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MEDIUM ENERGY NEUTRON TIME-OF-FLIGHT SPECTROMETER, II

NEUTRON DETECTION EFFICIENCY OF ORGANIC SCINTILLATORS

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The absolute detection efficiency of neutron counters using NE102 plastic scintillator in the energy region from 5 to 40 MeV has been measured using a difference technique. The results are compared with calculated values and with similar measurements made elsewhere.

1. Introduction

The absolute neutron detection efficiency of the organic scintillators described in the previous paper[1]) was required, as a continuous function of energy, in order that the true neutron flux incident on the detectors could be measured. Hence, absolute differential cross sections could be measured. The efficiency can be calculated fairly well at neutron energies up to 10 MeV from the systematics of single neutron-hydrogen collisions provided that the bias level is sufficiently well known and the scintillator dimensions are small[2]). Above this energy the calculations become more difficult and correspondingly less reliable since they must include the various neutron-carbon interactions which may contribute, rescattering due to both double and multiple scattering, losses due to edge and end effects, the anisotropy of the neutron-proton differential cross section and the pulse-height resolution of the scintillator.

For these reasons it is usually necessary to calibrate the detector experimentally in order to obtain the highest accuracy. Such an experiment is best carried out with a neutron flux that approximates to that used in the main experiment in its spatial, energy and angular distributions. This paper describes the measurement of the efficiency of the neutron detector, using the method due to Bowen et al.[3]), and presents the results for a plastic scintillator, NE102**, and a liquid scintillator, NE228**, over the energy range 5–40 MeV. The NE102 scintillator was 10.271 cm dia. by 5.080 cm thick and the NE228 scintillator 11.067 cm dia. by 4.354 cm thick.

Despite the inherent difficulties, Kurz[4]) has developed a Fortran program to calculate the detector efficiencies of plastic scintillator cylinders, over the energy range 1–300 MeV, with an estimated error of $\pm 10\%$. The values measured in this experiment together with other measurements available in the published literature, are compared with the computed values obtained from a modified version of Kurz's program in the final section of this paper.

2. Experimental principle

The method employed by Bowen et al.[3]) hinges on the fact that if the carbon to hydrogen ratio of two hydrocarbon scintillators is different, then the absolute efficiency of either is calculable from a measurement of the ratio of their detection efficiencies and a knowledge of the neutron total cross sections of hydrogen and carbon. Following their notation[3]), the number of detected neutrons N counted in a monoenergetic neutron flux of energy E_n and total intensity N_0, can be written as

$$N = N_0[(n_H\sigma'_H + n_C\sigma'_C)\Lambda + M(E_n,B)], \qquad (1)$$

where

$$\sigma'_H = \sigma_H K(E_n,B)(1-\Delta), \qquad (2)$$

and

$$\Lambda = \frac{1-\exp[-a(n_H\sigma_H + n_C\sigma_C)h]}{(n_H\sigma_H + n_C\sigma_C)}. \qquad (3)$$

n_H and n_C are the numbers of hydrogen and carbon nuclei per molecule of the scintillator, σ_H and σ_C are the neutron total cross section of hydrogen and carbon, σ'_H is the cross section for producing a detectable pulse by means of an initial neutron interaction with a hydrogen nucleus in the scintillator and σ'_C is the same quantity for a carbon nucleus. The quantity a is the number of molecules per unit volume of the scintillator and h is the scintillating volume thickness. The

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function $M(E_n,B)$ accounts for the detection of the neutron by a multiple process and not by its initial interaction alone and includes the $^{12}C(n,n'\gamma)$ reaction contributions as well as double and multiple scattering contributions. B is the proton recoil threshold, $K(E_n,B)$ is the correction for the anisotropy of the neutron-proton differential cross section. The function Δ is the fraction of proton recoils having insufficient energy to give rise to a detectable light pulse and is given by

$$\Delta = c + (B/E_n), \tag{4}$$

where c is the end and edge correction.

