MAJORITY-LOGIC NE-110 DETECTOR FOR keV NEUTRONS

N. W. Hill, J. A. Harvey, D. J. Horen,
G. L. Morgan,^a and R. R. Winters^b

Oak Ridge National Laboratory
Oak Ridge, Tennessee 37831

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Abstract

An NE-110 proton-recoil scintillation counter whose efficiency is reproducible and stable has been developed for neutrons in the energy range from 5 keV to 1 MeV. Majority-of-two logic at below the single photoelectron level is used between two or more phototubes viewing the same scintillator. Pulse height distributions as a function of neutron energy have been measured between 5 and 350 keV with two different detector configurations: a thin square slab of NE-110 and a cylinder of NE-110. The absolute efficiency of the slab detector has also been determined. The measured results are in good agreement with results from Monte Carlo calculations.

Introduction

Proton-recoil scintillation detectors have long been used for fast neutron counters. Their high efficiencies and fast time response combined with relatively low gamma-ray efficiencies and energy discrimination properties makes them one of the best types of detectors for MeV neutrons. Recent years have seen continuing improvement in the light output of scintillator materials and in the gain and noise characteristics of photomultiplier tubes (PMT). This has made possible the use of such detectors at ever decreasing neutron energies (see for example Refs. 1 and 2).

Two of the greatest difficulties encountered when using these detectors at low neutron energies are: 1) the problems in differentiating between noise and neutron-induced events and 2) the fact that detector efficiencies are extremely sensitive to bias level and therefore tend to be both unstable and difficult to reproduce. A long-used technique for noise rejection has been the requirement of fast coincidence between two or more

MASTER

^a Denison University, Granville, Ohio 43023

^b Now at Los Alamos National Laboratory, Los Alamos, New Mexico 87545

phototubes viewing the same scintillator. The advent of phototubes having good resolution for single photoelectrons has provided a means for using the coincidence technique to solve the second problem as well.

A detector system has been developed using two or more phototubes in a majority-of-two coincidence mode with each phototube biased below the single photoelectron level. This detector system permits the clean detection of keV neutrons with a stable and reproducible efficiency. Two configurations have been studied: 1) a thin, square slab of NE-110 scintillator viewed by three RCA 8850 PMT's and 2) a cylinder of NE-110 viewed by two RCA 8850 PMT's.

Detailed measurements have been made of the pulse-height distributions in these detectors as a function of neutron energy between 5 and 350 keV. The absolute efficiencies have been determined by comparison to a Li-glass detector of known efficiency. Monte Carlo calculations of the response have been made and are compared to the experimental results.

Experimental Technique

Schematic diagrams of the two detector configurations are shown in Fig. 1. The detector in part (a) of the figure was designed to maximize light collection efficiency in order to extend the useful range of the detector to as low neutron energies (~ 4 keV) as possible. Figure 1(b) shows a detector of more conventional geometry with high efficiency for neutron energies between 20 keV and 1 MeV. In each case selected RCA 8850 phototubes were attached to the NE-110 scintillator by means of a ultraviolet transmitting epoxy (EPO-TEK 305). This provided a good optical coupling as well as a mechanically strong and therefore stable attachment. The other surfaces of the scintillator were painted with NE 560 and loosely covered with 0.005 mm aluminum foil.

The voltage divider networks for the phototubes were separated from the tube bases by about 1 meter. This kept power dissipation away from the tubes and significantly reduced the dark current count rate of the tubes, particularly when used in an evacuated scattering chamber. As shown in Fig. 2, a fast three-way fanout amplifier and constant fraction

‡ Epoxy Technology, Inc., Billerica, MA 01821.

** Nuclear Enterprises, San Carlos, CA 94070.

discriminator were used on the output of the anode of each PMT. Another constant fraction discriminator whose input was the sum of the anode signals provided the timing information.

Figure 3 shows a typical dark current spectrum from one of the RCA 8850 PMT's. This spectrum consists of two components: 1) a continuum distribution due to thermionic emission from the dynode structure and 2) a peak due to emission of single electrons from the photocathode. Peaks due to two, three, etc. photoelectrons have orders of magnitude lower intensities and are not shown in Fig. 3. As shown in the figure, the discriminator level was set at about 50% of the pulse height due to single photoelectrons. Thus changes in the bias level of up to 50% did not appreciably change the efficiency for detection of single photoelectrons. Typical dark current counting rates for the single photoelectron peak were from a few hundred to approximately one thousand counts per second depending on the particular PMT.

