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IMPROVED PREDICTIONS OF NEUTRON DETECTION EFFICIENCY RESULTING FROM NEW MEASUREMENTS OF ^{12}C(n,p) AND ^{12}C(n,d) REACTIONS AT 56 MeV*

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We have obtained new data for the ^{12}C(n, p) and ^{12}C(n, d) reactions at 56 MeV and used these to obtain improved predictions of neutron detection efficiency for a plastic scintillator. Previously reported discrepancies between efficiency data and the predictions of Stanton's and Kurz's codes in the energy region 6 to 41 MeV are now largely resolved. The prime culprit, applying equally to Stanton's, Kurz's and the O5S codes, is the treatment of the ^{12}C(n, p) reactions. Alterations have also been made to the cross sections and to the scintillation light output function assumed by Stanton and Kurz. Following these changes, agreement between data and predictions for a 4.2 MeV threshold improved from the order of 10% to the order of 3%.

1. Introduction

In a recent measurement of neutron detection efficiencies for plastic scintillator[1]) we reported significant discrepancies between our measurements and the predictions of two widely used computer programs by Kurz[2]) and Stanton[3]). Modifications to Stanton's program[3]) together with new data for the carbon break-up reactions have resulted in considerably improved agreement between the computer-generated predictions and these data, as is shown in fig. 1.

Two regions of discrepancy were apparent both for detector thresholds of 1.0 and 4.2 MeV. In the first region, over the lower energy peak, the interaction of neutrons with the scintillator is dominated by elastic scattering of neutrons with hydrogen nuclei. Stanton's[3]) predictions, which incorporate a more complete treatment of neutron rescattering using the Monte-Carlo method, show better agreement[1]) than Kurz's[2]), but small discrepancies of up to 5% remain. These result partly from the use (by both Stanton and Kurz) of Kurz's empirical parameterisation[2]) of the light output data for plastic scintillator, which is accurate only to 5%. (As a separate point, note that Kurz misquotes his parameterisation, see ref. 4.) Inserting a small correction into Stanton's program to improve the agreement with the light output data[5]), together with the use of more reasonable carbon cross sections (see section 3), results in significantly improved agreement (see fig. 1).

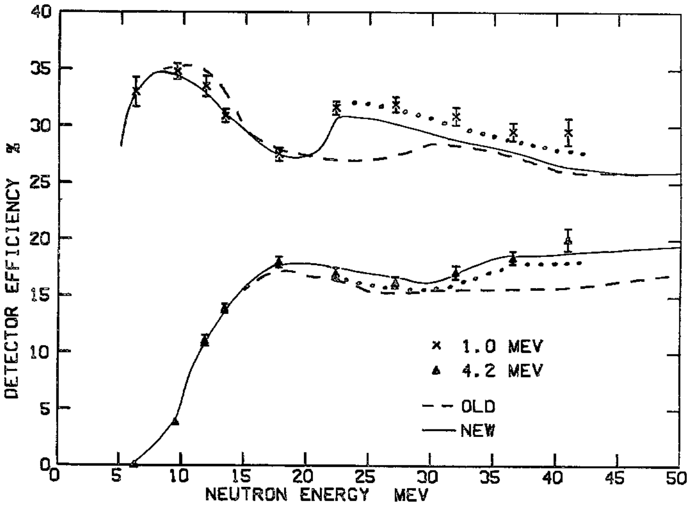

Fig. 1. Comparison of measured neutron detector efficiencies (ref. 1) with various predictions (old: Stanton's original; new: Stanton's modified; dotted: see text).

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The second region of discrepancy presents more difficulty. At higher energies the interaction of neutrons with carbon in the scintillator begins to contribute significantly, and the efficiency begins to rise despite the decreasing n–H cross section. The observed discrepancy here indicates that contributions of charged particles from carbon are more important just above threshold than are predicted by either Stanton or Kurz. The improved agreement shown in fig. 1 results primarily from a modified treatment of the $^{12}C(n, p)$ reaction.

