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CALIBRATION OF THE NEUTRON DETECTION EFFICIENCY OF A PLASTIC SCINTILLATOR, 1 TO 200 MeV*

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The absolute efficiency of a plastic scintillator neutron counter has been measured as a function of bias at thirteen neutron energies between 1.0 and 200 MeV, using two techniques: above 4 MeV, protons from free np charge exchange were used to tag a neutron beam, while below 4 MeV the tagged neutrons came from a ^{252}Cf fission source. Data is available for biases between 0.20 and 4.0 MeV electron equivalent. A Monte Carlo program was written to interpolate the measurements to different neutron energies and extend them to other counter geometries. A comparison of the results of the program with our measurements and those of others is presented.

1. Introduction

Neutron detection efficiencies have been measured as a function of light collection threshold (bias) and neutron kinetic energy for a plastic scintillator of large volume, using two different techniques. Efficiencies accurate to $\pm 5\%$ of themselves are presented for thresholds between 0.2 and 4.0 MeV electron equivalent and neutron kinetic energies between 4 and 200 MeV, obtained by using protons from free np charge exchange to tag a neutron beam. In addition, efficiencies accurate to about $\pm 10\%$ of themselves are presented for neutron energies between 1.0 and 3.0 MeV; these were obtained by using a ^{252}Cf fission source to supply the tagged neutrons. A Monte Carlo program has been written to permit interpolation of the measured efficiencies between energies, and to allow extrapolation of the measurements to other counter sizes and geometries; in this way our measurements can be compared with those of other groups[1–9]). With a few exceptions, the agreement of the results of the program with our measurements and those of others is within 5%.

To our knowledge the measurements presented here cover a wider range of bias and incident energy than any published result for a single counter. The measurements, and their extension via the Monte Carlo program, should be useful additions to the supply of data available for the design and use of neutron counters.

2. The counter

The scintillation counter which was calibrated by these measurements is described in detail elsewhere[10]). It is a rectangular prism of Pilot Y scintillator 6 in. high, 20 in. long and 6 in. thick, with a 58DVP phototube on each end. Counters similar to this one were used by the Carnegie–Mellon group in a measurement of K^0 charge exchange[11]), and counters identical to this one were used by the OSU-MSU-CU collaboration in a measurement of np charge exchange[12]).

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3. Calibration of threshold

To obtain meaningful efficiency measurements it is essential to know accurately the energy (in MeV electron equivalent) corresponding to a given pulse height from the counter. This is especially true for neutrons of the lowest energy which provide small light output. For this purpose comparison spectra from γ-ray sources (^{60}Co, ^{137}Cs, ^{24}Na) were taken frequently during the efficiency calibration. One must then known the energy corresponding to some feature (peak, halfway-down point) of the γ-ray spectra. This is not completely trivial since the scintillator is large enough for multiple Compton scatterings to be important; in addition, the spectra are smeared by the finite resolution of the counter. Two methods were used:

(a) The multiple-Compton recoil electron spectra for the γ-ray sources were simulated by a Monte Carlo program for several values of the resolution. The spectra from all three sources (γ-rays of 0.662, 1.17, 1.32, 1.37, 2.75 MeV) could be fit very well assuming an energy release in the scintillator of 0.06 MeV for each photoelectron in one of the photomultiplier tubes. For ^{60}Co, the average of the energies corresponding to the peak and to the halfway-down point of the measured spectrum was found to be 1.15 MeV for a wide range of values of the resolution.

(b) The ^{60}Co spectrum was calibrated against the electrons from a ^{90}Sr–^{90}Y source by fitting the experimentally observed spectrum to the Kurie plot for a first-forbidden β decay. The fit was everywhere quite good; extrapolation to the end point of 2.26 MeV gave an energy calibration for the ^{60}Co 5% lower than that of method (a).

4. Cyclotron calibration

The efficiency measurements for neutron energies between 4 and 200 MeV were performed in a series of runs at the Carnegie–Mellon University 400 MeV synchrocyclotron with the layout shown in fig. 1. The internal proton beam impinged on an internal carbon target. Neutrons produced at 0° were collimated to a 1.2 in. × 1.2 in. square at the 1.5 in. diameter liquid hydrogen target.

Forward protons were detected by the conventional differential range telescope shown in fig. 1. For most of the runs wire spark chambers were placed on the proton line for better determination of the proton direction. This permitted a more precise measurement of the recoil neutron energy, and also minimized effects due to multiple scattering losses by allowing us to find counter efficiencies for various effective sizes of the proton telescope.

Pulse heights from both ends of the neutron counter, the neutron time of flight, and the digitized outputs of the wire chambers were processed on-line by the CMU PDP-7 computer. The data were both displayed on-line and recorded on magnetic tape for later analysis.