Signals from the anode discriminators on each PMT were put in fast coincidence (~ 6 ns) on a majority-of-two basis. The output of this coincidence circuit was then used as a coincidence window for the constant fraction discriminator on the summed anode signals. This second coincidence was done in such a way that timing information was derived from the summed signal constant fraction discriminator.

The single and summed anode signals were also used as the input to an integrating stretcher circuit gated by the coincidence network. This provided a slow signal proportional to the total amount of light collected by the PMT's.

Pulse height distributions were measured from these two detectors using the Oak Ridge Electron Linear Accelerator as a pulsed white neutron source, although somewhat different techniques were used in each case. The slab detector was positioned in a collimated neutron beam 80 m from the linac target. A ^6Li -glass detector of known efficiency was mounted in a transmission configuration about 1.0 m upstream from the NE-110 detector (see Fig. 2). Incident neutron energies were determined by time of flight and a pulse height spectrum was recorded in a two-parameter array for a series of incident neutron energies. Three measurements were made. One used a neutron beam filtered through 30 cm of iron to produce spectra at a series of discrete neutron energies between 24 and 184 keV. The second measurement used the unfiltered beam

to measure pulse height distributions for neutron energies between 5 and 350 keV. The third measurement compared time-of-flight spectra for the ^6Li -glass and NE-110 detectors down to neutron energies of less than 1 keV using an unfiltered beam (with 1 in. Bi or Fe used for background determinations) and with "window neutrons" (transmitted through filters of 30 cm Fe or ^{58}Ni).

For measuring the pulse height distributions in the cylindrical detector a carbon slab scatterer was placed in the neutron beam 13 m from the linac target. The detector was mounted vertically about 20 cm from the scatterer at an angle of 90° . The neutron beam was filtered with 35 cm of iron to produce scattered neutrons at a series of discrete energies between 21 and 300 keV. No ^6Li -glass monitor was used with these runs. Only unnormalized pulse height distributions were determined for this detector.

The pulse height scale used in this work is the system of light units defined by Verbinski et al.³ The K-series x-ray from a silver fluorescent x-ray source⁴ (22 keV) had been calibrated on this pulse height scale in an earlier work² and was used as the pulse height calibration in the present study (Ag x-ray photopeak = 0.0143 light units = 200 keV proton recoil energy).

The calibration procedure was as follows: with the coincidence circuit operated in single-event mode, the high voltage on each PMT was adjusted to give the same signal voltage for the single photoelectron peak. The silver x-ray source was used to determine the pulse height scale for the summed signal. In addition, this source was also used to determine the fractional contribution of each PMT tube to the total summed signal. Likewise, the ratio of the x-ray photopeak signal to the single photoelectron signal measures the light (in light units) required on the average to produce a single photoelectron for each of the tubes. This ratio was determined by extrapolation of the pulse heights corresponding to two, three, and four photoelectrons to one photoelectron. The single photoelectron pulse height thus determined from the summed spectrum was in excellent agreement with that observed using the single-event gated mode. In the slab detector, the PMT coupled to the back face contributed about 72% of the total signal while each of the two side tubes contributed 14%. The amount of light required to produce a single photoelectron in the summed signal was 0.00055 light units (i.e., the silver x-ray peak corresponded to about 26 photoelectrons). For the

cylindrical detector each PMT contributed 50% and the silver x-ray peak corresponded to 19 photoelectrons.

As pointed out in earlier work,⁵ for the small number of photoelectrons involved here the effects of Poisson statistics on the calculated efficiency are significant. Thus determination of the average amount of light required to produce a photoelectron is an important factor in calculating the detector efficiency.

Calculation of Efficiency

The absolute differential efficiencies (pulse height distributions) of the detectors were calculated with the Monte Carlo code 05S.⁶ For a given incident neutron energy this code calculates the absolute response of the scintillator as a function of the light output (using the light scale and light production curves of Ref. 3). This code was developed about 16 years ago at ORNL by Textor and Verbinski who used it to calculate efficiencies for NE-213 scintillation counters. Absolute efficiency measurements⁷ were made at that time using associated particle techniques which verified the accuracy of the code. More recently Renner et al.^{2,8} tested the validity of the light production curves for NE-110 and showed that the code gave accurate results for the calculation of nearly black (thick) detectors in the neutron energy range 82 to 700 keV.

