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IMPROVED PREDICTIONS OF NEUTRON DETECTION EFFICIENCY FOR HYDROCARBON SCINTILLATORS FROM 1 MeV TO ABOUT 300 MeV*

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Several improvements have been made to the Monte-Carlo neutron detector efficiency code of Stanton to provide improved agreement with several different detector efficiency measurements. The improvements include a re-adjustment of the inelastic cross sections for neutron-induced reactions on carbon, adoption of new light-response functions, use of relativistic kinematics, and exact determination of light deposited by escaping charged particles. The improved calculations agree with measured efficiencies for both plastic and liquid hydrocarbon scintillators for neutron energies from 1 MeV to about 300 MeV and for detector thresholds from about 0.1 MeV to 22 MeV equivalent-electron energies; in most cases the agreement is good to within a few percent.

1. Introduction

In recent experiments[1-4]) at different accelerator facilities, we have measured neutron cross-sections and spectra at energies from about 1 MeV to several hundred MeV with plastic (NE-102) and liquid (NE-213) hydrocarbon scintillation counters of different sizes, geometries, and thresholds. Our scintillators ranged in size from 22 in. diam. by 2 in. thick to 10 in. high by 40 in. long by 4 in. thick and were operated at thresholds ranging from about 0.1 MeV to above 50 MeV. It is time-consuming and expensive to measure neutron detector efficiencies over a large energy range for a variety of detector geometries, threshold settings, and scintillator types. It is the purpose of this paper to report on an improved computer code for making reliable and accurate calculations of neutron detector efficiencies for hydrocarbon scintillators.

Earlier workers developed various methods of calculating neutron detector efficiencies[5-11]). The computer code of Kurz[5]) included neutron scattering by hydrogen and carbon nuclei and a parameterization of the light output for recoil charged particles. Thornton et al.[7]) modified the Kurz code to obtain good agreement with their own measurements of neutron detector efficiencies and to predict efficiencies at energies different from those of their experimental measurements. Stanton[8]) developed a Monte-Carlo computer code which includes neutron rescattering explicitly. Edelstein et al.[6]) modified the Stanton code to obtain good agreement with their own measurements. These earlier computer codes do not show consistent agreement with each other or with other available measurements of neutron counter efficiencies. These calculations often disagree with measured efficiencies by more than 20% at neutron energies above 40 MeV [9,12]). McNaughton et al.[9,10]) reported measurements of neutron-induced reactions on carbon, and used these measurements to improve the Monte-Carlo code of Stanton. Our calculations with the computer code of McNaughton et al, show better agreement with some available data than published calculations with other previous codes; however, these published calculations still predict efficiencies which are significantly larger than some measured efficiencies in the energy region between 20 and 50 MeV.

Del Guerra[11]) reported an extensive compilation of neutron inelastic cross-sections on carbon, which he used in a Monte-Carlo computer code to calculate neutron detector efficiencies. Del Guerra[11]) compared these calculations with several different available efficiency measurements. While the agreement is in general quite good, some systematic discrepancies still exist. These discrepancies are seen most clearly for measurements from one neutron counter with several different detector threshold settings between 1 MeV and 20 MeV electron-equivalent energy. The calculations generally agree with the measurements at low-threshold settings but underestimate the measured efficiencies at high-threshold settings. Since we sometimes set thresholds from lower than 1 MeV to higher than 20 MeV electron-equivalent

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energies in our various experiments, these discrepancies needed to be removed.

In an attempt to provide efficiency calculations that would be reliable over a wider range of neutron energies and detector thresholds than is possible with presently available codes, we decided to modify the computer code of McNaughton et al.[10]). This code incorporates the measurements of McNaughton et al.[9]) of important neutron inelastic cross-sections and energy and angular distributions of emitted charged particles for neutron-induced reactions on carbon which were unavailable to Del Guerra[11]). In order to produce reliable calculations at high energies, we adopted relativistic kinematics and included the effects of finite counter size. Additionally, we incorporated the new measurements of scintillator light response to protons by Madey et al.[13]) which provide a different response function than assumed previously for the NE-102 type scintillator. Since even the most recent measurements do not define adequately the necessary carbon inelastic cross-sections to be used in the efficiency calculation, we decided to adjust the calculations to fit many different sets of efficiency measurements simultaneously. While neutron efficiency measurements contain information pertinent to these cross-sections, the tuning of an efficiency calculation to a particular measurement is probably unreliable because of unknown systematic errors. Although this method of adjusting the cross-sections to fit several different efficiency measurements is difficult, it is certainly more reliable than tuning to any one measurement and should provide calculated efficiencies which are not biased towards a particular measurement.

