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Nuclear Astrophysics in an Underground Accelerator Laboratory

Experimental nuclear astrophysics is concerned with the study and measurement of nuclear processes that drive both the steady evolution and the explosion of stellar systems. In the Precision Era of nuclear physics, simulating stellar conditions in the laboratory is a crucial link for interpreting the wealth of observational elemental and isotopic abundance data from satellite-based observatories through complex computer simulation of stellar evolution and explosion. Two major goals have crystallized over the past decades. The first centers on understanding hydrostatic nuclear burning through the different phases of stellar evolution, determining the lifespans of the stars and the onset conditions of stellar explosions. The second goal focuses on the understanding of nuclear processes far off stability, which characterize nucleosynthesis in novae, X-ray bursts, and supernovae. They also determine the elemental and isotopic abundances observed in stellar atmospheres, in the meteoritic inclusions that have condensed in stellar winds and through gamma ray observatories. The laboratory measurement of nuclear processes in stellar explosions requires the development of a new generation of radioactive beam facilities both to produce the exotic short-lived nuclear species and to observe reactions that occur on the split-second timescales of stellar explosions (ISAC II, RIA, and Riken). Different techniques are needed for the study of reactions that characterize the long-lasting, quiescent periods of stellar evolution. A new generation of high intensity, low-energy accelerators for stable beams must be built to simulate within human timescales the processes that occur in nature over stellar lifetimes. To obtain empirical information regarding the effects of stellar plasma on fusion rates, one must go to very low energies in the laboratory where the effects of atomic electrons become most important. While more than thirty years of intense experimental study have allowed us to define the major features of nuclear burning during hydrostatic stellar evolution, so far only two fusion reactions have been studied at the actual stellar energy range (one of them with the first underground accelerator experiment LUNA I at the Laboratori Nazionale del Gran Sasso). Many other rates crucial to stellar modeling have been deduced indirectly from extrapolations of higher energy laboratory data. These extrapolations can be off by orders of magnitude in cases where the underlying nuclear structure is poorly constrained. The resulting uncertainties complicate the modeling of important phases of stellar evolution, such as the CNO reactions within massive main sequence stars and the later stages of nuclear burning where reactions on heavier species dominate (e.g. production of ^{26}Al in massive stars and novae). Descriptions of the red giant and the asymptotic giant helium and carbon burning phases, which probably are the sites for the slow neutron capture (s-) process responsible for the origin of more than half of the known elements, are also limited by nuclear physics uncertainties. Within our field we identified the following scientific problems which can be effectively addressed through the establishment of a low-background underground accelerator facility aimed at the direct measurement of nuclear reactions of astrophysical interest at stellar energies.

- A) ^{12}C$(\alpha,\gamma)^{16}$O.

The rate of this reaction determines the ^{12}C/^{16}O ratio produced by helium burning, and subsequently determines the structure and nucleosynthesis, as well as the final outcome of the evolution (neutron star or black hole). Calculation of the reaction rate in helium-burning conditions requires knowledge of the cross section near Ecm=300 keV, while experimental data exist only for $E_{cm} > 1$ MeV. In this case the extrapolation to lower energies is complicated by two states just below the $^{12}C + \alpha$ threshold; present data and extrapolations do not come close to the 10 % precision at 300 keV required to adequately constrain astrophysical calculations [1].

The existing experiments have primarily been limited by cosmic-ray background in gamma-ray detectors, beam-induced backgrounds (but diminishing at the lower energies), and limited beam currents. Several different techniques have been applied to this reaction with comparable levels of success. Two general possibilities are thus under consideration: an intense ^{12}C beam in conjunction with a ^{4}He gas jet target, gamma-ray detectors, and a recoil separator; or alternatively the use of ^{12}C targets, an intense ^{4}He beam, and gamma detectors. In either case the gamma-detection scheme would be a large solid angle array of either scintillator or high-purity Germanium detectors. A high-current accelerator facility located deep underground would clearly address the limitations of previous experiments.

- B) S-process Neutron Sources: $^{13}C(\alpha, n)^{16}O$ and $^{22}Ne(\alpha, n)^{25}Mg$

  In intermediate mass AGB stars, the $^{13}C(\alpha, n)$ reaction is thought to be the main s-process neutron source, operating about 1×10^8 K. The $^{22}Ne(\alpha, n)$ reaction operates at the somewhat higher temperature of $(2 - 3) \times 10^8$ K and is the dominant s-process neutron source in more massive stars. The rates of these reactions determine the neutron density during the s-process, and also help to pin down the site(s) of the s-process. S-process nuclei contribute significantly to the production of the elements between Fe and U, a scientific question identified in the NRC Report on "Physics of the Universe" among the most urgent to be addressed. Although measurements of the $^{13}C(\alpha, n)$ reaction have reached down to $E_{cm} = 300$ keV, the extrapolation to the needed range of 150-200 keV is hampered by uncertain subthreshold resonances – yielding a reaction rate uncertain by an order of magnitude. In the case of $^{22}Ne(\alpha, n)$ the reaction rate is thought to be dominated by narrow resonances. The rate is highly uncertain due to the possibility of unobserved weak resonances just above the threshold – according to the NACRE compilation the uncertainty at $T = 2 \times 10^8$ K is more than 2 orders of magnitude. Previous measurements of these reactions have detected neutrons by moderating them in polyethylene and then detecting the thermal or epithermal neutrons with ^{3}He-filled proportional counters. This method has a high efficiency for detecting neutrons (20-50 %) and is insensitive to gamma rays or charged particles. The detectors are however sensitive to all neutrons – including those produced by cosmic-ray spallation. The previous experiments (all exploiting active and passive shielding extensively) have all been limited in sensitivity by cosmic-ray generated neutrons. Moving these experiments to a deep underground laboratory thus offers an excellent and straightforward opportunity to improve our knowledge of these reaction rates. In the case of $^{13}C(\alpha, n)$ the cross section measurements could be extended to lower energies, while in the case of $^{22}Ne(\alpha, n)$ the possible lower-energy resonances could be either measured or much more tightly constrained. To reach the ultimate sensitivity it may also be profitable to develop ^{3}He-filled proportional counters with reduced levels of alpha emitters on the inside walls.

