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ABSOLUTE NEUTRON FLUX MEASUREMENTS USING AN NE-110 SCINTILLATION COUNTER*

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A neutron detector consisting of an NE 110 plastic scintillator has been calibrated for absolute neutron fluence measurements in the energy range 80 to 500 keV. Efficiencies were determined by Monte Carlo calculations. Comparisons of measured and calculated pulse height spectra are presented.

1 Introduction

Many applications in neutron spectroscopy require the absolute determination of neutron fluxes. Some desirable characteristics of a detector for such measurements are fast timing, flat response vs neutron energy, and ease and accuracy of calibration. This report describes the calibration and testing of an NE 110 scintillation counter capable of 1% accuracy over the neutron energy range from 80 to 500 keV.

In recent years the development of low noise photomultiplier tubes and organic scintillators with large light output and high transparency have made possible the use of proton recoil scintillation counters for relatively low energy (> 20 keV) neutron detection (see for example refs 1 and 2). Several workers^{3,4}) have developed scintillation detectors which are nearly black and almost totally absorbing. These detectors have been shown to have good time resolution and efficiencies which vary slowly with energy. To date these detectors have been studied mostly at neutron energies greater than 300 keV.

Two problems are encountered in attempting to employ this type of detector at even lower energies. These are (1) the uncertainties in the relation of proton recoil energy and light output and (2) the need for a convenient and accurate method of establishing a pulse height scale at the low light levels encountered.

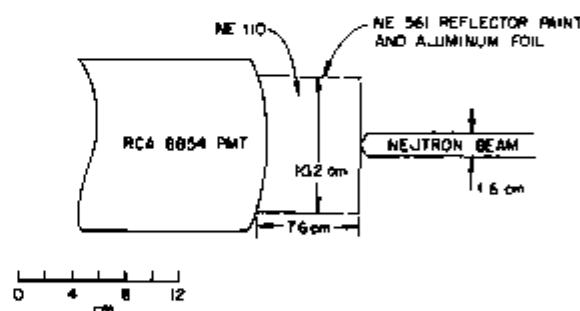
In this paper are presented the results of investigations of the pulse height vs energy curve, gain determinations using an X-ray source, and absolute calibration techniques employing Monte Carlo

calculations. Measurements with a thick NE 110 detector for neutron energies between 80 and 500 keV are presented.

2 Experimental technique

In the work reported here the Oak Ridge Electron Linear Accelerator (ORELA) was used as a pulsed white neutron source. Previous investigations⁵) have shown that a white neutron beam filtered by 20 to 30 cm of pure iron provides an effective tool for measurements in the energy range from 24 to 1000 keV. The total cross section of

1a) THICK SCINTILLATOR



1b) THIN SCINTILLATOR

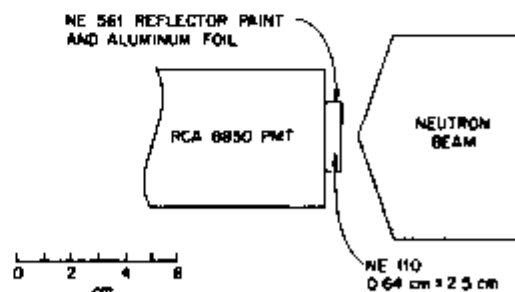


Fig. 1 Schematic diagram of scintillators, phototubes and collimated neutron beams.

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¹ Operated by Union Carbide Corporation for the Department of Energy.

iron has pronounced resonance structure with interference minima producing a series of windows which for thick filters of iron transmit neutrons only at discrete energies. This allows concentration of the counting rate at a number of well determined energies and permits very accurate determination of backgrounds by measurement in the energy regions outside the windows.

Two parameter data acquisition with on line computers was used to simultaneously obtain pulse height spectra at each of the window energies as well as background spectra from between windows. A fast signal from the anode of the phototube supplied the time of flight information needed to determine neutron energy. Flight paths of 80 or 30 m were used. An integrated linear signal from a dynode was used as a measure of light output from the scintillator.

Schematic diagrams of the two types of detectors used in this work are shown in fig. 1. The thin scintillator (part b fig. 1) was used to investigate pulse height vs energy relations and to develop gain calibration procedures. Thick scintillators (similar to part a fig. 1) were studied to determine the best trade off between total absorption and light collection. A narrow beam (1.6 cm diameter) was used with the thick scintillator in order to permit more effective trapping of neutrons in the scintillator. For the thin scintillator we used a neutron beam with a diameter somewhat larger than the detector.