Only protons of near-maximal range were used to

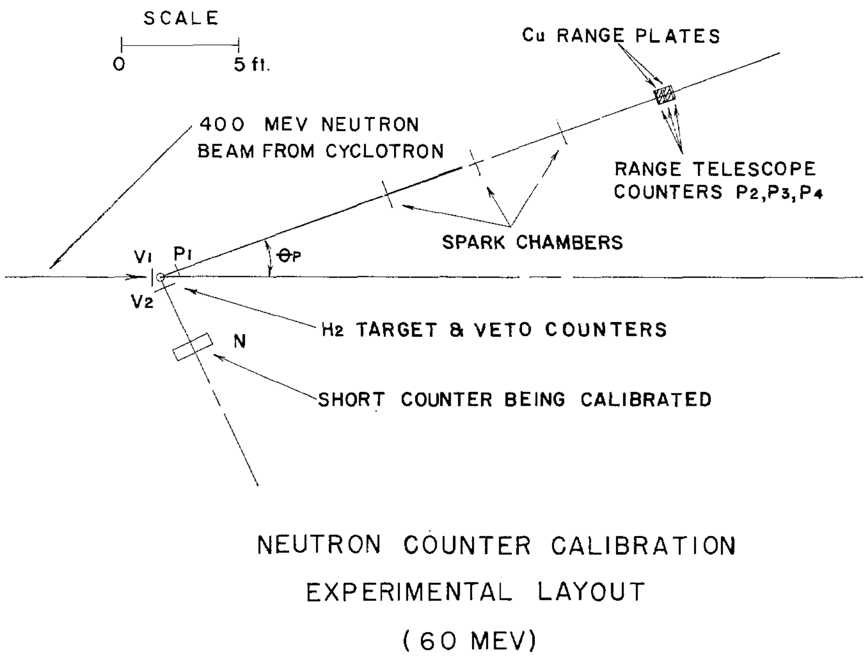

Fig. 1. Layout for the cyclotron measurements of neutron counter efficiency.

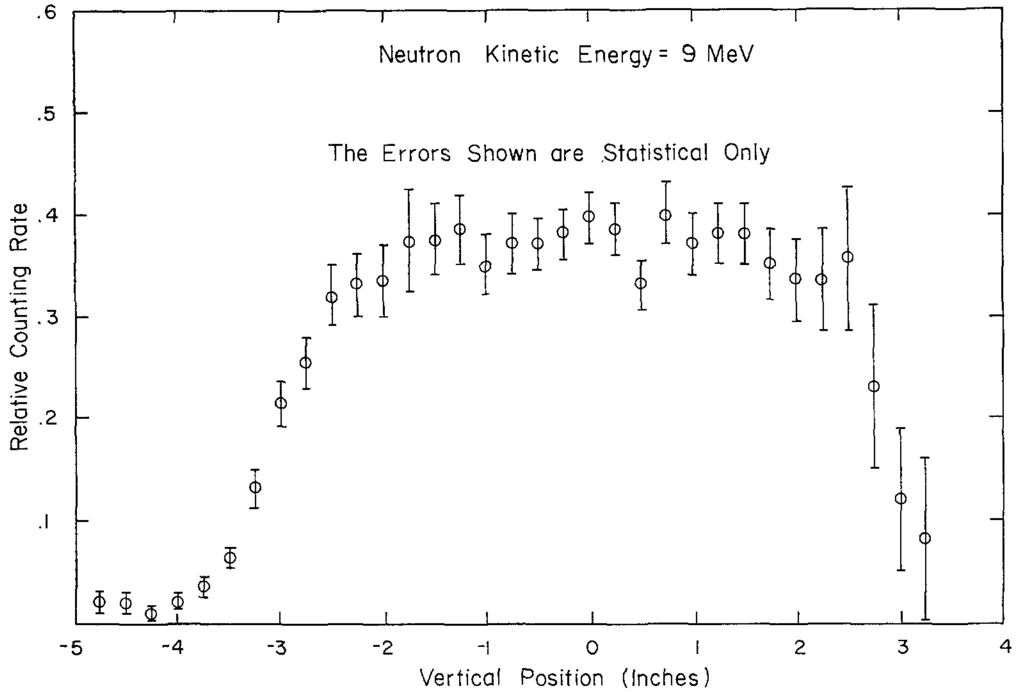

Fig. 2. Neutron scintillator counting rate as a function of neutron position in the cyclotron measurement, as inferred from the wire chambers in the proton arm.

tag recoil neutrons, minimizing possible background. Neutron energies were then inferred from the proton scattering angle. The cleanliness of this one-constraint fit was checked by measuring the tagged neutron counting rate as a function of the height of the neutron counter; true elastic events must be coplanar. Fig. 2 displays the rate as a function of position at the counter inferred from the proton wire chambers. The shape of the wings and tail on the curve are consistent within 0.1 in. with that predicted from plural and multiple scattering of the protons and from the 0.5 mrad spark chamber resolution of the proton arm. The full width at half maximum of the curve is consistent with the 6-in. height of the neutron detector.