In the next section, we discuss our improvements to the code; and in sect. 3, we compare our calculations with available measurements of neutron counter efficiencies.

2. Improvements to the Monte-Carlo code

The improvements made to the Monte-Carlo code of McNaughton et al.[10]) include:

1. Adjustment of the inelastic cross-sections and kinematics for neutron-induced reactions on ^{12}C.
2. Adoption of new light-response functions.
3. Use of relativistic kinematics.
4. Proper determination of light deposited by escaping charged particles.

Each of these improvements is described below.

2.1. Adjustment of the inelastic cross-sections and kinematics for neutron-induced reactions on ^{12}C

For neutron energies above about 30 MeV, the largest source of uncertainty in calculated neutron detector efficiencies arises from uncertainties in the cross-sections for the neutron-induced inelastic reactions on carbon. The measurements of Kellogg[14]) at 90 MeV have long been the only absolute determination of these inelastic cross-sections above 20 MeV. Recently, the measurements of McNaughton et al.[9]) at 56 MeV have provided important information regarding scattered proton energy and angular distributions; however, these measurements provide only an upper limit for the cross-sections because of double-counting of reactions in which two or more charged particles are produced. McNaughton et al.[10]) and Del Guerra[11]) provide excellent discussions of the difficulties involved in reliably determining the neutron-induced inelastic cross-sections on carbon. The inelastic cross-sections adopted for this work are shown in fig. 1. The available experimental measurements of cross sections for each channel are also shown; however, for clarity, the measured total inelastic and C(n, γ) cross-sections are omitted. These cross-sections are generally similar to those deduced by McNaughton et al.[10]) and Del Guerra

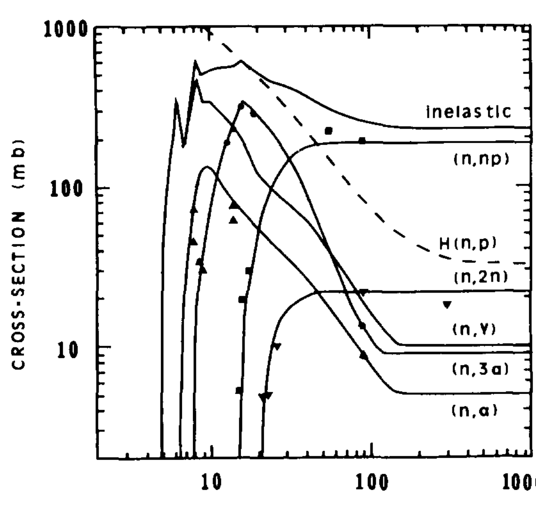

Fig. 1. Neutron–carbon inelastic cross-sections. The solid lines represent the cross-sections used in the Monte-Carlo computer code. The symbols denote cross-section measurements compiled by Del Guerra[11]) for inelastic reactions of neutrons on carbon.

et al.[11]) except for the C(n, np) and the C(n, 2n) cross-sections. Since the C(n, np) channel is the most important inelastic reaction above about 30 MeV where its cross-section becomes larger than the H(n, n) elastic cross-section, it is important to determine accurately both the C(n, np) inelastic cross-section and the energy and angular distributions of the emitted proton for this channel. Because of the lack of cross-section data, we tuned the C(n, np) cross-sections between 20 and 90 MeV to provide the best agreement between calculations with the computer code and several available measured neutron detector efficiencies, while remaining consistent with the cross-section measurements of Kellogg[14]) at 90 MeV and McNaughton et al.[9]) at 56 MeV. The resulting C(n, np) cross-section now rises much less sharply from threshold and levels off at a lower value than do the cross-sections determined by Del Guerra[11]) or McNaughton et al.[10]). Our need to lower the cross-section values for the C(n, np) channel from the values determined by Del Guerra[11]) may be the result of using different energy and angular distributions. Earlier codes[5,8,11]) have assumed a phase–space energy distribution and an isotropic angular distribution for the scattered proton in the C(n, np) channel. We have retained the energy and angular distributions for the emitted proton as determined by McNaughton et al.[9]) from their experimental measurements. The energy distribution is flat up to the maximum kinematically allowed energy. The angular distribution is forward peaked. The present code also considers a rescattered neutron in the final state of the C(n,np) reaction which is ignored in previous codes. Since many of our counters are large (e.g., 10 in. × 40 in. × 4 in. thick), this rescattered neutron can have a significant probability for interaction in the counter. Based on the data of Kellogg[14]) at 90 MeV, a rescattered neutron is included in 90% of the C(n, np) reactions simulated by the computer code. The energy of the neutron is taken to be the difference between the kinematic maximum energy and the previously determined proton energy. The angular distribution is taken to be the same as for the proton.