For the present work the code was modified to lower the cut-off energy (the energy below which a neutron history is terminated) from 20 keV to 100 eV. In addition, for the slab detector, the increased light output for carbon recoils used in Ref. 2 was also used here. However, it was found that the original carbon recoil light production curve of Ref. 3 gave a much better fit to the measured data for the cylindrical detector. Since the dependence of the carbon recoil contribution to the scintillator light output on scintillator geometry was included here as in Refs. 2 and 3, it is conjectured that carbon recoil light in NE-110 must have a shorter attenuation length ($1/e$) than proton recoil light. The data of Ref. 2 which indicated larger values for carbon recoil light were obtained using a thin (0.635 cm) scintillator. Thus these measurements are more or less consistent with the slab detector of the present work, whereas the cylindrical detector is nearly the same size and shape as the detectors³ for which the 05S code was originally developed.

The output of the 05S code was then processed by a second code which allowed for the specific properties of a particular detector, i.e., the Poisson statistics and the majority-of-two coincidence requirements. The procedure for matching the calculated spectra to the measured pulse height distributions was as follows: for each phototube the absolute response in each light bin is distributed among the possible events (with its integral number of photoelectrons) according to a Poisson distribution determined by the average number of photoelectrons for that light bin as measured from the x-ray spectrum for that PMT. This results in a distribution for each PMT of the form

$$P_i(n) , \quad (1)$$

where $P_i(n)$ is the probability that an incident neutron will result in n photoelectrons being produced in phototube i . These probabilities are then combined to produce the probability for detecting an event with N photoelectrons (total) according to the equation (e.g., for the slab detector with 3 PMT's)

$$P(N) = \sum_{i+j+k=N} P_1(i)P_2(j)P_3(k) , \quad (2)$$

where P is the probability that an incident neutron will produce N photoelectrons in the summed signal. The sum in Eq. (2) is subject to the constraint that $i+j+k=N$ and that at least 2 of the arguments are equal to or greater than 1. That is, terms of the form $P_1(0)P_2(0)P_3(2)$ will not contribute. This last constraint explicitly takes into account the majority-of-two coincidence requirement. The distribution $P(N)$ consists of a series of "spikes" at each integral value of N , the magnitude of P being the probability for a neutron to produce N photoelectrons with $\leq N-1$ in a single detector.

This distribution was then smeared by a Gaussian function whose width has a dependence on pulse height (number of photoelectrons, N) of the form

$$R^2 = A^2 + B^2/L^2(N) , \quad (3)$$

where the fractional resolution, R , is the FWHM, A and B are constants, and $L(N)$ is the light output corresponding to N photoelectrons. This smearing approximates the variations in light collection efficiency, gain variations in the PMT, and spreading due to PMT noise.²

The measured pulse height distribution was scaled in pulse height according to the gain as determined using the silver x-ray source. Then the measured spectrum was normalized to have the same area as the calculated response. A value of χ^2 between the experimental data and the calculated curve was then formed. This process was repeated, varying the gain of the measured spectrum and the width of the Gaussian smearing [the parameters A and B in Eq. (3)] until the value of χ^2 had been minimized. The Gaussian smearing was required to be consistent at all neutron energies. The exact value of the gain was not required to be the value given by the x-ray source and was allowed to vary somewhat with neutron energy. This was because differences in the volume of interaction for x-rays and neutrons lead to small differences in light collection efficiency. The gain used for the best χ^2 with the neutrons was within 5% of that obtained with the x-ray source and varied in a smooth, monotonic manner with neutron energy.

It should be noted that the calculated integral efficiency does not depend on either the gain or the Gaussian smearing width, but only on the average light per photoelectron and the fractional contribution of each PMT. Figures 4-9 compare calculated and measured pulse height distributions at several neutron energies for the two detectors. As indicated in the figures, agreement is quite good and thus indicates that the calculated shapes are consistent with the experimental spectra. The calculated efficiencies are listed in Table 1 and are shown in Fig. 10 for the slab detector.

As described in the previous section, the absolute integral efficiency of the slab detector was also determined by simultaneous measurement with a ^6Li -glass scintillation detector of a time-of-flight spectrum from the white neutron source. The ^6Li -glass detector was calibrated by determining the ^6Li content with low energy transmission measurements (in the $1/\nu$ region). The overall transmission of the detector in the energy region of interest (1-350 keV) was also measured by standard (sample in/sample out) techniques. The efficiency was calculated using the measured ^6Li content, the overall transmission, and multiple scattering corrections calculated by a Monte Carlo technique described in Ref. 8. The resulting values for the efficiency of the slab detector are also listed in Table 1. Agreement with the calculated efficiencies is generally good.