For two scintillators containing different ratios of hydrogen to carbon nuclei, then eq. (1) can be written, in terms of the efficiency ε, as

$$\varepsilon_i(E_n,B) = N_i/N_0 = [n_{H_i}\sigma'_{H_i} + n_C\sigma'_{C_i}]A_i + M_i(E_n,B), \tag{5}$$

where $i = 1$ or 2, and N_i is the number of detected neutrons in each detector. Assuming that the recoil proton threshold and the end and edge corrections are the same for both counters, this can be written as

$$N_i/N_0 = [n_{H_i}\sigma_H K(E_n,B)(1-\Delta) + n_{C_i}\sigma'_{C_i}]A_i + M_i(E_n,B) \tag{6}$$

using eq. (2). By further assuming that σ'_{C_i} has the same value for both scintillators, it can be eliminated from the two equations (6) to give the efficiency of scintillator 1, i.e.

$$\varepsilon_1(E_n,B) = \frac{[n_{H_1} - n_{H_2}n_{C_1}/n_{C_2}]\sigma_H K(E_n,B)(1-\Delta)A_1}{1 - A_1 n_{C_1} N_2/A_2 n_{C_2} N_1} + \frac{M_1 - A_1 n_{C_1} M_2/A_2 n_{C_2}}{1 - A_1 n_{C_1} N_2/A_2 n_{C_2} N_1}. \tag{7}$$

The first term in eq. (7) depends solely upon the chemical composition and the physical properties of the two scintillators, the neutron total cross sections for hydrogen and carbon, which have been measured over the energy range of interest and upon the ratio N_2/N_1, which can be found by measuring the respective count rates for identical incident neutron fluxes of known energy, in the two scintillators. The second term, which for the size of scintillators under investigation is very small compared with the first term, considers the additional effect of the multiple scattering processes. Its computation is discussed in a later section.

The assumption that σ'_{C_i} and Δ_i are the same for both scintillators necessitates that the counter thresholds be set at the same neutron energy and also that the scintillators exhibit roughly the same light output characteristics. By keeping the threshold low the value of Δ is small, and decreases slowly with increasing incident neutron energy. Also at low thresholds, σ'_C varies slowly with increasing neutron energy so both assumptions are more realistically achieved at low threshold energies. For these reasons it was decided to set the threshold at about 3 MeV incident neutron energy.

As can be seen from eq. (7), it is actually the difference between the efficiency ratio and unity which is used in the calculations. It is therefore desirable to use two scintillators having widely differing hydrogen to carbon ratios. The detectors, which are described in detail in the previous paper[1]), used the plastic scintillator NE102, which has a hydrogen to carbon ratio of 1.105:1, and a liquid scintillator NE228 (ref. 3) based on heptane and having a hydrogen to carbon ratio of 2.11:1. The NE228 scintillator cell, having roughly the same external dimensions as the plastic scintillator, was mounted on the XP1040 photomultiplier in the same way as described earlier. For these scintillators eq. (7) reduces to

$$\varepsilon_N(E_n,B) = \frac{6.03\sigma_H K(E_n,B)(1-\Delta)A_N}{1 - A_N N_P/A_P N_N} + \frac{M_N - A_N M_P/A_P}{1 - A_N N_P/A_P N_N}, \tag{8}$$

where the subscripts N and P refer to the NE228 and plastic scintillators respectively.

3. Measurement

3.1. Calibration of detection threshold of the counters

As mentioned in the companion paper[1]) the counter thresholds were set by biasing the fast discriminator at a level corresponding to the Compton edge of a ^{22}Na γ-ray source, which is approximately equivalent to the pulse output from a 3.34 MeV proton. However, owing to the non-linearity of the light output from organic scintillators for particles other than electrons, it does not necessarily follow that if the thresholds are set to the same level for detecting gamma rays then they will also have the same energy threshold for detecting neutrons. Before choosing the gamma ray bias levels to be applied to the chosen scintillators a measurement of gamma ray energy for the incident neutron energy giving the same pulse height had to be performed.

Neutrons of 3.00 ± 0.11 MeV were produced using the $d + d \rightarrow {}^3He + n$ reaction by bombarding a copper target with deuterons accelerated to 224 keV by the

PLA injector. The recoil proton pulse height spectrum produced by these neutrons in the two counters, was measured in the usual way. The response due to 3.00 MeV neutrons was then calibrated in terms of equivalent electron energy using the pulse height spectra measured from gamma ray sources of known energy. In particular, it was found that 75% of the pulse-height corresponding to the Compton edge from ^{22}Na gamma rays, was equivalent to the pulse-height produced by a 3.00 MeV proton. The equivalent level for the NE228 counter was found to be 55.1% of the same gamma ray pulse-height. These levels were then used to set the proton recoil thresholds for the efficiency measurement.