In order that the total inelastic cross-section be the sum of all the separate inelastic channel cross-sections used in the code, it was necessary to lower the total inelastic cross-section over the energy region from about 20 to 50 MeV where the C(n, np) channel cross-section was reduced. This lowered total inelastic cross-section is still in good agreement with the available data over this energy region because the data as compiled by Del Guerra[11]) either have large uncertainties ($\approx 30\%$) or are only lower limits.

In addition to the changes in the C(n, np) channel we have added a C(n, 2n) reaction channel. This channel has not been included explicitly in earlier neutron detector efficiency codes because it does not directly produce charged particles and (at 90 MeV) has a cross-section only about 10% of the dominating C(n, np) channel; however, for detectors with large efficiencies, omission of the C(n, 2n) channel can result in errors greater than 5% in the calculated efficiencies. We obtained the cross-section values for this new channel from the measurements of Brolley et al.[15]), Warshaw et al.[16]) and Barthow et al.[17]). The kinematics of the C(n, 2n) channel are assumed to be the same (except for a Q-value of -20.3 MeV) as the kinematics of the C(n, np) channel discussed above. Both neutrons produced in the final state of the C(n, 2n) reaction are followed through the scintillator by the Monte-Carlo method of the computer code.

2.2. Adoption of new light-response functions

Madey et al.[13]) measured the relative light response of NE-102, NE-224, NE-228 and NE-228A scintillators to protons from 2.43 MeV to 19.55 MeV. They represented these measurements and the earlier measurements of Czirr et al.[18]) at lower energies with an empirical expression of the form:

$$T_e = a_1 T_p - a_2[1.0 - \exp(-a_3 T_p^{a_4})], \tag{1}$$

where the electron energy T_e and the proton energy T_p are in units of MeV. These response functions differ significantly from expressions[13]) used previously. For the liquid scintillator NE-213, which is popular for its pulse-shape discrimination capability, we used this same expression to fit the proton light response measurements of Verbinski et al.[19]) and Czirr et al.[18]). Also, we introduced a new light-response function for alphas into the Monte-Carlo code. Since alphas produce much less light than protons, the accuracy of the light-response function for alphas is less important for the efficiency calculations than that for protons. We fit the calculations of Gooding and Pugh[20]) with the expression of eq. (1) to provide the alpha response function. In table 1, we present values of

TABLE 1

Coefficients in the light response function, eq. (1), for protons and alphas in various scintillators.

Particle and scintillator	Coefficient a_1	a_2	a_3	a_4
P, NE-102	0.95	8.0	0.1	0.90
p, NE-213	0.83	2.82	0.25	0.93
p, NE-224	1.0	8.2	0.1	0.88
p. NE-228, NE-228A	0.95	8.4	0.1	0.90
α, all scintillators	0.41	5.9	0.065	1.01

the coefficients of eq. (1) which are used in the efficiency calculation. These coefficients provide excellent fits to the experimental proton light response data and may be better representations of the scintillator light response than any one set of measurements. These fits are estimated to represent the proton light response to better than 5% over the energy region from about 0.1 MeV to about 30 MeV electron-equivalent energies.

2.3. RELATIVISTIC KINEMATICS

Stanton's[8]) original Monte-Carlo neutron detector efficiency code was written primarily to calculate efficiencies for low-energy neutrons. McNaughton's[10]) version of Stanton's[8]) code contains several improvements but uses relativistic kinematics for only the C(n, nγ) reaction channel. The need to calculate detector efficiencies for neutrons with kinetic energies above 100 MeV requires the use of relativistic kinematics. Thus, the computer code was modified to include relativistic reaction kinematics for all channels.

