminar at Jefferson Lab, Newport News, Nov. 25, (2009).
39. *Transverse Spin Physics at Jefferson Lab with Polarized  $^3\text{He}$* , Y. Qiang, Invited talk at the Workshop on Partonic Transverse Momentum in Hadrons: Quark Spin-Orbit Correlations and Quark-Gluon Interactions, Duke University, Durham, NC, Mar.12 - 13, (2010).
40. *Study of the Pygmy Dipole Resonance*, A. P. Tonchev, Duke, Aug. 24, (2009).
41. *Fine Structure of the Nuclear Dipole Response*, A. P. Tonchev, Ohio University, Athens, OH, Sep. 29, (2009).
42. *Fine Structure of the Pygmy Dipole Resonance*, A. P. Tonchev, National Superconducting Cyclotron Laboratory, Michigan State University, November 11, (2009).
43. *Precision Photo-Induced Cross-Section Measurements using the Monoenergetic and Polarized Photon Beams at HI $\gamma$ S*, A. P. Tonchev, SSAA Symposium, Washington DC, January 20, (2010).
44. *Use of Monoenergetic and Polarized Photon Beams for Basic and Applied Nuclear Physics*, A. P. Tonchev, Department of Physics and Astronomy, James Madison University, February 4, (2010).
45. *Fine and Gross Structure of the Pygmy Dipole Resonance*, A. P. Tonchev, The 24<sup>th</sup> International Nuclear Physics Conference (INPC), Vancouver, Canada.
46. *Astro-nuclear Physics with Medium Energy Photons from HIGS*, W. Tornow, Advanced Photons and Science Evolution 2010 (APSE2010), Osaka, Japan, June 14 - 18, (2010).
47. *Research Opportunities at HI $\gamma$ S*, H.R. Weller, Los Alamos National Laboratory Colloquium, Los Alamos, NM, March (2010).
48. *Development of an Aneutronic Fusion Reactor Using the  $^{11}\text{B}(p,\alpha)\alpha\alpha$  Reaction*, H.R. Weller, Massachusetts Institute of Technology Colloquium, March 30, (2010).
49. *A New Method for Identifying Nuclear Materials Based Upon Polarized ( $\gamma,n$ ) Asymmetries*, H.R. Weller, ARI Grantees Conference, Alexandria, VA, April (2010).
50. *Probing Chiral Dynamics with Photopion Experiments Near Threshold*, H.R. Weller, Meson-Nucleon Physics and the Structure of the Nucleon (MENU 2010), College of William and Mary, Williamsburg, VA, May 31, (2010).
51. *Neutrinoless Double Beta Decay At the Intersection of Particle and Nuclear Physics*, J.F. Wilkerson, 10th Conference on the Intersections of Particle and Nuclear Physics, La Jolla, CA, May, (2009).
52. *Experimental Approaches to Neutrinoless Double Beta Decay DM Detection, and Coherent Neutrino Scattering*, J.F. Wilkerson, International Neutrino Summer School, Fermilab, Batavia, IL, July, (2009).
53. *Beta Decay Probes of the Neutrino Mass Scale*, J.F. Wilkerson, International Neutrino Summer School, Fermilab, Batavia, IL, July, (2009).
54. *The Reticent, Yet Remarkable Neutrino*, J.F. Wilkerson, Physics Colloquium, Duke University, Durham, NC, September, (2010).
55. *A 1-tonne  $^{76}\text{Ge}$  Neutrinoless Double Beta Decay Experiment*, J.F. Wilkerson, DUSEL Science Workshop, Lead, SD, October, (2009).