This approach has several advantages over the direct method of irradiation by protons since it minimises surface effects, which can be important at low energies. Furthermore, the relative response can be measured with greater reliability since the incident neutrons can produce recoils more uniformly distributed throughout the scintillator, thus minimising geometrical effects such as loss of intensity due to reflection and transmission before reaching the photomultiplier.

3.2. Efficiency measurement

Since the only unknown in eq. (8) is the ratio of the counting rates for neutrons of a given energy in the two scintillators, it remained to measure this ratio over the energy range 5–40 MeV. This was done using the usual time-of-flight system described in the previous paper[1]). The neutron spectrum was obtained by bombarding a silver target with 50 MeV protons and observing the neutrons produced from the (p,n) reaction at 10°. This target was chosen since Batty et al.[5]) observed that the resulting neutron spectrum was fairly smooth throughout the energy range. The procedure for determining the ratio N_P/N_N was to measure, as a function of neutron time-of-flight, and hence, as a function of neutron energy, the total number of detected neutrons in both scintillators for the same number of protons incident on the target.

The data collection was divided into a series of short cycles of target in and target out runs, successive cycles being taken with one and then the other counter in the beam. Between cycles, the electronics was switched to the appropriate counter so that all parts of the system, except for the photomultipliers, E.H.T. power supplies, fast discriminators and zero-crossing discriminators, were common to each measurement. This, it was hoped, minimised the effects of any electronic drifts. The operation of the system was regularly checked using the procedure outlined in the companion paper[1]) and any effects due to electronic drifts were found to be negligibly small.

The major part of the experiment was taken up with the efficiency measurement, sufficient data being taken to calibrate the NE228 scintillation counter at a recoil proton threshold of 3.0 MeV. This measurement also calibrates the plastic counter at the same neutron energies, for a proton threshold of 3.0 MeV, by using the simple relation

$$\varepsilon_P = (N_P/N_N)\varepsilon_N, \tag{9}$$

where the symbols have previously been defined. The threshold used in routine differential cross section measurements was more conveniently obtained by setting the discriminator at a level corresponding to the Compton edge for ^{22}Na gamma-rays. Data was also obtained for an intercalibration of the calibrated NE228 counter set at a bias of 3.0 MeV and the standard plastic counter with its bias set at the 1.28 MeV ^{22}Na gamma-ray Compton edge by making use of eq. (9). The efficiency of the plastic counter was also measured, in the same way, with its bias set at a level corresponding to the Compton edge for 2.62 MeV ThC″ gamma rays. This is equivalent to a proton threshold of about 5.94 MeV according to the calculations and measurements of Gooding and Pugh[6]). Throughout the efficiency and intercalibration measurements, the thresholds were regularly checked, using the ^{22}Na and ThC″ gamma ray sources, and only extremely small shifts in both the threshold levels and the gain of the electronics observed.

4. Analysis of the results

The neutron spectra, for both counters, for each of the three measurements, were corrected for dead-time and background, and then normalized for equality of proton monitor counts (see ref. 1). The time spectra were then converted using the known time calibration to spectra as a function of neutron energy. Since the efficiency varies slowly with energy the spectra were grouped into 4 MeV intervals and a weighted mean count, with its associated error, used to give the two spectra N_P and N_N. The efficiency measurement and the intercalibrations will now be individually discussed.

4.1. Efficiency calibration of the NE228 counter

The corrected and normalised measured ratios for this measurement are given in table 1. These ratios were then substituted into eq. (8) to obtain the efficiency of the NE228 counter, ε_N. The selection and calculation of the other parameters also required in eq. (8), together with their associated errors will first be dis-

TABLE 1

The ratios N_P/N_N from the normalized neutron spectra for the efficiency and intercalibration measurements. The NE228 counter was always biased at 3.0 MeV proton recoil energy.