2.4. CHARGED PARTICLE ESCAPE

For each charged particle produced by a simulated neutron interaction in a counter, the computer code has been extended to calculate the range of the charged particle in the scintillator. Each charged particle is propagated through the scintillator until it deposits all of its energy or until it leaves the scintillator. An empirical relation is used to determine the energy lost in the scintillator by particles which leave the scintillator. Only the energy deposited in the scintillator is used to determine the amount of light produced by a charged particle. To obtain empirical range–energy expressions for use in the Monte-Carlo efficiency code, we used the method of least squares to fit a logarithmic polynomial to the range–energy tables of Janni[21]) for Pilot B scintillator. For protons, the functions are:

$$\begin{aligned}\ln R &= -3.8103 + 1.6171 \ln T + 0.08193 \ln^2 T - \\ &\quad - 0.020364 \ln^3 T + 0.003147 \ln^4 T - \\ &\quad - 0.0002321 \ln^5 T, \end{aligned} \tag{2}$$

$$\begin{aligned}\ln T &= 2.1964 + 0.56148 \ln R + 0.0010055 \ln^2 R - \\ &\quad - 0.00008885 \ln^3 R - 0.0001821 \ln^4 R + \\ &\quad + 0.00002742 \ln^5 R, \end{aligned} \tag{3}$$

The range R is expressed in millimeters and the energy T is in MeV. Eq. (2) reproduces the tables of Janni to better than 2% over the energy region from 0.1 to 1000 MeV. Eq. (3) reproduces the tables to 2% or better over the energy region from 0.5 to 1000 MeV. For alphas, we use the usual scaling relations

$$R_\alpha = R_p(T_\alpha/4), \tag{4}$$

$$T_\alpha = 4T_p(R_\alpha). \tag{5}$$

These range-energy relations are used in the code for scintillators with chemical compositions and densities similar to Pilot B.

3. Comparison of calculations with available experimental measurements

Since the purpose of the Monte-Carlo code is to provide reliable calculations of neutron counter efficiencies for different detector geometries, neutron energies, and detector thresholds, the best test of the code is comparison with a wide variety of efficiency measurements. We present here comparisons of calculations with the improved code against many different experimental measurements of neutron counter efficiencies. In these measurements, neutron energies vary from about 1 MeV to 340 MeV and counter thresholds from 0.12 MeV to 22 MeV equivalent-electron energy. When calculating the efficiencies, we attempted to reproduce the conditions relevant to each experiment, such as the correct geometry of the counter, the threshold setting, and the energy spread of the incident neutrons. Sometimes it was difficult to determine these parameters reliably from the available literature. The efficiencies near threshold are especially sensitive to the various experimental parameters and are expected to be more difficult to reproduce accurately. As presently written, the efficiency code translates the energy deposited in the scintillator by a monoenergetic charged particle into a Gaussian pulse-height distribution. This

Gaussian distribution function determines the shape of the calculated efficiency as a function of energy near threshold. For small pulse heights, the Gaussian approximation becomes invalid. The statistics of the Gaussian distribution function are determined in the computer code by the amount of energy deposited in the scintillator and by an input parameter specifying the amount of energy required to produce one photoelectron at the photocathode. As indicated in the report by Stanton[8]), one may try to reproduce the shape of a measured set of efficiencies near threshold by varying the energy per photoelectron parameter. We have not attempted to perform such adjustments; but instead we take the statistics to be determined by assuming an energy per photoelectron of 2 keV as suggested by the work of Lindstrom and Anderson[22]) for either an NE-102 or an NE-213 scintillator mounted on an RCA 7850 photomultiplier tube. Because the Monte-Carlo code needs to be modified to use a more accurate distribution function for small pulse heights, and because efficiencies near threshold are very sensitive to small errors in the assumed threshold value, the calculations should not be relied upon below about two times the threshold setting.