3. Light output and gain calibration

As in previous work^{1,4)} on black detectors the present work is based on the definition of light units and the light output vs energy curves of Verbinski et al.⁵⁾ These authors define a scale of light output in which the Compton edge for the 1.275 MeV gamma rays from a ²²Na source occurs at 0.895 light units. They also give a table of light output vs proton and carbon recoil energy for NE 213 scintillators. The proton curve is based on measurements above $E_p = 200$ keV but is an estimation based on empirical formulas for lower energies.

Using the thin NE 110 detector three questions were addressed:

(1) the light output from the ²²Na source is very large (≈ 30 times) compared to the light output from proton recoils of a few hundred keV and therefore a secondary standard with more compatible light output was needed.

(2) It was necessary to ascertain whether the light curve given in ref. 6 for NE 213 was applicable to NE 110.

(3) Measurements were needed to test the validity of the curves below 200 keV.

For convenience in setting up a detector a γ ray source with light output close to that for approximately 200 keV protons is desirable. Previous work¹⁾ has shown that organic scintillators show some non linearity in response to electrons at the lower energies. Therefore after choosing an appropriate γ ray source it was necessary to standardize this source against the ²²Na source. This standardization was carried out using the thin scintillator and an amplifier for the linear signal which had an accurately measured factor of 10 in gain change. The linearity and zero intercept of the entire system (pre amp, amplifier and ADC) was measured with a precision pulser.

The γ ray source selected was an X ray source⁶⁾ in which the K series X rays from silver are produced by fluorescence with 59 keV γ rays from ²⁴¹Am. These X rays have an average energy of 23 keV. Even in the thin scintillator these X rays produced a very well defined peak corresponding

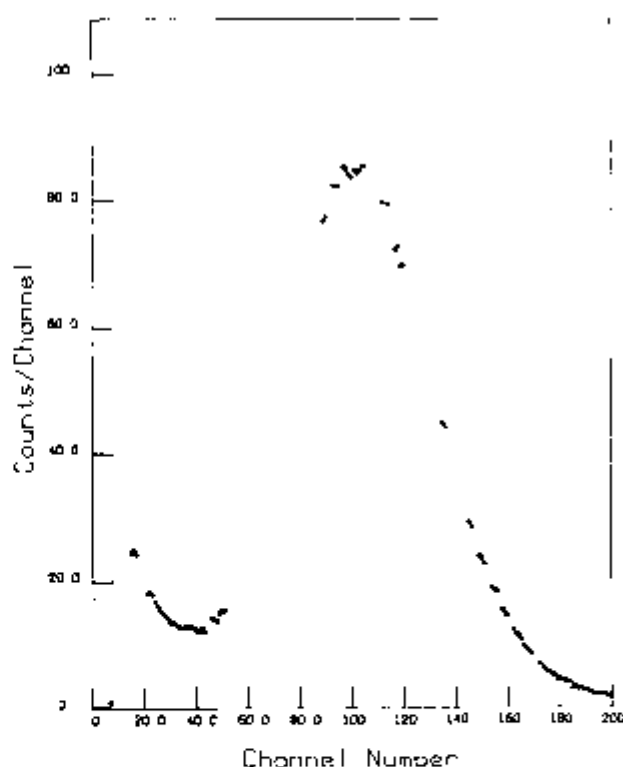


Fig. 2. Pulse height distribution in the thick NE 110 scintillator due to K series X rays from silver.

to the total energy of the X ray. The position of this peak was at 0.0146 ($\pm 2\%$) light units.

Figs 2 and 3 show the pulse height distribution due to the Ag X rays in the thick NE 110 scintillator. Fig 2 is a linear plot where the gain was such that the single photoelectron peak is below the lower cut off. Note that the total energy peak is well defined and its position can be accurately and easily determined. Fig 3 shows the same source but on a semi log plot where the gain has been increased to allow observation of the single, double and triple photoelectron peaks. This is an important measurement since, as discussed below, photoelectron statistics are important in calculating detector efficiencies⁴. This spectrum permits determination of the average number of photoelectrons produced per light unit for a given scintillator-phototube combination.

Using the ^{22}Na source as a calibration and an unfiltered neutron beam from ORELA, pulse height distributions were measured for neutron energies from 1 to 20 MeV. Because the scintillator was small, multiple scattering was negligible and the position of the half height at the end of the pro-

ton recoil distribution was used as a measure of the light output for protons with $E_p = E_n$. To within the accuracy (3%) of these measurements, the light curve for NE 110 was identical to that for NE 213 given in refs 6 and 9 (see fig 4).

The iron filtered neutron beam and the Ag X ray source were used to test the light curve below $E_p = 1$ MeV. Pulse height spectra were obtained for 12 energies between $E_n = 24$ keV and $E_n = 955$ keV. The validity of the light curve was checked by comparing calculations of the pulse height distributions to the measured relative distributions. Typical spectra are shown in figs 5 and 6. The calculation is described in a later section of this report, but the main point of figs 5 and 6 is that the end point of the distributions (at which $E_p = E_n$) are accurately reproduced by the calculation based on the light curve of refs 6 and 9. Note that multiple scattering (included in the calculation) is not negligible but is still rather small in the thin scintillator at these energies. These results are summarized in fig 4.