The cross sections for carbon break-up by neutrons are not well known. To select one example, the $^{12}C(n,p)^{12}B$ reaction cross section at 50 MeV is assumed by Kurz to be 125 mb [2]), by Stanton to be 204 mb [3]) and in the ORNL code O5S to be 61.5 mb [6]). Stanton's philosophy is that neutron efficiency data contain information on these cross sections, so he has tuned the cross-section data to obtain fits to the efficiency data. This approach, while valid in principle, is ambiguous in practice because of the complexity of the problem. Kellogg[7]) lists 65 reaction cross sections for carbon break-up, each of which produces one or more charged particles, with various final state energy and angular distributions, and various scintillation properties. Stanton and Kurz approximate this complexity with just three reaction channels: (n, p) (n, α) and (n, 3α).

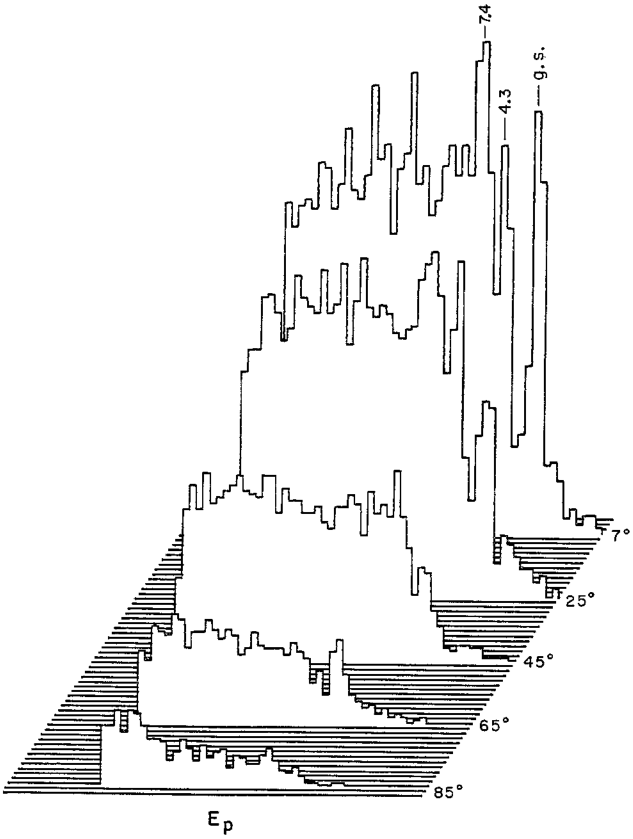

Fig. 2. Proton energy spectra from $^{12}C(n, p)$ reaction for various lab. angles from 7° to 85°. The vertical scale is proportional to cross section. The proton energy scale (E_p) runs approximately from 0 to 51 MeV.

2. Cross sections: measurements

Differential cross sections for the $^{12}C(n,p)$ and $^{12}C(n,d)$ reactions have been obtained for 56 MeV incident neutrons on a 28 mg/cm^2 carbon target. Angular distributions were taken between 7° and 85°. The experimental arrangement and data acquisition system have been described previously[8]). Briefly, 56 MeV neutrons are obtained from the $^7Li(p,n)^7Be$ reaction using 58 MeV protons from the Crocker Nuclear Laboratory cyclotron and are collimated onto the target in an evacuated scattering chamber. Emitted charged particles are detected in telescopes of Si ΔE-detectors and NaI E-detectors. Neutrons of the full bombarding energy are selected by reference to the incident neutron time-of-flight, while particle identification is by $\Delta E \cdot E$ correlation.