There are numerous measurements of the neutron detection efficiency of plastic scintillators available in the literature. We used the proton light response for NE-102 scintillator in the Monte-Carlo calculation to compare with the following measurements on various plastic scintillators since their chemical compositions and densities are nearly identical. Comparisons of the Monte-Carlo predictions against experimental measurements of neutron counter efficiencies with thresholds from 0.2 MeV to 4.2 MeV equivalent electron energy are shown in fig. 2. The experimental efficiencies of Wiegand et al.[23]) for a plastic scintillator (97% polystyrene, CH) 15.0 cm

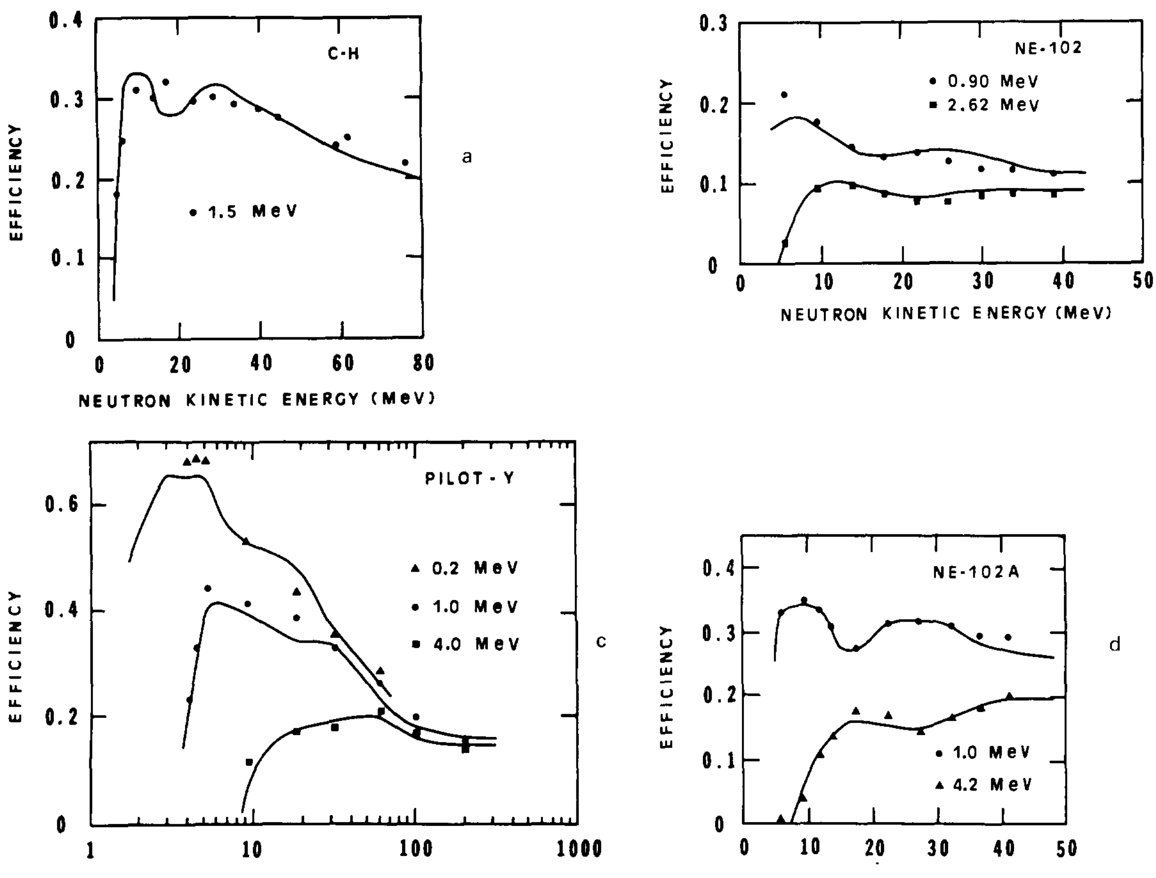

Fig. 2. Comparison of efficiency measurements with calculations of the Monte-Carlo computer code for plastic scintillators with thresholds set from 0.2 to 4.2 MeV equivalent-electron energies: (a) Wiegand et al.[23]), (b) Hunt et al.[24]), (c) Edelstein et al.[6]) and (d) McNaughton et al.[10]).