56. *Neutrino Mass from Double Beta Decay*, J.F. Wilkerson, Institute for Nuclear Physics Workshop on the Future of Neutrino Mass Measurements, Seattle WA, February, (2010).
57. *Status of the MAJORANA DEMONSTRATOR Project*, J.F. Wilkerson, GERDA Collaboration Meeting, Gran Sasso, Italy, March, (2010).
58. *The Reticent, Yet Remarkable Neutrino*, J.F. Wilkerson, Physics Colloquium, Va. Tech., Blacksburg, VA, March, (2010).
59. *The Reticent, Yet Remarkable Neutrino*, J.F. Wilkerson, Physics Division Seminar, Argonne National Laboratory, Argonne, IL, March, (2010).
60. *A New Search for the Neutron Electric Dipole Moment*, Q. Ye, Seminar, Indiana University Cyclotron Facility, Bloomington, IN, January 15, (2010).
61. *A New Search for the Neutron Electric Dipole Moment*, Q. Ye, Seminar, University of Kentucky, Lexington, KY, January 21, (2010).
62. *A New Search for the Neutron Electric Dipole Moment*, Q. Ye, Seminar, Argonne National Lab, Argonne, IL, January 28, (2010).
63. *A New Search for the Neutron Electric Dipole Moment*, Q. Ye, Seminar, Princeton University, Princeton, NJ, February 5, (2010).
64. *Fundamental Physics with Ultracold Neutrons: A New Approach to a Challenging Problem*, A. R. Young, McGill College Colloquium, November (2009).
65. *Fundamental Physics with Ultracold Neutrons: A New Approach to a Challenging Problem*, A. R. Young, Indiana University Colloquium, September (2009).
66. *Fundamental Physics with Ultracold Neutrons: A New Approach to an Old Problem*, A. R. Young, University of Vermont Colloquium, September (2009).

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**Seminars at TUNL**

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1. Lt. Col. Nick Prins, Domestic Nuclear Detection Office of the Department of Homeland Security, (09/17/2009)  
*Progress in Detection of Nuclear Materials*
2. Seth Hoedl, University of Washington, (09/24/2009)  
*A Torsion Pendulum Based Axion Search.*
3. Gail McLaughlin, North Carolina State University, (10/01/2009)  
*Neutrinos from Supernovae and Compact Object Mergers*
4. Luke Myers, University of Illinois, (10/08/2009)  
*Neutron Polarizabilities Via Deuteron Compton Scattering At MAX-lab*
5. Jay Davis, LLNL, (10/20/2009)  
*Twenty Years of Tricks with Tandems*
6. Adriana Banu, Texas A & M University, (10/29/2009)  
*Reaction Rates for H-burning in Novae and X-ray Bursts from Breakup at Intermediate Energies*
7. Florian Fraenkle, Karlsruher Institut für Technologie (KIT), (11/12/2009)  
*Measurements with the KATRIN Pre-spectrometer*
8. Changchun Sun, Duke University, (11/19/2009)  
*Characterizations and Diagnostics of Compton Light Source*
9. Oliver Jahn, Institut für Kernphysik, Mainz, (11/23/2009)  
*The GDH Experiment at MAMI*
10. Babatunde Oginni, Ohio University, (12/03/2009)  
*Test of Level Density Models from Nuclear Reactions*
11. John Watson, Kent State University, (01/21/2010)  
*From the Nuclear Shell Model to Short-Range Correlations: The Adventure of a Lifetime*
12. Chris Howard, University of Alberta, (02/25/2010)  
*The Sudbury Neutrino Observatory: Searching for hep Neutrinos*
13. Kevin Veal, NNSA, (03/04/2010)  
*Personal Experiences as a Nuclear Nonproliferation Practitioner*
14. Simona Malace, University of South Carolina, (03/18/2010)  
*Pinning Down the Nucleon's Quark Distributions at Large Bjorken-x*
15. Richard Firestone, Lawrence Berkeley National Laboratory, (03/30/2010)  
*The IAEA/LBNL Evaluated Gamma-Ray Activation File (EGAF)*
16. Jason Detwiler, Lawrence Berkeley National Laboratory, (04/01/2010)  
*1 count / tonne-year? Battling Backgrounds in the MAJORANA DEMONSTRATOR*
17. Bernd Surrow, Massachusetts Institute of Technology, (04/08/2010)  
*First W Results from RHIC STAR*
18. Larry Nittler, Carnegie Institution of Washington, (04/22/2010)  
*Stellar Fossils: Presolar Stardust in the Solar System*
19. Dr. Vladimir Litvinenko, Brookhaven National Laboratory, (04/27/2010)  
*eRHIC high luminosity electron-ion collider at BNL*

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20. Jocelyn Monroe, MIT, (04/29/2010)  
*Directional Dark Matter Detection and Recent Progress with the DMTPC Detector*
  21. Robert Charity, Washington University of St. Louis, (04/29/2010)  
*Two and Four-Proton Decay modes of Proton-Rich Nuclei*
  22. Diana Parno, Carnegie Mellon University, (05/06/2010)  
*High-Precision Compton Polarimetry in Hall A of Jefferson Lab*