Fig 6 at $E_n = 24$ keV is of additional interest because of its very low energy. The peaks in the lower part of this spectrum are due to one, two, three, etc. photoelectrons. The calculated peaks are higher than the data because the fast discriminator used to gate the ADC was set to cut off the single photoelectron peak and reaches unit efficiency only for light output greater than 0.003.

In fig 5 the rise at low pulse heights is due to

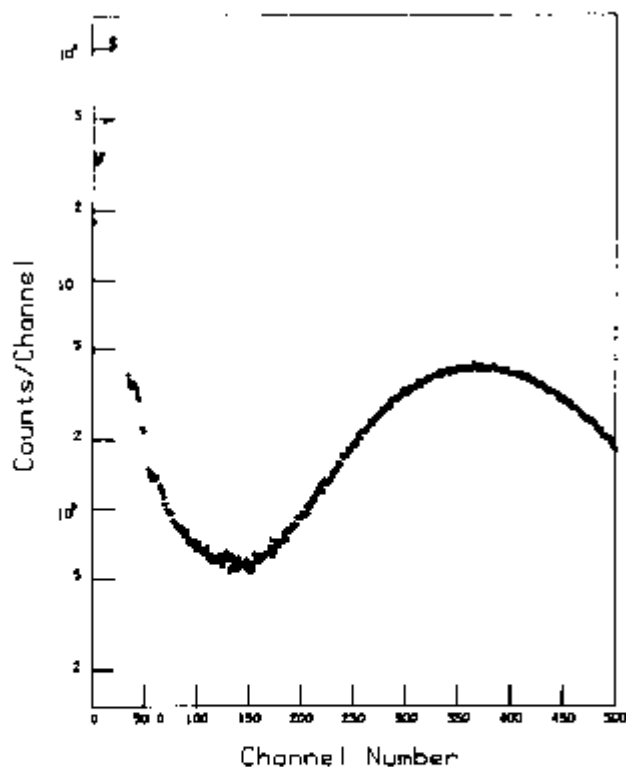


Fig 3 Ag X ray spectrum with gain expanded to show single, double and triple photoelectron peaks.

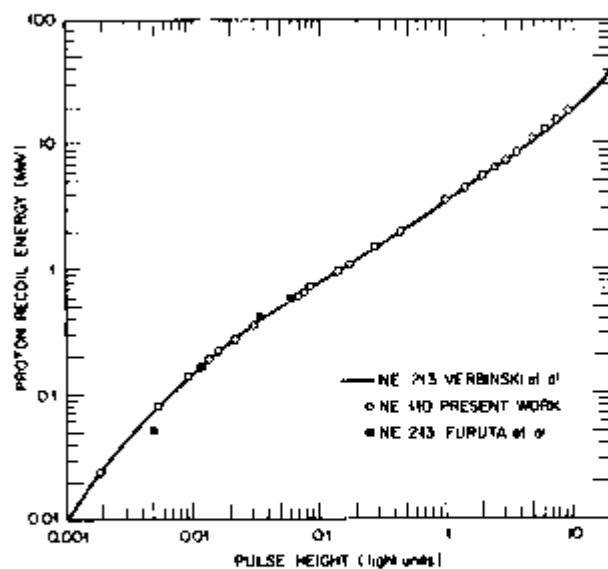


Fig 4 Present results for the light output as a function of proton energy compared to the data of refs 2 and 6.