At each angle a $E + \Delta E$ spectrum as shown in fig. 2

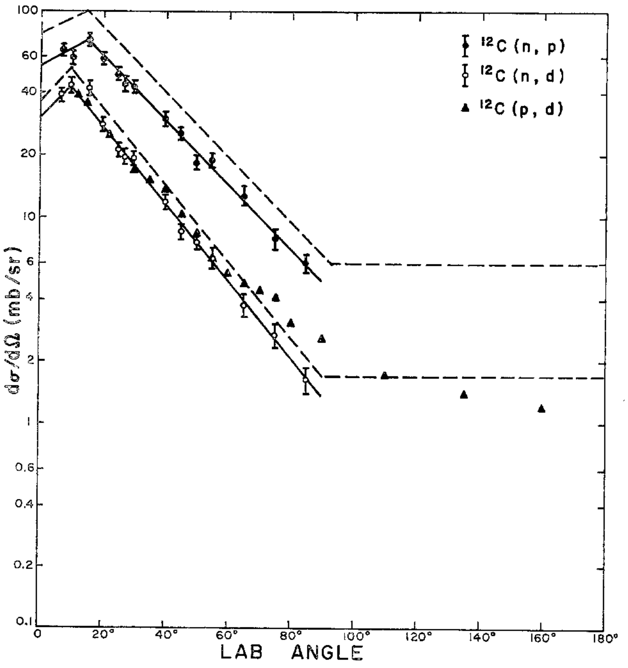

Fig. 3. Lab. differential cross sections for $^{12}C(n, p)$ and $^{12}C(n, d)$ (our measurements) compared with $^{12}C(p, d)$ from ref. 9. The discrepancy at large angles is explained by the lower cut off energy for the proton data. The lines were used for the integration and are discussed in the text.

TABLE 1

Integrated cross sections for 56 MeV neutrons on ^{12}C.

^{12}C(n, p)^{12}B:	$\sigma_0 = 3.4 \pm 0.6$ mb	(g.s., 1$^+$)
	$\sigma_1 = 5.2 \pm 0.6$ mb	(4.3 MeV, 2$^-$)
	$\sigma_2 = 4.3 \pm 0.6$ mb	(7.4 MeV, 1$^-$)
^{12}C(n, p):	$\sigma_{exp} = 126 \pm 7$ mb	(COE 12 MeV, $7° \leq \theta_{lab} \leq 85°$)
	$\sigma_t = 219$ mb	($\sigma = 173 \pm 15$ mb at 90 MeV[7]))
^{12}C(n, d)^{11}B:	$\sigma_0 = 20 \pm 2$ mb	(g.s. 3/2$^-$)
	$\sigma_1 = 3 \pm 1$ mb	(2.12 MeV, 1/2$^-$)
^{12}C(n, d)	$\sigma_{exp} = 54 \pm 3$ mb	(COE 15 MeV, $0° \leq \theta_{lab} \leq 85°$)
	$\sigma_t = 78$ mb	($\sigma = 71\ 1 \pm 0.3$ mb at 61 MeV[9]), COE 1.5 MeV)

is obtained and integrated to give the data of fig. 3 and table 1. An energy threshold in the *E*-detector results in a 12 MeV and 15 MeV cut-off energy (COE) in the proton and deuteron data respectively. Uncertainties in the cross sections are purely statistical. The energy integrated data is well represented by the straight lines shown in fig. 3 and allows an integration over angle to obtain the cross sections in table 1. The solid lines represent the experimental data with the low energy threshold and result in the total cross sections σ_{exp}. Dashed lines include an estimate for the low energy contribution to the cross section at each angle as well as a constant cross section for angles greater than 90° and result in the total cross sections σ_t. The latter assumption is based on the behavior of the back-angle proton-induced reaction data[9]) and the fact that contributions from compound nuclear processes, which are roughly independent of angle, dominate the cross section.

The notation ^{12}C(n,p) includes all final states in which a free proton occurs and therefore includes a double contribution from ^{12}C(n,2p). The ^{12}C(n,pd) reaction is necessarily included in both ^{12}C(n,p) and ^{12}C(n,d) reaction cross sections. In addition to composite proton and deuteron cross sections, total cross sections for excitation of three "giant resonances" via the ^{12}C(n,p)^{12}B reaction (see fig. 2 and ref. 10) and two states in ^{11}B from the ^{12}C(n,d)^{11}B reaction[10]) are also given in table 1. These total cross sections are obtained from DWBA calculations normalized to the differential cross sections. The uncertainties are based on variations in magnitude obtained when different optical model parameters were used as input to the DWBA calculations. The fact that the shapes predicted by these calculations agreed well with the data served as justification for this approach. No uncertainties have been placed on σ_t due to the model dependence and the number of assumptions included in their calculation.

