A HIGH-PRESSURE ^{3}HE GAS SCINTILLATION NEUTRON SPECTROMETER*

Mark S. Derzon
Department of Nuclear Engineering
University of California
Berkeley, California 94720

and

Dennis R. Slaughter and Stanley G. Prussin†
Lawrence Livermore National Laboratory
P.O. Box 808, L-405
Livermore, California 94550

Abstract: A high-pressure, ^{3}He-Xe gas scintillation spectrometer has been developed for neutron spectroscopy on D-D fusion plasmas. The spectrometer exhibits an energy resolution of (121 ± 20 keV) keV (FWHM) at 2.5 MeV and an efficiency of (1.9 ± 0.4) x 10^{-3} $(n/cm^2)^{-1}$. The contribution to the resolution (FWHM) from counting statistics is only (22 ± 3 keV) keV and the remainder is due predominantly to the variation of light collection efficiency with location of neutron events within the active volume of the detector.

I. Introduction

The measurement of time resolved Doppler widths on the 2.5 MeV neutrons from D-D fusion plasmas requires a spectrometer with good resolution (~100 keV), moderate efficiency (~10^{-2} $(n/cm^2)^{-1}$) and the capability of operation at high event rates. Because of its potential to meet these requirements, we have studied the properties of the ^{3}He gas scintillation spectrometer (^{3}He-GSS). This type of device has an extensive history as a particle detector and spectrometer.[1-3] Unfortunately, the energy resolution reported by different investigators has varied widely and no clear understanding for this has been presented. We have attempted to quantify the contributions of detector design parameters to the instrument resolution in an effort to optimize spectrometer performance for the present purpose.

The reaction utilized in spectrometers of this type is

$$n + {}^3He \longrightarrow p + {}^3H \quad (1)$$

which has a Q-value of 0.764 MeV and a cross section of 0.76 b at 2.5 MeV. The energy lost by the charged reaction products in slowing down in the fill gas leads to the emission of light with an intensity proportional to the energy deposited.[4] The pulse-height spectrum from the interaction of D-D neutrons in a typical detector is composed of a discrete peak at 3.2 MeV, a continuum extending from the peak to lower energies due to events where product trajectories intercept the chamber walls, a second continuum with a maximum energy of 1.9 MeV that arises from elastic scattering of 2.5 MeV neutrons on ^{3}He and a discrete peak due to thermal and epithermal neutrons which are inevitably present from neutron scattering in materials external to the detector.

The principal factors governing the inherent resolution of a ^{3}He-GSS are the statistics of light production and detection and the spatial dependence of the light collection efficiency. The overall contribution to the energy resolution from these factors can be estimated from the variance

$$\sigma_s^2 = NF \quad (2)$$

where N is the mean number of detected photons and F is the Fano factor for light production in the slowing down process. N can be calculated from

$$N = E\Omega q/\epsilon_\gamma \quad (3)$$

where E is the energy deposited in the active volume of the detector, Ω is the fraction of scintillation photons reaching a light sensor, ϵ_γ is the mean energy deposited per photon produced and q is the quantum efficiency for photon detection. The Fano factor for noble gas scintillation has been measured as F = 0.170 ± 0.007[5] and we have used the value ϵ_γ = 28 ± 4 eV.[6] The quantum efficiency for the photomultiplier tubes used to measured the light from our detectors was taken from the supplier's measurements.[7]

The photon collection efficiency is dependent upon the details of the spectrometer design which include detector geometry, gas pressure and the composition of and properties of the chamber walls and windows. In order to model light transport under various conditions, we have developed a MonteCarlo ray-tracing code[8] which permits simulations with wavelength-dependent reflectivities, index of refraction and transmission and with the presence of wavelength conversion at the chamber walls and windows. We investigated detector geometries for which the active volume was viewed by either a single (1-window) or two (2-window) photomultiplier tubes. Both pyrex and quartz windows were studied.[9] The simulation indicates that N varies with the location of the event in the chamber active volume. The effect of the variance in N due to spatial variation, σ_V^2, upon the resolution is summarized in Table 1. Two of the more promising designs were constructed, evaluated experimentally and their performance compared with the performance calculated from the computer simulations.

II. Detector Description

A schematic of the stainless steel, high-pressure chamber designed for both the 1-window and 2-window geometries is shown in Figure 1. The active volumes for the two geometries are defined by the aluminum shell inserts shown in Figure 2. The surfaces of the shells were first coated with Kodak

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†Permanent Address: Department of Nuclear Engineering, University of California, Berkeley, California 94720.