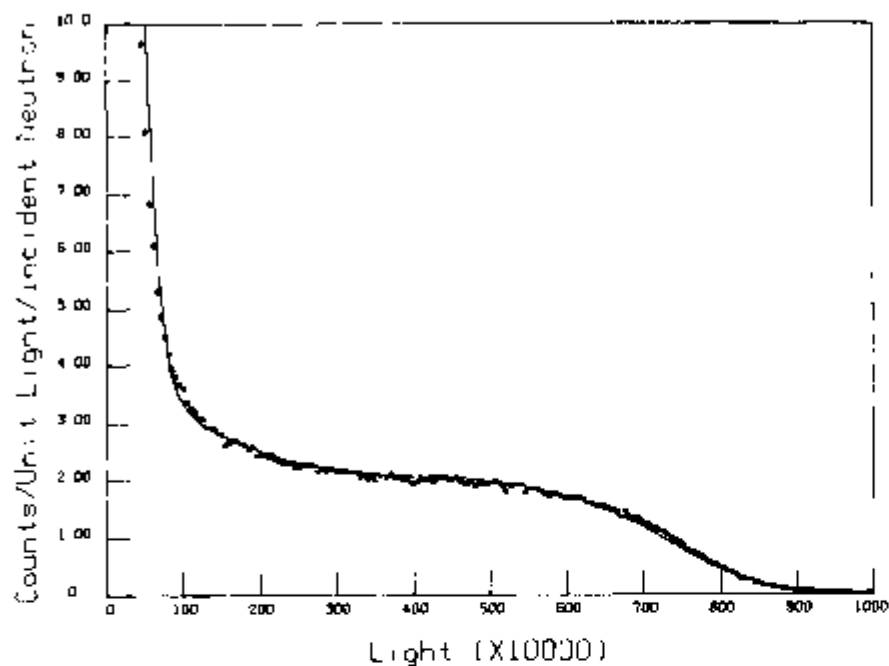


Fig. 5. Response of the thin NE 110 scintillator to 641 keV neutrons. The solid curve is calculated as described in section 5. The sharp rise in response below 0.01 light units is due to carbon recoils. The data are relative measurements normalized to the same area as the calculation.

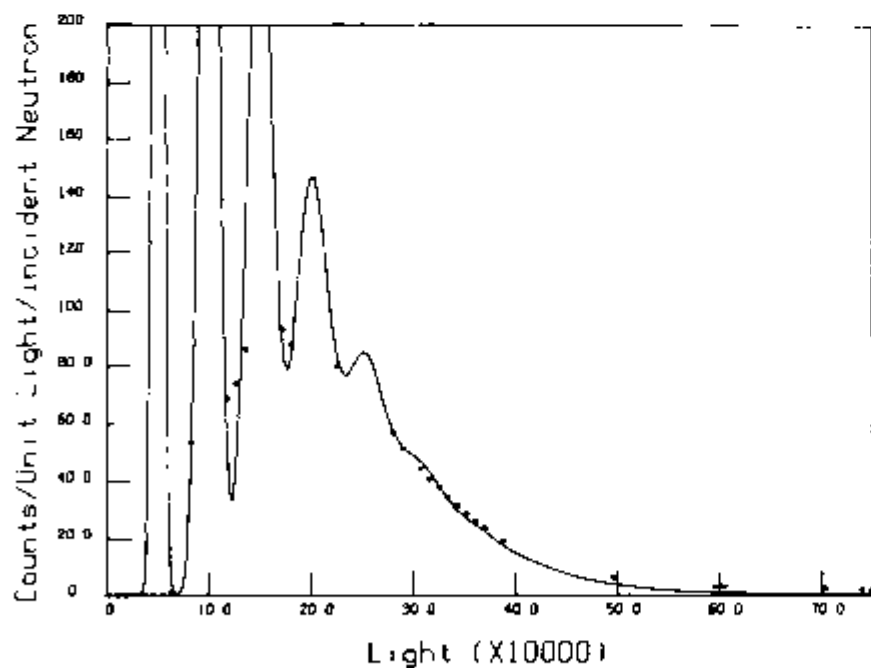


Fig. 6. Measured and calculated response of the thin scintillator at $E_n = 24$ keV.

carbon recoils. The light curve for carbon ions in refs. 6 and 9 was adjusted somewhat in order to fit this rise. This adjustment varied from a factor of 1 at zero energy to a factor of 3 at 0.3 MeV (carbon recoil energy).

Note that for calculation of the distributions in a thick scintillator the carbon light curve is only of secondary importance.

4 Thick scintillator design

There are a number of distinct advantages in having a detector which is as close to totally absorbing as possible. Large slowly varying efficiencies can be calculated more accurately than small ones. High efficiency allows rapid determination of low fluxes.

Our first choice in the design was to utilize a 12.5 cm diameter phototube (RCA 8854) since this is a relatively large size, widely available, but small enough to be easily handled. For such a tube a 10 cm diameter scintillator just covers the photocathode; thus the diameter of the scintillator is thereby fixed. The only choices remaining were the scintillator thickness and the question of whether to use a re-entrant hole in the face of the

scintillator. The re-entrant hole was rejected because it complicates fabrication, causes larger variations in light collection, and restricts the diameter of the neutron beams which can be measured.

For the work reported here the incident neutron beam was collimated to a diameter of 1.6 cm. The beam was incident on the front face of the detector (see fig. 1). Using this configuration pulse height distributions were measured for detectors with thicknesses of 2.0, 7.6 and 15 cm. Figs. 7 and 8 show pulse height distributions at $E_n = 274$ keV for the 2.0 and 7.6 cm detectors.