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**Advances in Physics Lectures and Seminars**

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1. Richard Prior, North Georgia College and State University, (6/4/2010)  
*Introduction to Nuclear Reactions*
2. Mohammad Ahmed, Duke University, (6/7/2010)  
*Introduction to Nuclear Structure*
3. Mohammad Ahmed, Duke University, (6/7/2010)  
*Introduction to Nuclear Electronics*
4. Gencho Rusev, Duke University, (6/10/2010)  
*Investigation of Nuclear Structure with Real Photons*
5. Qiang Ye, Duke University, (6/24/2010)  
 *$^3\text{He}$  Relaxation Time Measurements for the Neutron Electric Dipole Moment ( $n\text{EDM}$ ) Experiment*
6. David Haase, North Carolina State University, (7/1/2010)  
*Nuclear Physics at Low Temperatures*
7. Sean Stave, Duke University, (7/15/2010)  
*Interrogation of Special Nuclear Materials Based Upon Polarized ( $\gamma$ ,  $n$ ) Asymmetries*
8. Reyco Henning, University of North Carolina at Chapel Hill, (7/22/2010)  
*Searching for the Rarest Events in the Universe*

## A.4 Professional Service Activities

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### Advisory/Fellowship/Review Committees

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1. Member, Editorial Board of the Physical Review C HRIBF Users Executive Committee, 2009 - 2010, *A. Champagne*
2. Member, Southeastern Universities Research Association/Jefferson Science Associates Jefferson Laboratory Advisory Committee, 2009 - 2010, *T.B. Clegg*
3. Member, Fellowship Committee, Division of Nuclear Physics of APS, 2009 - 2010, *H. Gao*
4. Member, International Advisory Committee, the 12th International Symposium on Meson-Nucleon Physics and the Structure of the Nucleon, College of William and Mary, May 31, 2010 - June 4, 2010, *H. Gao*
5. Member, International Advisory Committee, Second International Conference on Nuclear Physics and Applications, Ulaanbaatar, Mongolia, July 2010, *C. Gould*
6. Member, Nuclear Physics and Applications, Ulaanbaatar, Mongolia, July 2010, *C. Gould*
7. Member, National Research Council: Panel on Neutron Research at NIST, 2010, *C. Gould*
8. Member, Executive Committee of the Division of Nuclear Physics of the APS, *C.R. Howell*
9. Member, Majorana Senior Advisory Committee, *C.R. Howell*
10. Member, 2010 Dissertation Grant Selection Panel for the Mellow Mays Undergraduate Fellowship Program, *C.R. Howell*
11. Member, 2010 Stockpile Stewardship Graduate Fellowship program Selection Committee, *C.R. Howell*
12. Member, DOE Review Panel for the nuclear physics program at Yale University, 2009, *C.R. Howell*
13. Member, DOE Review Panel for the nuclear physics program at the Massachusetts Institute of Technology, 2010, *C.R. Howell*
14. Member, Organizing Committee for the 10th Torino Workshop, New Zealand, 2009, *C. Iliadis*
15. Member, Organizer for the Nuclear Astrophysics Workshop, Chapel Hill, NC, 2009, *C. Iliadis*
16. Member, Program Committee, Division of Nuclear Physics of APS, 2009 - present, *C. Iliadis*
17. Member, the EuroGENESIS (European Science Foundation), 2009-present, *C. Iliadis*
18. Member, International Advisory Committee, Second International Ulaan Baatar Conference on Nuclear Physics and Applications, Ulaan Baatar, Mongolia, 2007 - 2010, *G.E. Mitchell*
19. Member, International Advisory Committee, International Workshop on Gamma Strength and Level Density in Nuclear Physics and Nuclear Technology, Dresden, Germany, 2008 - 2010, *G.E. Mitchell*
20. Member, Program Advisory Committee for Fundamental Physics for Los Alamos Neutron Science Center (LANSCE), 2004 - 2010, *G.E. Mitchell*
21. Member, Program Advisory Committee for Fundamental Physics for Los Alamos Neutron Science Center (LANSCE), *A.P. Tonchev*
22. Member, the Scientific Program Committee, 19th International Conference on Few-Body Problems in Physics, Bonn, Germany, 2009, *W. Tornow*