thick by 60.0 cm diameter are shown together with the calculated efficiencies in fig. 2(a). The agreement is seen to be good from threshold up to the highest measurement at about 75 MeV. The Monte-Carlo predictions are shown compared against the experimental data of Hunt et al.[24]) for a 5.08 cm thick by 10.27 cm diameter NE-102 ($CH_{1.1}$) counter at two different thresholds in fig. 2(b). The agreement is seen to be excellent for all the data except the point near threshold for the lowest threshold setting. In fig. 2(c) we show the comparisons of the calculations with the measurements of Edelstein et al.[6]) for a 15.24 cm thick by 15.24 cm PILOT-Y ($CH_{1.1}$) scintillator at three different thresholds. The agreement is seen to be good except that the calculations for neutron energies near 4 MeV for the lowest threshold (0.2 MeV equivalent-electron energy) are somewhat low, although still in agreement with the data to better than 10%. This slight discrepancy would be removed if there is a small error in the values of the threshold setting. The good agreement over the entire range of neutron energies from 4 MeV to 200 MeV is quite striking. The measurements of McNaughton et al.[10]) are shown together with the Monte-Carlo calculations in fig. 2(d). The neutron counter was 15.2 cm thick by 7.1 cm diameter NE-102A ($CH_{1.1}$). The data are considered to represent careful measurements and the agreement is excellent.

The most significant improvement in the agreement of these calculations with experimental measurements over earlier calculations is for high threshold settings. In fig. 3, we present a comparison of the calculations with experimental measurements at threshold settings up to 22 MeV equivalent-electron energy. Fig. 3(a) is a comparison of calculations with the improved Monte-Car-