Incident neutron energy* (MeV)	$\frac{N_P(E_B=3.0\text{ MeV})}{N_N(E_B=3.0\text{ MeV})}$	$\frac{N_P(E_B=1.28\text{ MeV }\gamma\text{ rays})}{N_N(E_B=3.0\text{ MeV})}$	$\frac{N_P(E_B=2.62\text{ MeV }\gamma\text{ rays})}{N_N(E_B=3.0\text{ MeV})}$
5.87	0.9439 ± 0.0017	0.7490 ± 0.0022	0.0999 ± 0.0007
9.89	0.9680 ± 0.0030	0.8827 ± 0.0041	0.5053 ± 0.0041
13.94	0.9703 ± 0.0083	0.9011 ± 0.0054	0.6246 ± 0.0060
18.00	1.0247 ± 0.0044	0.9104 ± 0.0062	0.6428 ± 0.0067
22.09	1.1145 ± 0.0051	1.0200 ± 0.0069	0.6286 ± 0.0069
26.16	1.1258 ± 0.0058	1.0690 ± 0.0082	0.6920 ± 0.0082
30.33	1.1538 ± 0.0068	1.1072 ± 0.0099	0.7907 ± 0.0106
34.62	1.1950 ± 0.0093	1.1367 ± 0.0138	0.8456 ± 0.0154
39.05	1.2187 ± 0.0137	1.1788 ± 0.0210	0.9078 ± 0.0239

* The energy is that corresponding to the average energy of the 4 MeV interval over which the count rate was obtained (see text).

cussed before giving the final results. The values used are given in table 2.

1. σ_H: Groce et al.[7]) recently reported neutron-proton total cross sections to an accuracy of $\pm\frac{1}{2}\%$ at 19.57, 23.95 and 27.95 MeV. These results were compared with the predictions of the semiphenomenological equation obtained by Gammel[8]) for energies up to 40 MeV and agreed within the quoted errors. It was therefore decided to use the latter equation to generate the total cross sections to be used in the calculation. Since the predicted cross sections are within $\pm\frac{1}{2}\%$ of the accurately measured values, it seemed reasonable to assume an error of $\pm\frac{3}{4}\%$ on the cross section throughout the energy range.

2. $K(E_n,B)$: The anistropy correction was calculated, with an insignificant error using

$$K(E_n,B) = \frac{1+\frac{1}{3}D[1-(2B/E_n)+(4B^2/E_n^2)]}{1+\frac{1}{3}D}, \quad (10)$$

where $D = 2(E_n/90)^2$, with E_n in MeV. This result makes use of the well known proportionality between the recoil proton energy spectrum and differential cross section for neutron-proton scattering, and Gammel's empirical expression for the latter in the range 14–42 MeV[9]).

3. $(1-\Delta)$: The fraction of recoil protons produced by an initial interaction with hydrogen which give rise to sufficient light output so that they may be detected was calculated using the method outlined by Skyrme[10]). He calculated the fraction of energy lost from a cylindrical ionisation chamber by the escape of scattered protons before all their energy had been absorbed, and these calculations were slightly modified[11]) to give $(1-\Delta)$.

This calculation of $(1-\Delta)$ requires a knowledge of the range energy relationship for the particular scintillator concerned and since these are different for the two scintillators the end and edge correction C in eq. (4), may be different, necessitating a slight correction to eq. (8). Fortunately, for the thicknesses and radii of the scintillators used in this experiment, the correction was the same for both. Due to the large sizes of scintillators used, the end and edge corrections were small, varying from 1.7% of $(1-\Delta)$ at 6 MeV to 4% of $(1-\Delta)$ at 40 MeV.

The errors associated with the computed values of $(1-\Delta)$ were calculated assuming that the recoil proton threshold was 3.0 ± 0.11 MeV as obtained from the recoil proton response calibration and that the error in the end and edge correction was ± 10%.

4. σ_C: The total neutron carbon cross section was required for the computation of the Λ_i terms, eq. (3). Although the data obtained by Bowen et al.[12]) for the neutron-hydrogen total cross section are systematically about 2% lower than the more accurate data of Groce et al.[7]), their values of the total neutron-carbon cross sections are in excellent agreement, within the errors with those obtained by Measday and Palmieri[13]), but differ by approximately 2% with the values reported by Hillman et al.[14]) and Taylor et al.[15]) in the energy range 80–160 MeV. It was therefore decided to use the data of Bowen et al.[12]) with a 5% error. It should be noted that, to first order, the value of the total neutron-carbon cross section does not greatly affect the values of Λ_i.

5. Λ_i: These were calculated from eq. (3) using the selected values of the data given in table 2. The error associated with the thickness of the NE228 scintillation

was obtained from measurements carried out by the manufacturers, and that associated with the plastic scintillator from measurements during its machining. The error in the number of molecules/barn cm for each was estimated from the errors in densities and molecular weights and was found to be less than 0.1% for both scintillators and therefore neglected. The errors associated with Λ_i were then calculated by adding all the contributing systematic errors in quadrature.