It is clear from fig. 7 that with 2 cm thickness the escape probability for first collided events is much larger than for the 7.6 cm thickness. Performance of the 15 cm detector was slightly better than that of the 7.6 cm detector (as determined by peak to valley ratio of the spectrum). However, light collection is poorer for the 15 cm detector (i.e. fewer photoelectrons per light unit) and it was concluded that the 7.6 cm detector represented a good compromise between neutron energy absorption and light collection efficiency.

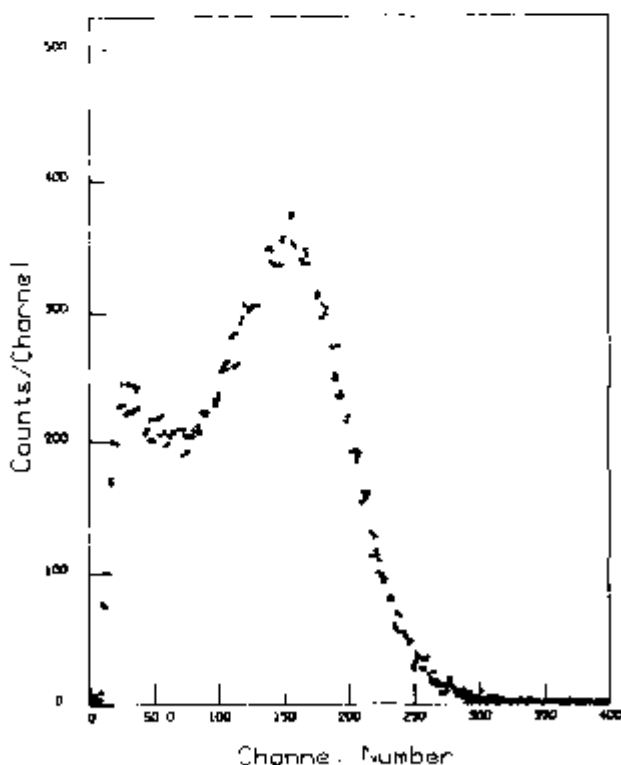


Fig. 7. Response to 274 keV neutrons of a 10 cm diameter by 2 cm thick scintillator. Neutron beam diameter is 1.6 cm.

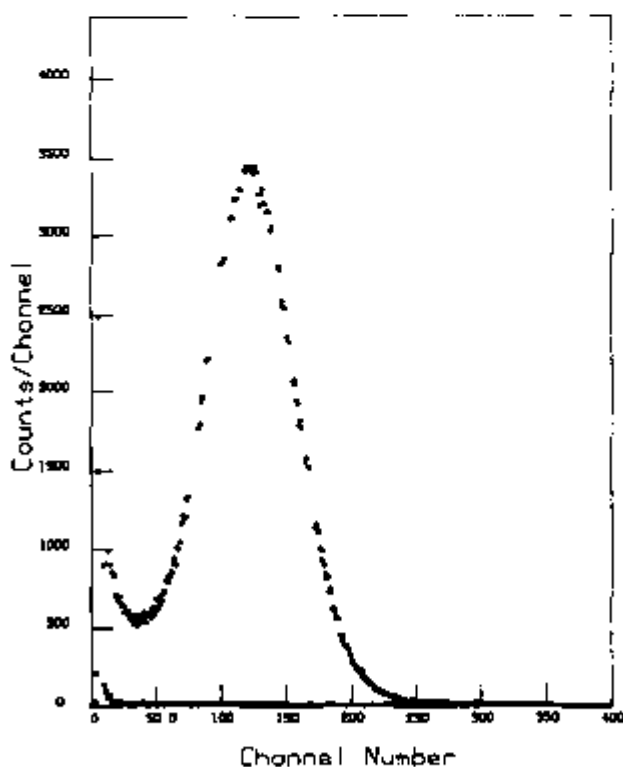


Fig. 8. Response to 274 keV neutrons of a 10 cm diameter by 7.6 cm thick scintillator. The X's represent the contribution of background and PMT noise.

5 Calculation of efficiency

The absolute distribution of light output from the detector for each incident neutron energy was calculated using the code O5S^{6,9)} This code was developed about 10 years ago at ORNL by Textor and Verbinski who used it to calculate efficiencies for NE 213 scintillation counters. Absolute efficiency measurements¹⁰⁾ were made at that time using associated particle techniques which verified the accuracy of the code.

For the present work three modifications were made to the code. First as stated in section 3 the light curve for carbon recoils was modified. Second the cut off energy (the energy below which a neutron history is terminated) was lowered from 20 keV to 1 keV. Third the smearing of the calculated light distribution was modified to include Gaussian smearing after smearing based on Poisson statistics for the average number of photoelectrons for each light bin. Lamaze et al⁴⁾ have shown that for the small quantities of light produced by low energy neutrons correct treatment of the Poisson statistics is essential. This smearing was performed after the O5S calculation so that the smearing parameters could be adjusted to a particular scintillator phototube combination.