- C) Very Light Systems: ^{3}He$(\alpha,\gamma)^7$Be and ^{2}H$(\alpha,\gamma)^6$Li

  The ^{3}He(α,γ) reaction is a key process for the pp-chains II and III leading to the production of the high energy ^{7}Be and ^{8}B neutrinos from our sun. Having a Q-value of 1586 keV, the gamma-spectrum consists of three lines at approximate energies of E_γ = 1.6, 1.2 and 0.43 MeV. The energy of the lowest data point measured up to now is E_{cm} = 107 keV, while the Gamow window of this reaction in the sun is centered around 22.9 keV with a width of 12.8 keV. The ^{2}H$(\alpha,\gamma)^6$Li reaction is responsible for ^{6}Li production in the big bang. Laboratory measurements only extend down to E_{cm} = 600 keV, considerably higher than the 50-200 keV energy range needed for big bang predictions. Although at present no ^{6}Li has been detected which can be attributed to standard big bang production, an improved estimate of the reaction rate is important for several reasons: (1) primordial ^{6}Li may eventually be observed in metal-poor halo stars, (2) non-standard big-bang models predict higher ^{6}Li production, and (3) a firm understanding of the primordial ^{6}Li is needed in order compare ^{6}Li observational data to cosmic-ray production and chemical evolution models.

- D) Hydrogen burning scenarios

  Other hydrogen burning reactions occuring in the CNO, NeNa and MgAl cycles (or chains) are important in main sequence stars as well as in evolving stars and have significant rate uncertainties at low energies, both in the non-resonant and resonant rate contributions [2]. Without going into detail in individual cases, we note that low background studies are needed for (p,γ) and in some cases (p,α) reactions on the isotopes of N, O, Ne, Na, Mg and Al, probably also up to K. The CNO cycle contributes significantly to the solar neutrino spectrum and all cycles are needed for an understanding of the observed isotopic abundance anomalies (such as ^{17}O, ^{22}Ne and ^{26}Al) showing unequivocally that solar system formation did not completely erase the history recorded in material that became the solar system [3].

- E) Physics Summary

  In addition to direct astrophysical motivations, it is highly desirable that neutrino physics and cosmological conclusions not be limited by uncertainties in the nuclear physics input. A low-background underground accelerator laboratory would provide a means for the nuclear astrophysics community to continue to address these needs into the future. Most of the scientific motivation had already been discussed [4] in the planning process for the extension of the underground accelerator experiment at Gran Sasso (LUNA). Due to financial and (more important) space constraints at Gran Sasso, most of the recommendations of this report could not be realized and limit the capabilities of the LUNA II facility. We plan to use the new scientific opportunities following a three-stage process, which could start immediately with the operation of the National Underground Science Laboratory (NUSL).

- F) Equipment

– Stage I: In the first stage we would need to concentrate on gamma and neutron detector development (moderated neutron detector, different large scintillation detector) to find the optimum solutions for low intrinsic background in the underground detector setups. Here we will also need to select materials for chamber, target and shielding constructions. Area: 5m $\times$ 10m $\times$ 3m high; 50 kW electrical; ventilation and chilled water.
– Stage II: Setting up a 0.6 - 1 MeV, 1-10 mA light ion (p and α) machine, for a variety of measurements as well as for target (reduction of beam induced background) development. As every reaction brings its own background problems, we anticipate being able to address only one or two reactions each year, thus requiring stringent selection in our scientific program. Area: 15m $\times$ 10m $\times$ 5m high; 200 kW electrical; ventilation and chilled water; crane.
– Stage III: In parallel to the above stages a heavy ion linear accelerator with recoil separator and gas jet target needs to be developed, which will address the measurements which require the use of reverse kinematics (which often helps reduce beam induced background). We see this setup as the key to a low energy measurement of the $^{12}C(\alpha,\gamma)^{16}O$ reaction, as well as for certain proton induced reactions. Area: 15m $\times$ 30m $\times$ 5 m high; 900 kW electrical; ventilation and chilled water; crane.

A depth of 4850 feet would be fully sufficient for our research. The technical approaches and experimental details will be discussed at a workshop early in 2002, which shall also generate an organizational structure for the collaboration. All stages will need strong technical and infrastructure support from the participating accelerator laboratories.

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