6. M_i: The terms accounting for the multiple processes in which a neutron is detected not by its initial interaction but by a subsequent interaction were computed using a version of Kurz's program[4]) modified for a scintillator of composition CH_n. The contributions included were those due to the $^{12}C(n,n)$, $^{12}C(n,n'\gamma)$ and $^{12}C(n,n')3\alpha$ reactions or an initial scattering by hydrogen, together with a subsequent interaction of the neutron with hydrogen or carbon. It seemed reasonable to assume an error of $\pm 20\%$ on these values since the computation of the single scattering efficiency is better than 10% and the derivation of the multiple scattering efficiency involves the use of fundamentally the same calculation twice.

Substitution of these parameters and the measured count rate ratios into eq. (8) gave the final values of the efficiency of the NE228 scintillation counter at a proton recoil threshold of 3.0 ± 0.11 MeV and these are presented in table 3. The errors were obtained from those quoted above, the systematic errors being added in quadrature and finally added linearly to the statistical errors. In the low energy region the main source of error is the uncertainty associated with the proton recoil threshold, and at higher energies, the errors are largely due to the inaccuracies involved in determining the ratio Λ_N/Λ_P, which basically reflects the uncertainties in the thicknesses of the scintillators, and the measured value of the count rate ratio N_P/N_N. The statistical errors involved in the determination of this ratio play little part in the overall accuracy at low energy but become more significant at higher energies. For instance, they lead to errors in the total efficiency varying from roughly 0.25% at 6 MeV to 3% at 40 MeV.

Corrections due to the effect of neutron interactions with the thin aluminium entrance windows on both counters were investigated, and found to be extremely small, being less than 0.1% at 5 MeV increasing to about 0.2% at 40 MeV, and were thus neglected.

4.2. Efficiency intercalibrations with the plastic counter

The efficiencies of the standard plastic counter, at

Table 2

Selected values of σ_H, $K(E_n,B)$, $(1-\Delta)$, σ_C, Λ_N, Λ_P, M_N and M_P with associated errors.

Energy (MeV)	σ_H (barn)	$K(E_n,B)$	$(1-\Delta)$	σ_C (barn)	Λ_N* (barn)	Λ_P* (barn)	M_N	M_P
5.87	1.4450 ± 0.0108	1.0000	0.4804 ± 0.0170	1.060 ± 0.053	0.01743 ± 0.00016	0.02967 ± 0.00020	0.0500 ± 0.0100	0.0405 ± 0.0081
9.89	0.9503 ± 0.0071	0.9981	0.6827 ± 0.0101	1.159 ± 0.058	0.01855 ± 0.00019	0.03118 ± 0.00022	0.0188 ± 0.0038	0.0225 ± 0.0045
13.94	0.6957 ± 0.0052	0.9962	0.7670 ± 0.0074	1.360 ± 0.068	0.01889 ± 0.00020	0.03142 ± 0.00023	0.0134 ± 0.0027	0.0202 ± 0.040
18.00	0.5408 ± 0.0041	0.9943	0.8121 ± 0.0060	1.510 ± 0.076	0.01910 ± 0.00021	0.03150 ± 0.00024	0.0114 ± 0.0023	0.0215 ± 0.0043
22.09	0.4365 ± 0.0033	0.9924	0.8399 ± 0.0051	1.410 ± 0.071	0.01950 ± 0.00021	0.03226 ± 0.00025	0.0095 ± 0.0019	0.0192 ± 0.0038
26.16	0.3623 ± 0.0027	0.9906	0.8582 ± 0.0046	1.330 ± 0.067	0.01980 ± 0.00022	0.03285 ± 0.00025	0.0062 ± 0.0012	0.0123 ± 0.0025
30.33	0.3057 ± 0.0023	0.9888	0.8712 ± 0.0045	1.250 ± 0.063	0.02006 ± 0.00022	0.03338 ± 0.00025	0.0041 ± 0.0008	0.0078 ± 0.0016
34.62	0.2610 ± 0.0020	0.9872	0.8808 ± 0.0044	1.190 ± 0.060	0.02027 ± 0.00023	0.03379 ± 0.00026	0.0028 ± 0.0006	0.0046 ± 0.0010
39.05	0.2249 ± 0.0017	0.9855	0.8880 ± 0.0044	1.110 ± 0.055	0.02048 ± 0.00023	0.03426 ± 0.00026	0.0020 ± 0.0004	0.0035 ± 0.0007

* Where $a_N = 0.005321$ molecules/barn cm, $a_P = 0.007908$ molecules/barn cm, $h_N = 4.354 \pm 0.051$ cm and $h_P = 5.080 \pm 0.041$ cm.