3. Cross sections: Appraisal

We now return to consider the predictions of detection efficiency in the light of these cross-section measurements. Our data (table 1) indicate that Stanton's tuned cross-section value of 197 mb for ^{12}C(n,p) at 55 MeV is reasonable. In the process of tuning, Stanton raised the (n,p) cross section from the lower starting value estimated for the earlier codes[2,6]) and lowered the (n,3α) cross section to compensate and yield a reasonable total cross-section value. Our present feeling, however, is that he did not lower the (n,3α) cross section far enough.

A survey of the literature reveals that the estimates of the (n,3α) cross section above 20 MeV rest on Kurz's interpretation of Kellogg's paper. Kurz (page 3 of ref. 2) refers to table II of Kellogg's paper[7]) and takes the sum of the cross sections for the 32 reactions with a charged particle multiplicity of three or more as the (n,3α) cross section at 90 MeV (107 mb). But this includes contributions from ^{12}C(n,pα)Li (18 mb), ^{12}C(n,2p)Be (6 mb), ^{12}C(n,pd)Be (10 mb) etc. The reaction ^{12}C(n,3α)n is listed as 9.8 ± 2.0 mb, while the sum of all reactions with 2 or more α-particles is only 37.7 mb, so that by including all the reactions that he does, he obtains a considerable cross section overestimate for 3α emission.

The reduction of Kellogg's 65 reactions to Stanton's 3 is not easy, but a sensible step in this direction seems to be to group reactions under the headings (n,p), (n,d), (n,t) and (n,α) according to the lightest (and so most efficiently scintillating) particle that is produced. There might be an argument for including a reaction such as (n,pd) under both (n,p) and (n,d) headings, or including (n,2p) with twice the strength. (Our own results, presented in this paper, unavoidably include reactions more than once in this manner.) For insertion into Stanton's code, however, we prefer to avoid this where possible for three reasons:

1) Lighter particles scintillate more efficiently than heavier particles so (n, pd) is better dealt with under (n, p).

2) The error introduced by an inadequate knowledge of the charged particle energy spectra is equivalent to and larger than the error introduced by treating two final state charged particles of lower energy as one charged particle of higher energy.

3) Using an artificially high n-^{12}C cross section has the effect of removing neutrons into low efficiency carbon break-up channels before they have a chance to interact with hydrogen in a high efficiency elastic scattering, and can actually reduce the predicted efficiency.

On this basis, comparing with the data of table 1, we have retained Stanton's (tuned) values for (n, p) (197 mb at 55 MeV, 170 mb at 90 MeV). This provides good agreement both with Kellogg and with the total cross sections of BNL-325 [11]). Measurements made at this laboratory[12]) give slightly higher total cross-section values, but this is to be expected since we have not included the (n, 2n) or (n, d) reactions. Stanton suggests that the more weakly scintillating deuteron from the (n, d) reaction can be simulated by increasing the (n, p) contributions. The dotted line in fig. 1 shows the result of increasing the (n, p) cross section (by 25%) for low energy (<8 MeV) protons only. This is discussed further in section 5.

LeLeux et al.[13]) have pointed out similar uncertainties (summarized by Obst[14])) in the ^{12}C(n, α)^{9}Be cross section below 25 MeV. The low energy and poor scintillation of the alphas make these cross sections less critical, but LeLeux et al. demonstrate the effect of the various values on the predicted efficiency. In addition there is evidence[15]) that the (n, n'γ) cross sections should be generally higher than those used by Stanton. It is impossible to accomodate these higher values and the higher (n, α) values reported by Obst without exceeding the total cross sections of BNL-325, but some increase in both of these seems indicated, especially as Stanton's total cross section lies below BNL-325 in the range 7 to 25 MeV.

In summary we have made the following modifications to the cross sections used by Stanton:

1) We have lowered the (n, 3α) values from 45 to 126 MeV to a smooth line including 58 mb at 55 MeV, 37 mb at 90 MeV.

2) We have altered the (n, n'γ) values from 7 to 16 MeV to agree more closely with ref. 15.

3) We have raised the (n, α) values to compromise values that approach those of Obst[14]) and give total cross sections in agreement with BNL-325.