The direct comparison to the ^6Li -glass detector, both with continuous, unfiltered neutron beams (with 1 in. Bi or Fe) and with "window neutrons" (with thick filters of Fe or ^{58}Ni) indicate that the slab detector has higher efficiency than the ^6Li -glass (1.3 cm thick) for neutron energies above 4 keV. In addition, its time resolution is superior. Backgrounds in the slab detector are generally lower than with the ^6Li -glass, probably due to its insensitivity to thermal neutrons.

Applications

Examples of the use of majority-logic detectors for measurements involving neutrons with energies in the keV range are given in Refs. 9 and 10. The measurement of inelastic neutron scattering to the level at 45 keV in ^{238}U is summarized here as an illustration of such applications. The experimental arrangement is shown in Fig. 11. Neutrons from the pulsed white neutron source at ORELA were filtered through iron to produce a sharp line at 82 keV. These neutrons were then scattered from a sample of ^{238}U . Elastically and inelastically scattered neutrons were detected using the slab detector described above. The overall time of flight from source to sample to detector was somewhat longer for those neutrons which are inelastically scattered and therefore reduced in energy to 37 keV. The good time resolution of the detector permitted separation of the two energy groups and thus allowed determination of the relative cross sections for elastic and inelastic scattering. A time-of-flight spectrum is shown in Fig. 12. The calculated relative efficiencies as shown in Fig. 10 were used to reduce these peak areas to relative cross sections.

Conclusions

A detector has been designed which uses majority coincidence logic combined with the single photoelectron resolution of high quality, modern photomultiplier tubes. Coupling such phototubes with a scintillator having high light output and transparency, such as NE-110, results in a neutron detector with a high and stable efficiency for neutrons in the keV region. Monte Carlo calculations of the response of the two detectors described here show good agreement with measured data. For the slab detector, comparison to a calibrated ^6Li -glass detector confirmed that the calculated integral efficiencies are correct to 5%. Time-of-flight measurements with

the slab detector and ^6Li -glass detector demonstrate that the detector developed in the present work is superior to ^6Li -glass scintillation detector for neutron energies down to 4 keV.

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Figure Captions

1. Schematic diagram of the neutron detector.
2. Schematic diagram of detector configuration and electronics.
3. Typical dark current spectrum for an RCA 8850 PMT. The vertical arrow indicates the discrimination level.
4. Measured and calculated response for the slab detector at a neutron energy of 7.3 keV.
5. Measured and calculated response for the slab detector at a neutron energy of 82 keV.
6. Measured and calculated response for the slab detector at a neutron energy of 350 keV.
7. Measured and calculated response for the cylindrical detector at a neutron energy of 21 keV.
8. Measured and calculated response for the cylindrical detector at a neutron energy of 142 keV.
9. Measured and calculated response for the cylindrical detector at a neutron energy of 300 keV.
10. Integral efficiency of the slab detector as calculated by Monte Carlo code and as determined by comparison to ^6Li -glass.
11. Experimental arrangement employing majority-logic detector for the measurement of inelastic neutron scattering.
12. Typical time-of-flight spectrum for neutrons scattered from ^{238}U . The peak near 2305 ns is due to elastically scattered neutrons, while that near 2350 ns is due to

neutrons inelastically scattered from the 45-keV level.

Table 1. Tabulated Efficiencies

Neutron Energy (keV)	Analytic Zero Bias Eff.	Monte Carlo Eff. (3 PMT's)	Eff. by Comparison to Li-Glass
A. Slab Detector (3 PMT's)			
0.78			0.009
2.23			0.041
7.3	0.909	0.240	
11.4			0.31
15.3			0.34
16.8	0.894	0.386	
24.5	0.883	0.456	0.45
30.3	0.881	0.497	
37.0	0.873	0.531	
50.4	0.856	0.580	
82.0	0.826	0.623	0.68
104.7	0.805	0.630	
128.7	0.788	0.632	
137.5	0.776	0.626	0.66
168.1	0.756	0.624	
173.3	0.757	0.625	
184.0	0.750	0.622	
250.0	0.707	0.600	
350.0	0.660	0.573	
B. Cylindrical Detector (2 PMT's)			
20.7	0.954	0.456	
69.4	0.933	0.727	
116.3	0.909	0.762	
142.0	0.896	0.752	
186.0	0.880	0.740	
232.0	0.863	0.729	
263.0	0.851	0.714	
300.0	0.842	0.706

1a

4.3cm dia. x 7.6cm LONG NE-110

1b

ORNL-DWG 80-15173

ORNL - DWG 80 - 14874