TABLE 3
Measured efficiencies.

Incident neutron energy (MeV)	NE228 $\varepsilon_N(E_B=3.0$ MeV)	NE102 $\varepsilon_P(E_B=3.0$ MeV)	NE102 $\varepsilon_P(E_B=1.28$ MeV γ rays)	NE102 $\varepsilon_P(E_B=2.62$ MeV γ rays)
5.87	0.2226 ± 0.0088	0.2101 ± 0.0089	0.1667 ± 0.0072	0.0222 ± 0.0011
9.89	0.1824 ± 0.0056	0.1766 ± 0.0056	0.1610 ± 0.0059	0.0922 ± 0.0036
13.94	0.1484 ± 0.0046	0.1440 ± 0.0046	0.1337 ± 0.0052	0.0927 ± 0.0039
18.00	0.1287 ± 0.0046	0.1319 ± 0.0045	0.1172 ± 0.0054	0.0827 ± 0.0041
22.09	0.1247 ± 0.0054	0.1390 ± 0.0056	0.1272 ± 0.0070	0.0784 ± 0.0046
26.16	0.1108 ± 0.0050	0.1247 ± 0.0052	0.1184 ± 0.0069	0.0767 ± 0.0047
30.33	0.1019 ± 0.0049	0.1176 ± 0.0051	0.1128 ± 0.0073	0.0806 ± 0.0055
34.62	0.0972 ± 0.0056	0.1162 ± 0.0060	0.1105 ± 0.0090	0.0822 ± 0.0069
39.05	0.0891 ± 0.0062	0.1086 ± 0.0068	0.1050 ± 0.110	0.0809 ± 0.0089

the three different recoil proton thresholds were obtained from the results of the efficiency and intercalibration measurements by using eq. (9), where ε_N is the efficiency of the calibrated NE228 counter and N_P/N_N the count rate ratios of the two counters corrected for equal numbers of incident neutrons. Substitution of the measured ratios, table 1, into eq. (9) gave the measured efficiencies and these are presented