4. Energy spectra and angular distributions

These changes raise the predicted efficiencies slightly, but do not greatly improve the major features of disagreement between data and predictions. In particular we noted that the only significant contribution to the efficiency in the region of disagreement (apart from n – H elastic) was from the ^{12}C(n, p) process, and that this contribution rises very slowly with neutron energy (regardless of the assumed value for the total reaction cross section), which is in disagreement with the sharp rises observed at 22 MeV (1 MeV threshold) and 32 MeV (4 MeV threshold). This, we find, is a result of unrealistic angular and energy distributions for ^{12}C(n, p) that are assumed in all three efficiency codes investigated[2,3,6]). In the absence of any data, the assumption made in all three codes is that the process is compound nuclear, and is therefore described by a statistical model, giving angular distributions that are isotropic in the centre of mass, and proton energy spectra that are peaked at low energy and fall rapidly at higher energies. (Stanton's assumed energy distribution (4 body phase space, subroutine ENGDIS) is peaked at one fifth the maximum kinematically allowed energy.) Figs. 2 and 3 show these assumptions to be false.

A compound nuclear process would be expected for heavy nuclei at low energies. For light nuclei at high energies a direct reaction process would be expected which would yield a proton energy spectrum peaked near the maximum. For ^{12}C at 50 MeV a compromise is reasonable, yielding the fairly flat energy spectra which we observe (fig. 2). Bertrand's data for 39 and 61 MeV protons on carbon[9]) show similar spectrum shapes, though with some indication of dominance of a statistical model at lower energies and backward angles.

For simplicity we assumed that the proton energy spectrum was completely flat from zero to the maximum kinematically allowed energy. We obtained the best fits to our efficiency data[1]) if we assumed the Q value for ^{12}C(n, np)^{11}B (– 15.96 MeV), rather than for ^{12}C(n, p)^{12}B (– 12.59 MeV) as used by Stanton in subroutine NPB. This is in accord with the dominance of the ^{12}C(n, np)^{11}B process as observed by Kellogg[7]).

Our observations together with Bertrand's[9]) show that the C. M. angular distribution is forward peaked rather than isotropic as assumed by Stanton[3]), Kurz[2]) and in O5S [6]). Once more a simple assumption is needed to insert into Stanton's code. We have assumed that the lab. angular distribution for ^{12}C(n, p) is the same as for n-p elastic scattering (varying as cos θ) corresponding naively to a direct quasi-elastic (n, np) process. The existence of a rescattered neutron at 90° to the proton may be incorporated into the code, but makes little difference at these high energies.

5. Conclusion

The resulting calculations made with Stanton's code after all these modifications are shown in fig. 1. The predictions of the unmodified code are shown for comparison. We emphasize that the changes that we have introduced into Stanton's code[3]) to obtain this new prediction apply also to O5S [6]) and to Kurz's code[2]).

The agreement with the 4.2 MeV threshold data is quite satisfactory (as stated in ref. 1 we are less confident about the 41 MeV data). The agreement is improved but is still not satisfactory for the 1 MeV threshold. There is evidence from the ^{12}C(p, p′) and ^{12}C(p, d) data[9]) for a low energy peak in the final state energy spectra (below our threshold). Such a peak, resulting from statistical model contributions and being confined to final state energies less than about 8 MeV, increases the 1 MeV predictions but slightly lowers the 4.2 MeV predictions. The dotted line in fig. 1 shows the result of a 25% increase in the (n, p) cross section (50 mb at 55 MeV) consisting entirely of protons uniformly distributed between 1 and 8 MeV. We are expecting to obtain a more complete data set soon, including proton and deuteron spectra extending to lower energies. With these more complete data we expect to be able to include the (n, d) reaction explicitly, and obtain even better fits to the efficiency data.

It is not feasible to incorporate the full complexity of the n-^{12}C reaction into any computer calculation of detector efficiencies. But by measuring cross sections, energy spectra and angular distributions for reactions grouped under the broad headings (n, p), (n, d), (n, t), (n, α) for a range of incident neutron energies, it should be possible to make more reliable calculations of neutron detection efficiencies. Such measurements would also find application in better dosimetry calculations for the neutron beams that are increasingly being used for cancer therapy. We plan to embark on such a series of measurements in the near future here at Crocker Nuclear Laboratory.

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