The typical counting rate was 0.2 to 0.5 proton triggers/sec. Random triggers were less than 1%; target empty np triggers were about 1%, and target empty triggers from the proton arm varied between 15 and 20%, depending on the scattering angle. Blocking by the anti-coincidence counters placed in front of the neutron counters, typically 2%, was continuously monitored. Corrections for absorption losses of scattered neutrons in the target, target walls, air and anti-coincidence counters ranged from 1% for 200 MeV neutrons to 25% for 4 MeV neutrons. Appropriate corrections were applied using existing neutron cross-section data[13–15]).

Since the neutron counters were overmatched to the recoil neutron beam, there might be some question that edge effects could lower the overall efficiency of the counter. From the curve shown in fig. 3, it may be calculated that such an effect would be less than 5%. The Monte Carlo calculation described in section 5 predicts a 3% reduction in efficiency for uniform counter illumination (efficiency with uniform illumination equals efficiency at the center times 0.97). The data presented here do not contain this calculated reduction in efficiency.

The results of the cyclotron calibration, labeled method NP, are presented in fig. 3a. Efficiency measurements for nine neutron kinetic energies and five values of bias are given. (Since the neutron pulse height for each event was recorded, the efficiency is available as a continuous function of bias.) Only statistical errors are shown. The curves in fig. 3a are calculated by the Monte Carlo program described in section 6.

5. Calibration using a ^{252}Cf source

In addition to the cyclotron measurements, two of us[16]) have investigated a second method of calibration for low energy neutrons. Briefly, the technique is as follows[17]): the isotope ^{252}Cf decays by spontaneous fission; in the fission process and in the subsequent decay of the daughters neutrons are released. A thin

^{252}Cf source is placed inside a gas scintillation counter which detects the light output from the fission fragments, thus tagging the presence of a neutron. The time-of-flight between the gas scintillator pulse and the neutron counter pulse is measured over a flight path of 5–10 ft, so that the energy of each detected neutron is known. In order to measure the efficiency of the neutron counter one must also know: (a) The solid angle subtended by the neutron counter (which can be calculated). (b) The mean number of neutrons per fission from ^{252}Cf. This has been measured in several experiments; the value used here (3.750 ± 0.028) was taken from the compilation in ref. 18. (c) The energy spectrum of the neutrons. Meadows[19]) has shown that this spectrum is fit well between 0.5 and 10 MeV by a Maxwellian distribution