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Comparison of predicted and measured number of photoelectrons and resolution (keV)

		Thermal neutrons, $E_n \cong 0$		
1 window system	Predicted no. of photoelectrons[a]	Measured no. of photoelectrons	$2.35\,(\sigma_v^2 + \sigma_\gamma^2)^{1/2}$ (keV)	FWHM (keV)
Pyrex	2800 – 2940[b]	3100 ± 440	86 – 200[b]	77 ± 5
Quartz	3180 – 3720	4400 ± 140	65 – 165	46 ± 5
2 window system				
Pyrex	2460 – 3300	–	27 – 84	76 ± 8
Quartz	3660 – 3780	–	23 – 50	–
		$E_n \cong 2.5$ MeV		
1 window system			Collimated[c]	
Pyrex	–	–	75 – 111	–
Quartz	–	–	75 – 118	121 ± 20

a) $N_0 \equiv$ number of photoelectrons if 100% light collection = 6000 ± 1000 photoelectrons predicted, based on $q = .22 \pm .02$ and $E_\gamma = 28 \pm 4$ eV

b) The range of values was obtained by simulating changes in the thickness of waveshifter on the window surface

c) With collimator referred to in text

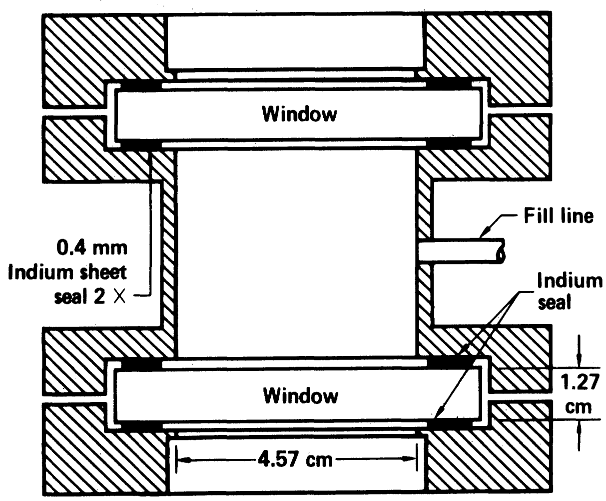

Figure 1. High pressure chamber.

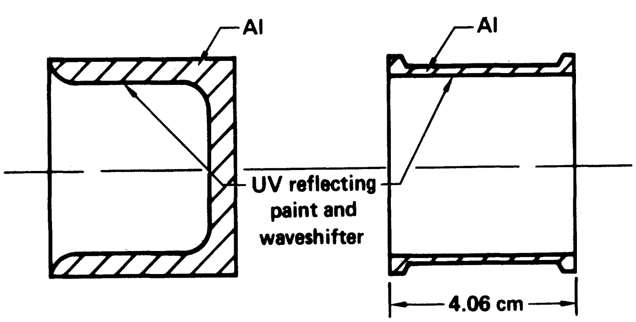

Figure 2. Aluminum inserts.

VUV high-reflectance paint[10] and then with an optically thick coating of p-terphenyl which serves as a wavelength shifter. The latter was prepared by spraying a solution of p-terphenyl in toluene with a low-pressure atomizer and evaporating to dryness.

Based on the results of previous studies,[1,3,4] a thin layer of p-terphenyl was also applied to the internal window surfaces in an effort to provide both high VUV conversion efficiency and good transmittance. We obtained our best results by direct evaporation of a solution of p-terphenyl in toluene on the windows which produced a finely divided coating of uniform thickness.

To control gas purity at the highest level possible, the system was assembled with metal gaskets and all surfaces were thoroughly cleaned with alcohol before assembly. Both ^{3}He and Xe were supplied from vessels maintained at 80° K and extended gettering was accomplished with titanium.[6]

To reduce personnel hazard in the event of window failure, the detector chamber and phototubes were placed inside of a secondary containment constructed of aluminum. The chamber was lined with mu metal to reduce external magnetic fields and by cadmium to shield against thermal neutrons.

III. Comparison of Detector Performance and Modeling

Experimental evaluation included measurement of the number of photons detected with both glass and quartz windows on the chamber. The absolute light gain of an RCA 8850 phototube (glass window) was determined by observing the dynode current due to single photoelectrons (see Figure 3). Because of its poor signal-to-noise ratio, the absolute gain of a RCA C31000M phototube (quartz window) was determined by observing its current output when coupled to the same visible light source as the RCA 8850. From these calibrations, the mean number of detected photons from individual neutron events in the detector was determined. These results are given in Table 1 along with those obtained from the Monte Carlo simulations. The good agreement between the calculated and measured quantities lends confidence to the reliability of the light collection efficiencies obtained from our transport model.

The response of the detector to 2.5 MeV neutrons was measured with D-D neutrons produced by a Kaman Nuclear neutron generator. Most of our measurements were taken with the 1-window geometry and with the detector at an angle of 95° with respect to the deuteron beam. To reduce neutron scattering in detector materials outside the active volume, the source was viewed by the detector through a 1.3 cm (diameter) hole in a 51 cm thick polyethylene collimator.