The procedure for matching the calculated spectra to the measurement is as follows: the absolute response in each light bin is distributed

among the possible number of photoelectron events according to a Poisson distribution determined by the average number of photoelectrons for that light bin as determined from the X ray spectrum (see fig. 3). The result is then smeared by a Gaussian distribution which approximates the variation in light collection in the scintillator as well as gain variations in the phototube. The measured pulse height distribution is scaled in pulse height according to the gain determination using the Ag X ray source. A lower limit in pulse height is selected (usually in the minimum below the primary peak). The measured spectrum is then normalized to have the same area as the calculation above this lower limit. A value of χ^2 between data and calculation above the lower limit is then calculated. This process is repeated varying the gain of the measured spectra and the resolution of the Gaussian smearing until the value of χ^2 has been minimized. The fwhm of the Gaussian smearing was found to be between 18 and 20% for all neutron energies. The gain was allowed to vary slightly from the value determined by the Ag X ray source because for such a thick scintillator differences in the volume of interaction for X rays and neutrons lead to small variations in light collection efficiency. The gain for neutrons was within 5% of that obtained with the X ray source and varied

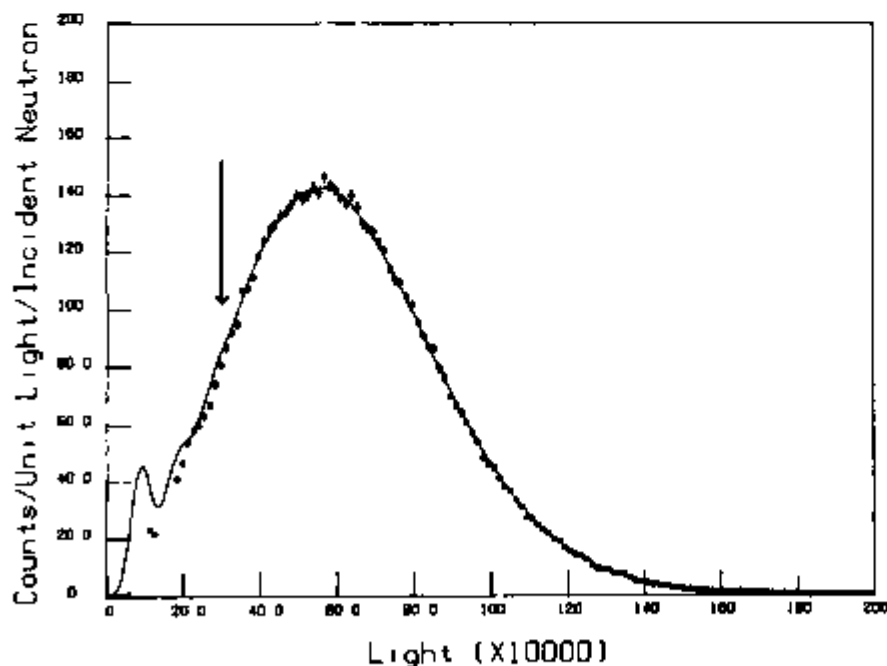


Fig. 9. Measured relative response at 82 keV normalized to calculated area above the pulse height indicated by the arrow.