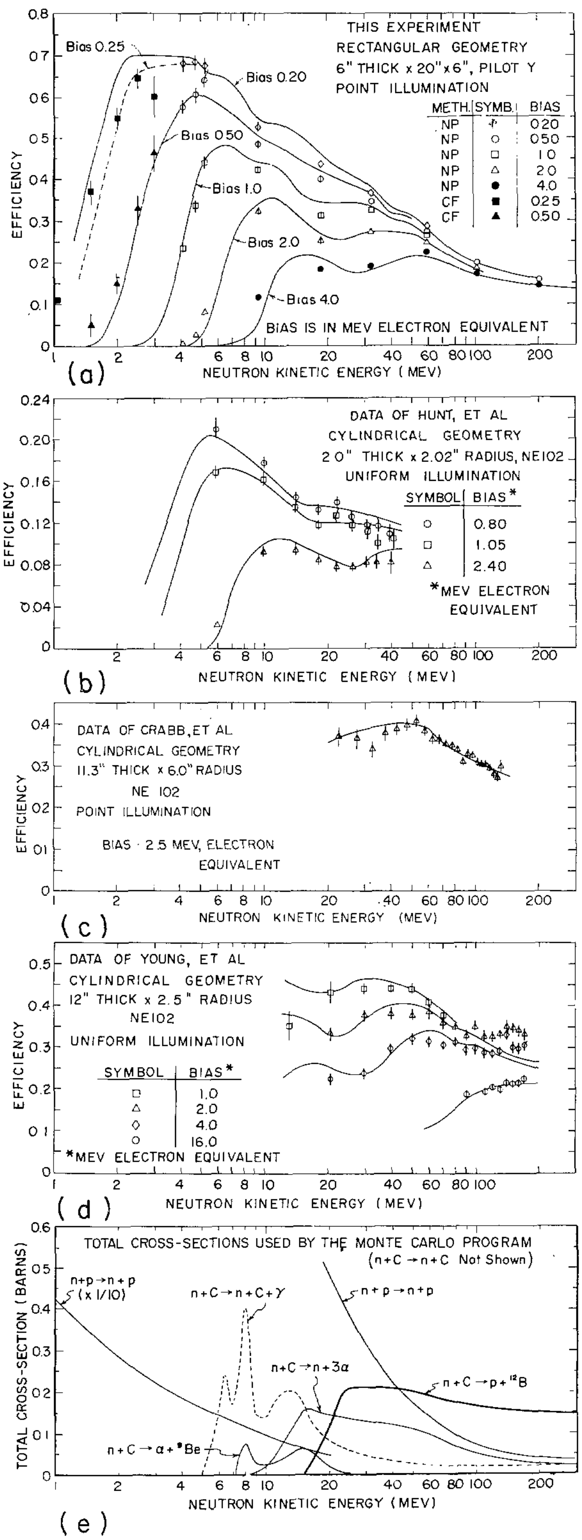

Fig. 3. (a) Results of our efficiency calibrations. Method NP refers to the cyclotron measurements, while method CF refers to the fission source measurements. The curves are the results of the Monte Carlo program. (b)–(d) Comparison of the efficiency measurements of other groups with the Monte Carlo results. (e) Total cross sections used by the Monte Carlo program. The neutron–carbon elastic channel is not shown.

$$N(E) \sim E^{\frac{1}{2}} \exp(-E/T),$$

where T is a temperature parameter which is approximately 1.5 MeV. The essential point is that for neutron energies below 3 MeV the energy spectrum is quite insensitive to the exact value of T. Furthermore, if an efficiency measurement for the counter already exists at higher energy (e.g., the 4 MeV point from our cyclotron measurements), T may be empirically determined.

Some preliminary results of efficiency measurements made with the ^{252}Cf source are shown in fig. 3a, labeled method CF. Data are presented for 1.0, 1.5, 2.0, 2.5 and 3.0 MeV neutrons, for biases of 0.25 and 0.5 MeV electron equivalent. The size of the error bars is determined principally by the uncertainty in T.

6. The Monte Carlo program

To allow interpolation of our efficiency data between measured energies, and to allow extrapolation to scintillators of different sizes and shapes, a simple Monte Carlo program[20]) has been written which calculates the efficiency as a function of neutron energy and pulse height for scintillators of rectangular or cylindrical geometry. This program is essentially a reworking in Monte Carlo form of the successful program of Kurz[21]) which uses an analytical approach. The physical assumptions of Kurz were retained whenever possible and extended only when necessary or especially convenient. The advantages of the Monte Carlo method are: (a) The accuracy for low energy neutrons in thick scintillators is greatly improved because thirdand higher order scatters are included. (b) It is no longer necessary to assume cylindrical symmetry about the incoming neutron direction. (c) Edge effects may be investigated. (d) Pulse height spectra are available for comparison with experiment.

As an input for the program, the existing total cross sections for neutron–carbon inelastic interactions has been adjusted within reasonable limits (two standard deviations) to reproduce our efficiency data. Fig. 3e shows the total cross sections used by the program as a function of neutron kinetic energy for five of the six reaction channels simulated by the program; the cross section for the channel $n+C \rightarrow n+C$ (not shown) is given in ref. 14.

It should be noted that below about 25 MeV the major contribution to the efficiency comes from np elastic scattering. This total cross section is known much better than the intended accuracy of the program and has not been adjusted. For these low energies only small changes to the calculated efficiency can be made, at the expense of large adjustments to cross sections in other channels. Below the carbon inelastic threshold of 4.7 MeV there is essentially no freedom to adjust any cross sections. For neutrons more energetic than about 50 MeV, on the other hand, carbon inelastic channels dominate the efficiency and the cross section data are quite limited, so that it is easy to produce good fits to our measurements. The final cross sections used by this program above 50 MeV are probably better described as efficiency parameters than as physically meaningful quantities.

The results of the Monte Carlo calculation are compared in fig. 3a with the data from our efficiency calibration. Except at the highest bias the agreement is better than 5%. The excellent fit above 50 MeV is of course the result of the freedom to adjust the carbon cross section; it is the good agreement below 10 MeV which is especially gratifying because of the lack of adjustable parameters.

As an additional check, the efficiencies for the counters used in three other recent calibration experiments were calculated using the same cross sections; comparisons with the data are shown in figs. 3b, 3c and 3d. The smallest counter was 2 in. thick, while the largest was 12 in. thick. Biases ranged between 0.80 and 16 MeV electron equivalent. Once again the agreement is typically better than 5% except for the high-energy end of fig. 3d, where the data of ref. 6 shows a rise in efficiency at low bias which is not reproduced by the Monte Carlo program. In ref. 10 high-statistics neutron pulse-height spectra (taken during the course of the experiment of ref. 12) are compared with the Monte Carlo predictions. The agreement is generally good; in particular, the integral pulse height distributions for neutrons of 140–160 MeV in a 10-in. thick counter (based on 2100 counts) are completely consistent with the Monte Carlo predictions.

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