In order to determine the inherent resolution of the spectrometer, the energy dispersion of the

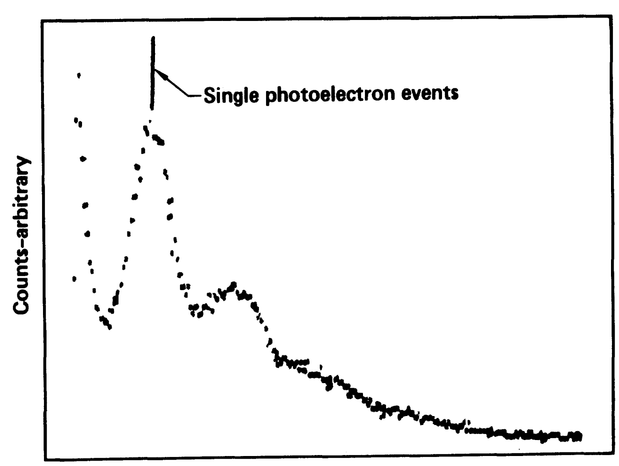

Figure 3. Photoelectron pulse height spectrum.

neutron source under these conditions was measured with a Shalev-Cuttler[11] gridded ionization chamber which yielded a width of 75 ± 16 keV for the 2.5 MeV peak and a width of 35 ± 1 keV for the thermal peak. From these measurements, the energy dispersion of the beam was determined to be 47 ± 16 keV.

In Figure 4 is shown a spectrum acquired when the chamber was filled with both ^{3}He and Xe at partial pressures of 200 ± 10 atm. and with a coating of nominally 1 mgcm^{-2} of p-terphenyl on the chamber window. The measured resolution (FWHM) of the 2.5 MeV peak is 130 ± 13 keV. Adjusting for the beam dispersion leads to a resolution of 121 ± 21 keV for the ^{3}He-GSS under these conditions. As seen in Table 1, the resolution predicted for a 2-window system is comparable to that for the corresponding 1-window system.

The efficiency of the spectrometer in this configuration was determined by calibration of the source strength with a DePhanger Precision Long Counter (PLC).[12] With the ^{3}He-GSS at the same angle relative to the deuteron beam as the PLC, the efficiency of the ^{3}He-GSS is given by

$$\epsilon_{GSS} = \epsilon_{PLC} \left(\frac{N_{GSS}}{N_{PLC}}\right)\left(\frac{r_{GSS}}{r_{PLC}}\right)^2$$

where N_{GSS} = number of counts in the GSS full energy peak
N_{PLC} = number of counts in the PLC after correction for scattered neutrons
ϵ_{PLC} = efficiency of the PLC, ~3.5 counts/(n/cm^2)
r_{GSS} = distance to GSS center
r_{PLC} = distance to PLC effective center for 2.5 MeV neutrons

The efficiency measurement for collimated neutrons incident on the detector used a borated paraffin block (15 x 15 x 38 cm) with a 1.3 cm diameter hole through the center to view the source. The efficiency was found to be (1.9 ± 0.4) x 10^{-3} counts/(n/cm^2) when collimated and (6.7 ± 0.5) x 10^{-3} counts/(n/cm^2) when uncollimated.

IV. Discussion

The detector described here is viable as a neutron spectrometer for fusion experiments. It is capable of approximately 120 keV resolution for nominally 2.5 MeV neutrons. The full energy peak includes a large shoulder on the low-energy side which may be due to neutron elastic scattering in materials near the active volume. Collimating the detector reduces the width of the peak and reduces the relative height of the shoulder. Future development with different window coatings, higher-strength windows, low-mass inserts, and studies of 1-window and 2-window designs may further improve the resolution of the GSS.

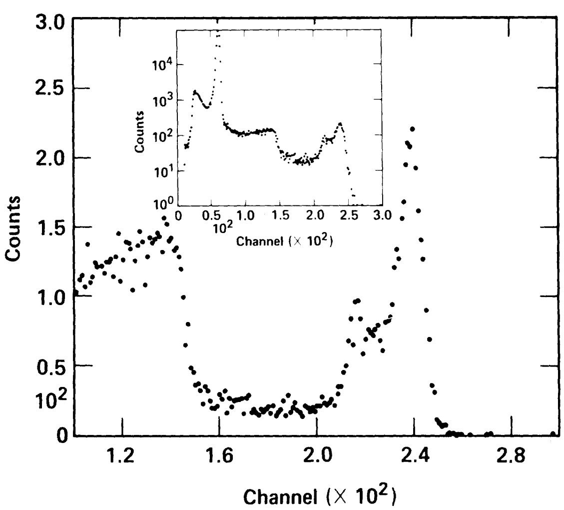

Figure 4. ^{3}He-GSS 2.5 MeV Neutron Pulse Height Spectrum.

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