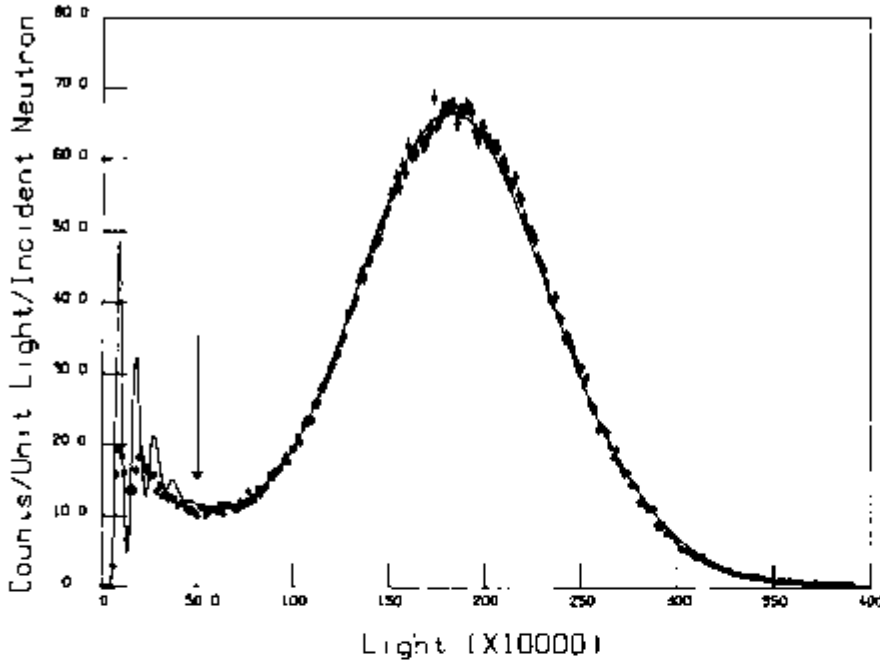


Fig 10 Measured relative response at 137 keV normalized to calculated curve

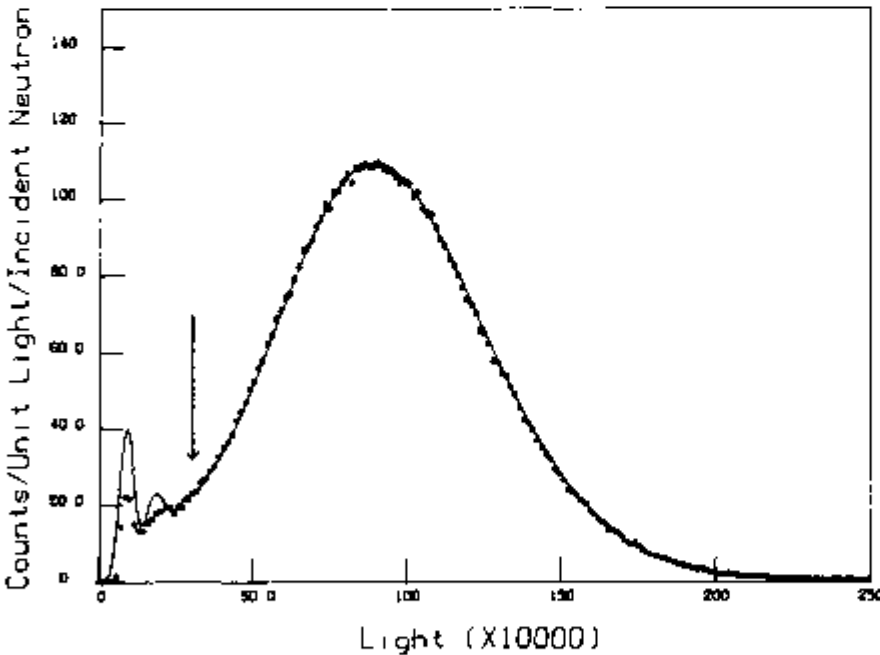


Fig 11 Measured relative response at 274 keV normalized to calculated curve

with neutron energy in a smooth monotonic manner

Figs 9-12 compare calculated and measured pulse height distributions at a number of neutron energies between 80 and 500 keV. The lower limit described above is indicated by the vertical arrow

in each figure. Agreement above this arrow is very good at all energies. Below the limit agreement between data and calculation is not as good. This is due to two problems. One, any errors in the light curve for carbon or proton recoils will show up in this region since this part of the spectrum