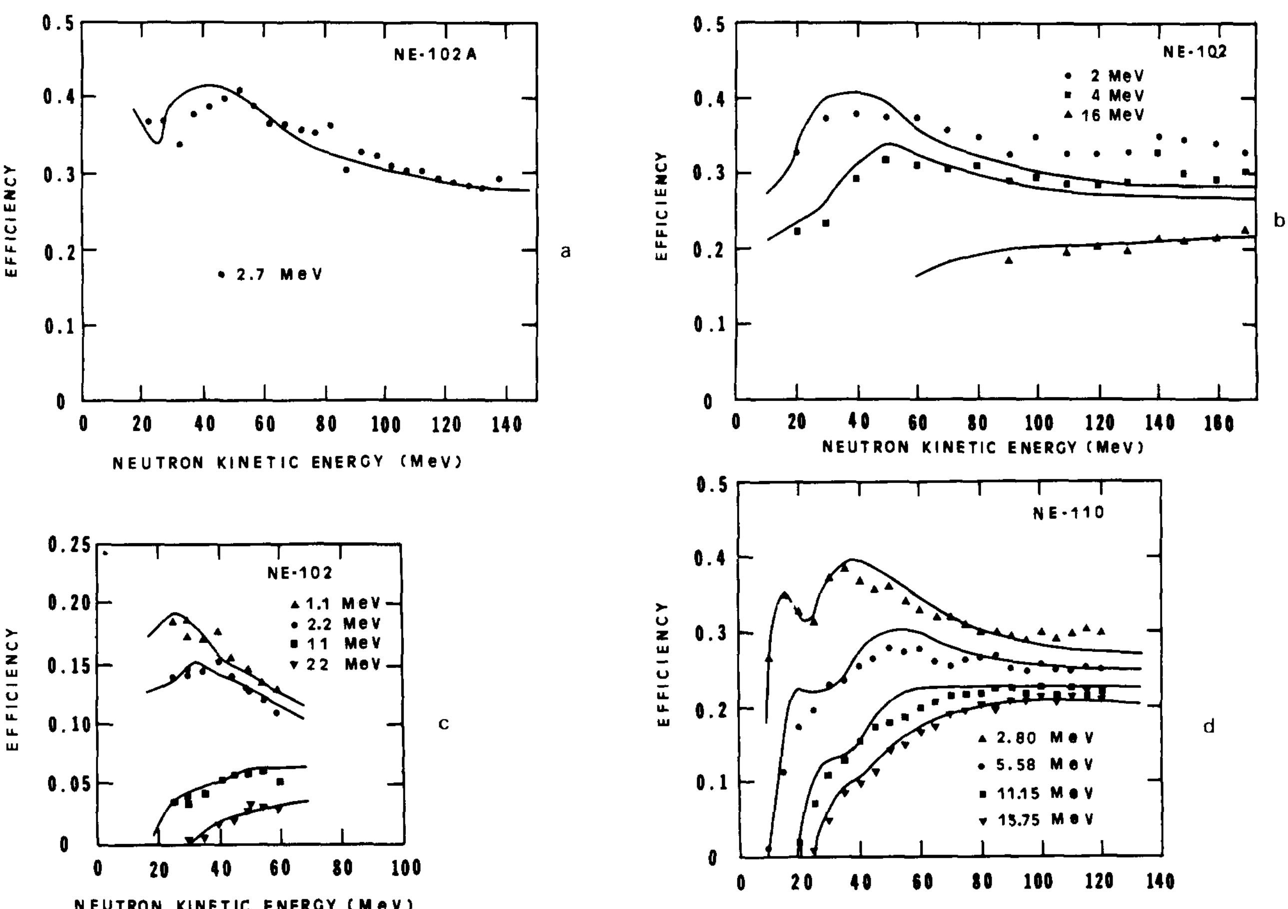

Fig. 3. Comparison of efficiency measurements with calculations of the Monte-Carlo computer code for plastic scintillators with thresholds set from 1.1 to 22.2 MeV equivalent-electron energies: (a) Crabb et al.[25]), (b) Young et al.[26]), (c) Riddle et al.[12]) and (d) Betti et al.[27]).

lo code with the experimental measurements of Crabb et al.[25]) for 28.6 cm thick by 30.0 cm diameter NE-102A counter at a threshold of 6 MeV proton energy. The agreement is good over the entire neutron energy range from 20 MeV to 140 MeV. The data of Young et al.[26]) for a 30.5 cm thick by 12.7 cm diameter NE-102 counter are shown compared to the calculated efficiencies in fig. 3(b) for three thresholds up to 16.0 MeV equivalent-electron energy. The agreement is excellent at the highest threshold settings. The rise of the measured efficiencies at high energies for the two lowest threshold settings is not reproduced by the efficiency calculations. At the 4 MeV threshold setting, the measurements above 120 MeV are 5–10% higher than the calculations. At the 2 MeV electron-equivalent threshold setting, the measurements above 90 MeV are 5–15% higher than the calculations. In fig. 3(c) we compare the Monte-Carlo calculations with the measurements of Riddle et al.[12]) for a 7.6 cm thick by 17.78 cm diameter NE-102 counter at four thresholds between 1 and 22 MeV equivalent-electron energies. The calculations reproduce the measurements well at all thresholds. The recent measurements of Betti et al.[27]) for a 15.3 cm diameter by 27.0 cm thick NE-110 ($CH_{1.1}$) scintillator are shown compared against calculated efficiencies in fig. 3(d) for four thresholds from 2.80 MeV to 15.75 MeV equivalent-electron energy. Again the agreement is good, especially for the two highest thresholds. The consistently excellent agreement of the calculations with high threshold data is not seen in any of the earlier computer calculations of neutron detector efficiencies.

The computer code can also be used to calculate detector efficiencies for liquid scintillators. Fig. 4 shows measurements of neutron detector efficiencies for four different liquid scintillators. Fig. 4(a) shows the calculations of the code compared with the efficiency measurements of Hunt et al.[24]) for an NE-228 ($CH_{2.00}$) scintillator 5.08 cm thick and 10.271 cm in diameter. The agreement is good above 10 MeV. Fig. 4(b) shows a comparison of