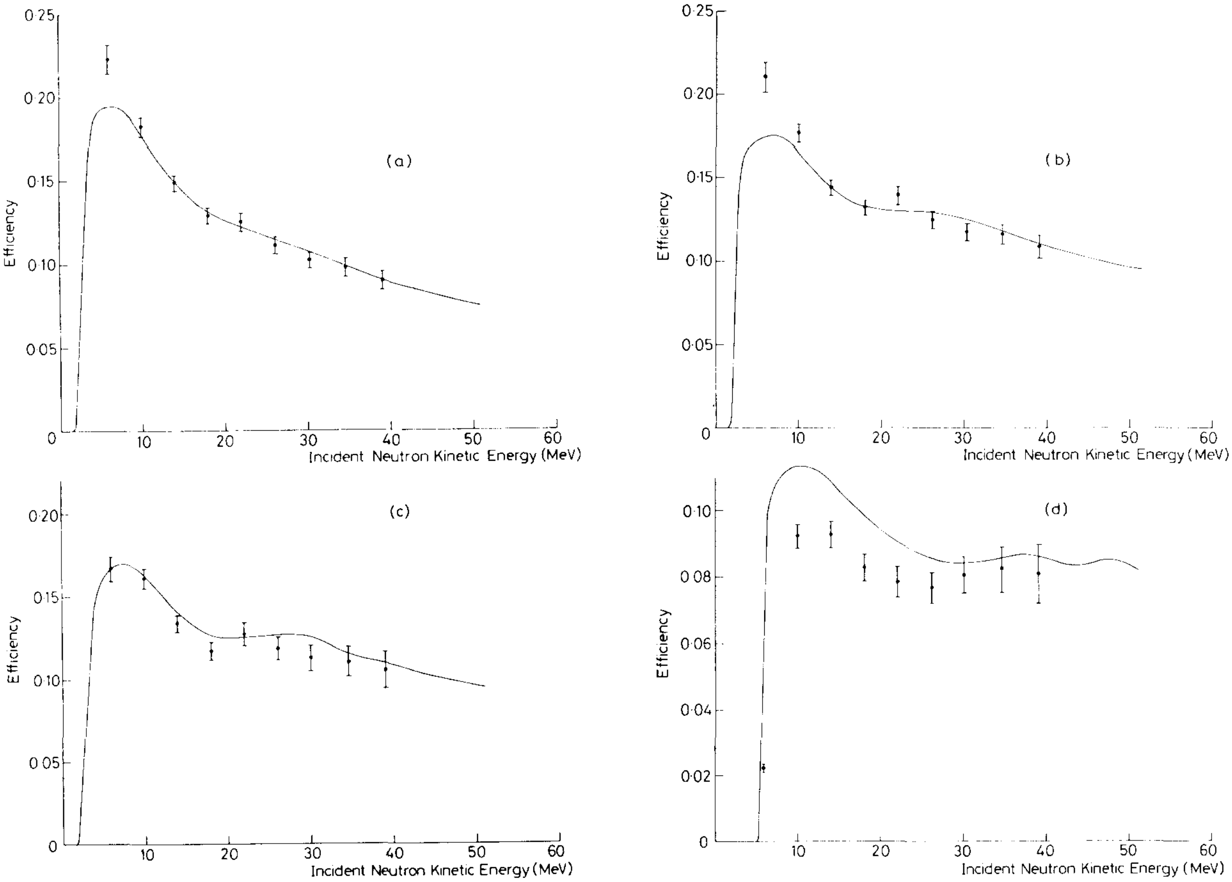

Fig. 1. Measured values of the detection efficiency as a function of neutron energy for a) NE228 scintillator biased at 3.0 MeV proton energy, b) NE102 scintillator biased at 3.0 MeV proton energy, c) NE102 scintillator biased at a level corresponding to the Compton edge from 1.28 MeV γ rays and d) NE102 scintillator biased at a level corresponding to the Compton edge from 2.62 MeV γ rays. The full line gives the values calculated using the program of Kurtz.

in table 3. The main contribution to the errors is due to the uncertainties in the measured efficiencies of the NE228 counter, this being the dominant source at low energies and decreasing to about half the error at the higher energies.

5. Comparison with the computation of detection efficiency

The computer program developed by Kurtz[4]) calculates for a specific neutron energy E_n, in the energy range 1–300 MeV, the absolute efficiency for detection of neutrons in a plastic scintillator. It assumes a cylindrical scintillator, of any size, having a composition CH, with the neutron incident parallel to its central axis. The calculation includes first and second scattering effects from interactions with both hydrogen and carbon. Effects due to the anistropy of the neutron-proton differential scattering, the non-linearity of light response of the scintillator and its finite resolutions are also included. The calculation does not include a correction for the end and edge effect, but this is only a very small correction for the sizes of scintillators considered here. This program was modified so that it assumed a composition CH_n, where n is the ratio of hydrogen to carbon atoms in the molecule, but it still assumed that the light output-energy relationships are the same as those for plastic scintillators.

The measured efficiencies are plotted in fig. 1 together with the calculated efficiencies obtained using the computer program. The agreement is very good for the lower bias measurements, but for the higher bias intercalibrations the results are significantly lower than the calculation, especially for the low energy points. This apparent difference is not understood.

The calculated efficiencies for the detectors used by Young et al.[16]), Bowen et al.[3]), Crabb et al.[17]), Wiegand et al.[18]), Gatti et al. [19]), and Grassler et al.[20]) are shown in fig. 2 together with the published measured efficiencies. The agreement in all cases except that of Grassler et al. (fig. 2d) is very good, but there is