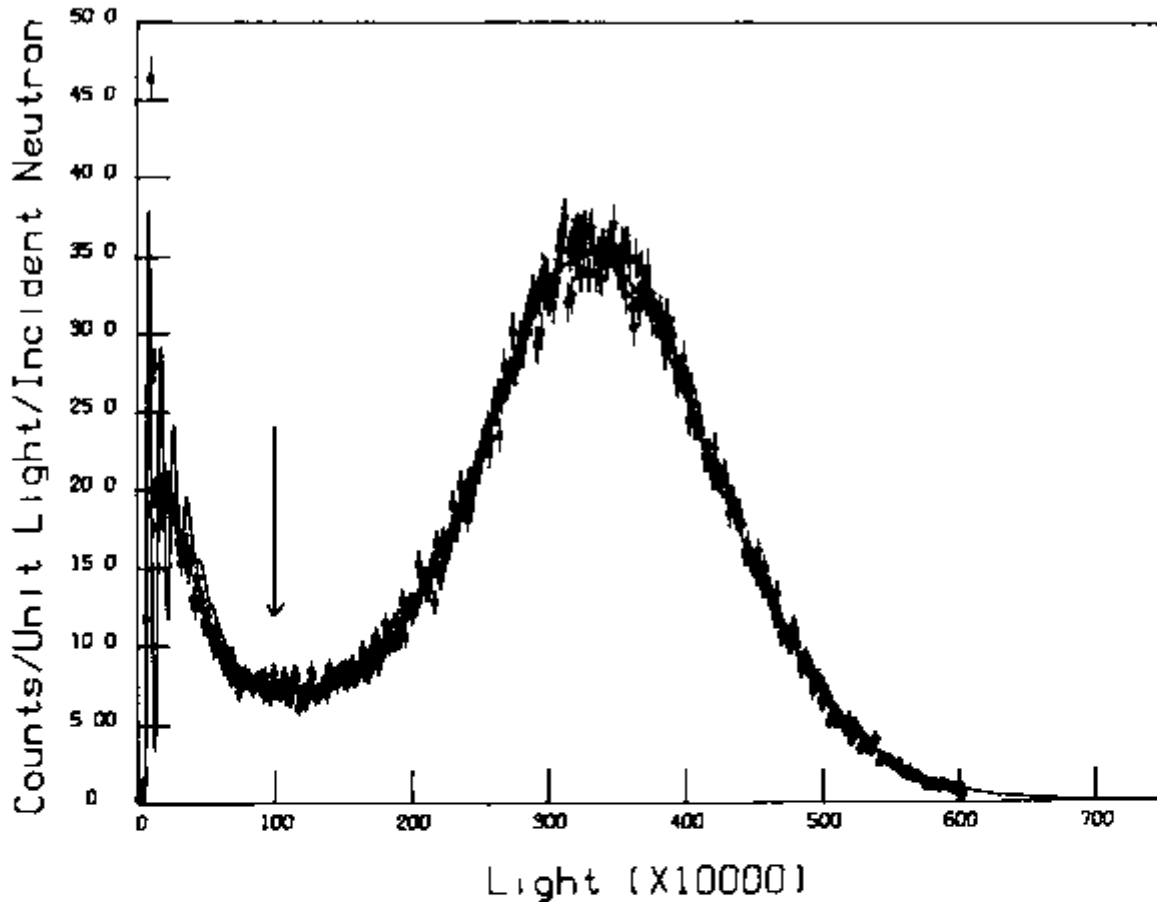


Fig. 12. Measured relative response at 467 keV normalized to calculated curve.

is made up of events in which the neutron escapes after giving up only a small part of its energy. Two in this work the fast discriminator (gating the ADC) was set to reject the single photoelectron events and has less than unit efficiency for events up to about 0.003 light units.

To test the sensitivity to the free parameters the gains and resolutions were each varied to produce a factor of 2 increase in the value of χ^2 over its minimum. The integral of the calculated efficiency and the number of measured counts above the lower limit were compared to their values at the minimum of χ^2 . Differences were less than 0.5%.

For a measurement of neutron flux in which a pulse height spectrum is recorded at each neutron energy one can use the analysis described above to determine the neutron fluence, i.e. counts above the lower limit divided by the integral calculated efficiency above the lower limit. The efficiency for a given integral electronic bias (as might be used

in a one parameter time of flight measurement) can be calculated by scaling the integral calculated efficiency by the ratio of the counts above a chosen bias to the counts above the lower limit for the measurements shown in figs 9–12. For the bias selected the efficiency was constant to 0.5% from 80 to 450 keV.

The results of the calibration described here are summarized in table 1. Applications of the technique in measurements of the ${}^7\text{Li}(n, \alpha)$ cross section are described in ref. 11.

Based on the present accuracy of the hydrogen and carbon¹²) cross sections for $E_n > 500$ keV, on the good agreement between calculated and measured shapes and on our tests of sensitivity to gain and resolution we estimate the calculated efficiency to be accurate to about 1%.

6. Conclusions

The results presented here show that the calculational technique (gain calibration and light

TABLE I

Neutron energy (keV)	Calculated zero bias efficiency	Lower limit for normalization (high units)	Integral efficiency above lower limit	Integral efficiency above electronic bias
82	0.998	0.0030	0.843	0.956
128	0.997	0.0030	0.910	-
137	0.996	0.0030	0.916	0.953
168	0.994	0.0030	0.970	0.954
184	0.993	0.0030	0.923	0.955
219	0.991	0.0040	0.904	0.948
244	0.989	0.0050	0.894	0.957
274	0.987	0.0050	0.895	0.947
311	0.985	0.0050	0.891	0.942
352	0.981	0.0060	0.880	-
376	0.979	0.0070	0.866	0.942
439	0.974	0.0100	0.837	0.953
467	0.972	0.0100	0.829	-
704	0.926	0.0200	0.739	0.905

curves of refs. 6 and 9 can be used to accurately calculate the efficiency of thick NE 110 scintillators used as nearly black totally absorbing detectors. Accurate calibrations good to about 1% have been attained. These detectors which have good timing characteristics can be easily used for fluence measurements in the region of neutron energy from 100 to 1000 keV. The silver K series X ray is a convenient source for gain calibrations in this energy region.

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