23. Member, International Advisory Committee of International Symposium on Advanced Photons and Science Evolution, Osaka, Japan, 2010, *W. Tornow*
24. Member, International Advisory Committee of 21st European Conference on Few-Body Problems in Physics, Salamanca, Spain, 2010, *W. Tornow*
25. Member, Review Committee for the NRF Program at PNNL, 2009 - 2010, *H.R. Weller*
26. Invitee, DOE SBIR-STTR Exchange Meeting, Gaithersburg, MD, 2010, *H.R. Weller*
27. Member, DOE/NSF Nuclear Science Advisory Committee, 2007 - 2009, *J.F. Wilkerson*
28. Member, the Editorial Board Physical Review C, 2007 - 2009, *J.F. Wilkerson*
29. Member, the Program Committee for the Division of Nuclear Physics, American Physics Society, 2008 - 2009, *J.F. Wilkerson*
30. Member, the Organizing Committee for the International Neutrino Summer School, 2008 - 2009, *J.F. Wilkerson*
31. Member, the International Organizing Committee, Conference on the Intersections of Particle and Nuclear Physics, 2008 - 2009, *J.F. Wilkerson*
32. Member, the International Advisory Committee, XIIth International Conference on Topics in Astroparticle and Underground Physics, 2010 - present, *J.F. Wilkerson*
33. Member, the International Scientific Program Committee, the 31<sup>st</sup> International FEL Conference, Liverpool, UK, August 23 - 28, 2009, *Y.K. Wu*
34. Member, Member, the Scientific Advisory Board (SAB) of the First International Particle Accelerator Conference (IPAC '10), Kyoto, Japan May, 24 - 28, 2010, *Y.K. Wu*
35. Member, Panel for the DOE Office of Nuclear Physics, Early Career Award Program Review, DOE Headquarters, Germantown, Maryland, December 3 - 4, 2009, *Y.K. Wu*
36. Member, the International Scientific Program Committee, the 32<sup>nd</sup> International FEL Conference, Malmö, Sweden, August 23 - 27, 2010, *Y.K. Wu*
37. Member, the Scientific Advisory Board (SAB) of the Second International Particle Accelerator Conference (IPAC '11), San Sebastian, Spain, September 5 - 9, 2011, *Y.K. Wu*
38. Member, the Scientific Program Committee, 2011 Particle Accelerator Conference (PAC '11), New York, March 28 - April 1, 2011, *Y.K. Wu*
39. Member, Organizer for the Workshop "Research Opportunities with Ultracold Neutrons in the US", Nov. 2009 (with S. Wilburn, of Los Alamos National Laboratory), *A.R. Young*
40. Member, Review Committee for NSERC, NSF and DOE, *A.R. Young*
41. Member, Journal review for Phys. Rev. A, C and Letters, and Nucl. Instrum. and Methods, *A.R. Young*

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**Conferences, APS Meetings and Workshops**

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1. Chair, the Workshop on Partonic Transverse Momentum in Hadrons: Quark Spin-Orbit Correlations and Quark-Gluon Interactions, Duke University, March 12 - 13, 2010, *H. Gao*
2. Member, National Nuclear Physics Summer School (NNPSS) Committee, 2009 - 2010, *H. Gao*
3. Vice President, Overseas Chinese Physicist Association, January 2009 - December 2010, *H. Gao*
4. Member, APS/AIP/AAPT National Task Force on Teacher Education in Physics, *D.G. Haase*
5. Past Chair, the Southeastern Section of the American Physical Society, *D.G. Haase*
6. Chair, the Nuclear Astrophysics Workshop, Chapel Hill, NC, 2009, *C. Iliadis*

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## Other Service

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1. Member, Program Advisory Committee, Jefferson Lab, 2009 - Current, *H. Gao*
2. Panel Member, DOE Early Career Award Research Application Review, December 3 - 4, 2009, *H. Gao*
3. Associated Member, the EuroGENESIS (European Science Foundation), 2009 - present, *C. Iliadis*
4. Field Editor, Experimental Physics of Few-Body Systems, Springer Verlag Journal, *W. Tornow*
5. Member of Editorial Board for Physical Review C, *H.R. Weller*
6. Panel Member, the Deutsche Forschungsgemeinschaft (DFG), Sept. 2009, *A.R. Young*
7. Spokesman, UCNA project, *A.R. Young*