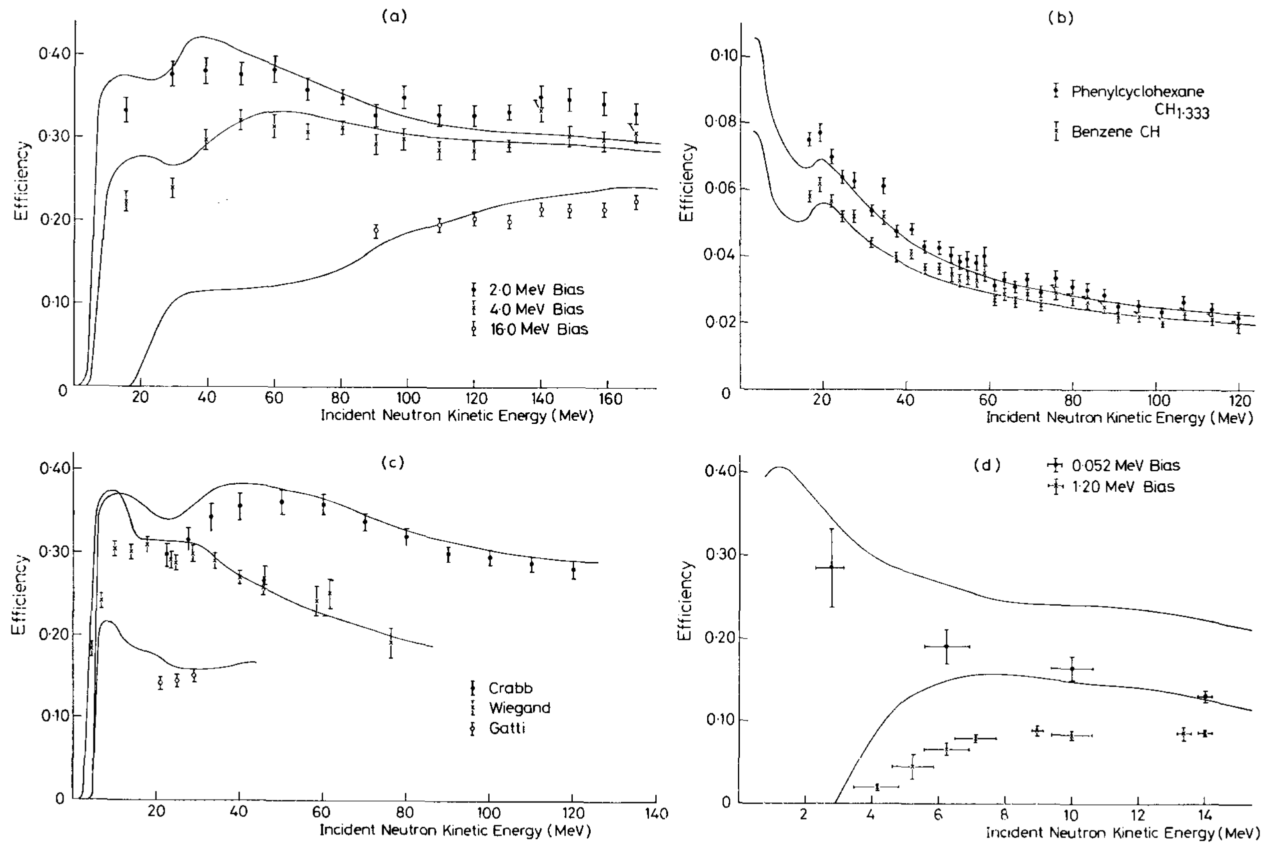

Fig. 2. Measured values of the detection efficiency as a function of neutron energy for a) NE102 scintillator biased at 2.0, 4.0 and 16.0 MeV electron energy[6]), b) phenylcyclohexane and benzene counters[3]), c) NE102 scintillator as used by Crabb et al.[17]), Wiegand et al.[18]) and Gatti et al.[19]), and d) Pilot B scintillator biased at 0.5 and 3.5 MeV proton energy[20]). The full line in each case gives the values calculated using the program of Kurtz.

a significant difference for neutron energies up to about 30 MeV; the calculation always being slightly higher than the measured values. This is the region where the partial neutron-carbon cross sections are not well known, particularly near their respective thresholds, and this lack of information may well be reflected in the calculation. The agreement with the results of Grassler et al.[20]) is very poor and cannot be accounted for solely by a change in the proton-recoil threshold.

6. Conclusion

The efficiencies measured in the present experiment are in excellent agreement with other published values, as can be seen by the generally good agreement in all cases with the calculated values. The program can also be used to compute the efficiencies of various scintillators, including some liquid scintillators as is evidenced by the agreement with the results of Bowen et al.[3]) and the present results for the NE228 counter. This comparison confirms that the calculations have an accuracy of the order of 10% or better, and for this reason, they were used to calculate the efficiency in the range from 40 to 50 MeV which could not be measured in this experiment.

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