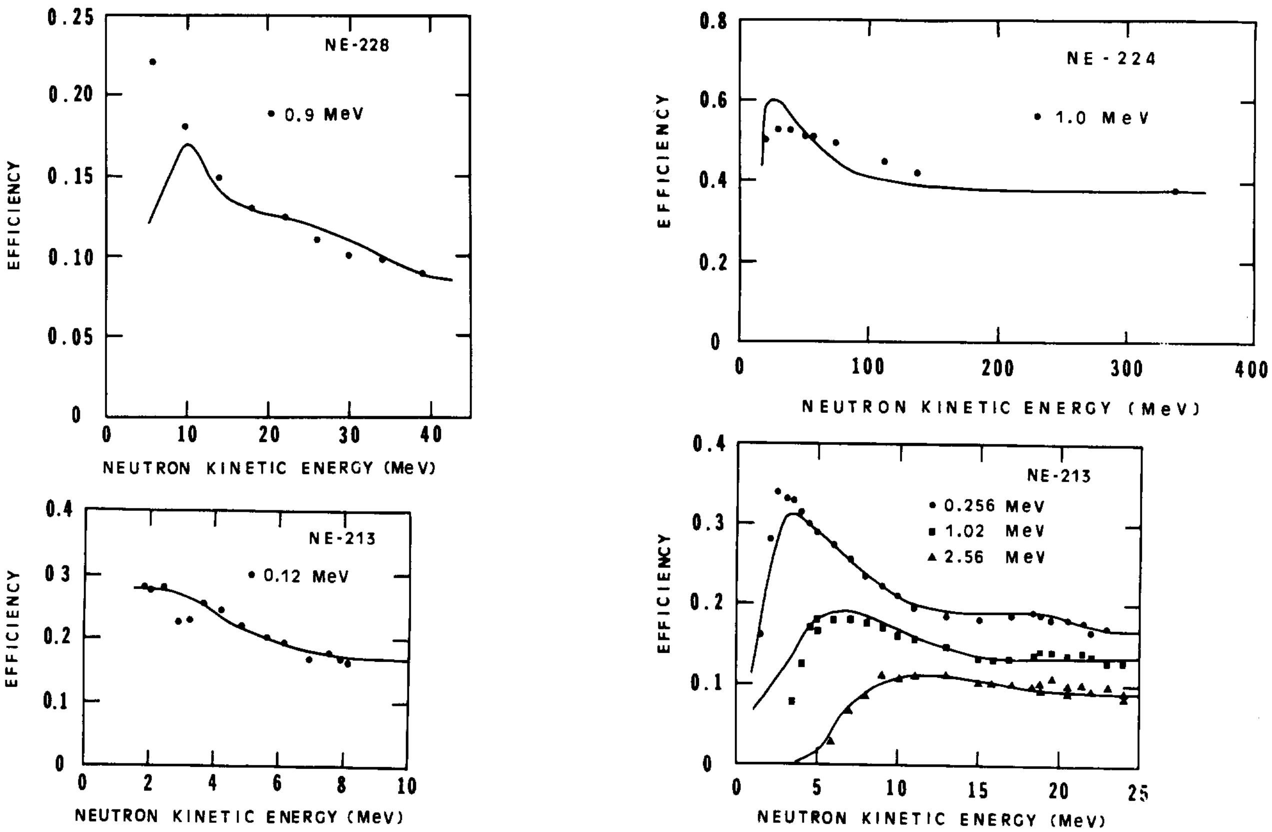

Fig. 4. Comparison of efficiency measurements with calculations of the Monte-Carlo computer code for liquid scintillators with thresholds set from 0.256 to 2.56 MeV equivalent-electron energies: (a) Hunt et al.[24]), (b) Parsons et al.[28]), (c) Thornton and Smith[7]), and (d) Drosg et al.[29]).

the calculations with the data of Parsons et al.[28]) for an NE-224 ($CH_{1.33}$) scintillator array 45 cm thick. The data are compared out to the highest energy measurement at 340 MeV. The low-threshold measurements of Thornton and Smith[7]) compare well with the calculations of the code in fig. 4(c). These measurements were made with an NE-213 ($CH_{1.21}$) scintillator 3.8 cm thick and 12.7 cm diameter. In fig. 4(d), we compare the calculations with the measurements of Drosg[29]) for an NE-213 scintillator 5.6 cm thick and 12 cm in diameter. The measurements extend from 1 MeV up to 25 MeV for three different thresholds. The agreement with the calculations is exceptionally good even for the very low threshold of 0.256 MeV equivalent-electron energy.

4. Conclusions

The calculations of neutron counter efficiencies with the improved Monte-Carlo code presented here provide good agreement, especially at high detector thresholds, with available experimental measurements. Since the calculations agree with the available data to better than 10%, and usually much better, and since any one efficiency measurement probably includes some systematic error, we estimate that these calculations are accurate to a few percent (except near threshold) for the range of experimental parameters tested here, namely, for neutron energies from 1 MeV to about 300 MeV and for detector thresholds from about 0.1 MeV to above 22 MeV equivalent-electron energies. The calculations may be reliable over an even wider range of neutron energies and detector thresholds, but remain untested because of a lack of experimental measurements.

Our improved calculations are the result of several modifications to an earlier version of the computer code. These modifications include a new adjustment of the cross-sections and kinematics for the carbon inelastic reaction channels, addition of a C(n, 2n) reaction channel, adoption of new light-response functions, the use of relativistic kinematics, and the correct determination of light deposited by charged particle recoils which escape the counter. Of these various changes, the most significant improvements over earlier codes result from the new adjustment of the cross-sections and kinematics for the C(n, np) reaction channel.

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