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$^{12}C(d, n)^{13}N$ Total Cross Section from 1.2 to 4.5 MeV*

R. J. JASZCZAK,† R. L. MACKLIN, AND J. H. GIBBONS
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830
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The total cross section for the $^{12}C(d, n)^{13}N$ reaction has been measured for deuteron energies between 1.2 and 4.5 MeV using the Oak Ridge National Laboratory 5.5-MV Van de Graaff and a 4π graphite-sphere neutron detector. Thin natural-carbon targets (deposited onto platinum backings by electron bombardment of carbon) of thicknesses 80.0 ± 0.5 and 92.0 ± 0.5 $\mu g/cm^2$ were used to derive the cross-section values. Ten peaks were observed in the total cross section in the above energy region. The thin-target yield was numerically integrated and a comparison was made with the experimentally determined thick-target yield. The usefulness of the $^{12}C(d, n)^{13}N$ reaction for the production of an accurately known flux of monoenergetic neutrons and its importance in the absolute calibration of neutron detectors are discussed.

I. INTRODUCTION

IN recent years the $^{12}C(d, n)^{13}N$ reaction has been of considerable interest for several reasons. The effects of interference between direct reaction and compound-nucleus formation have been investigated.[1–6] These experiments in general stressed a comparison of the experimental differential cross section with the stripping theory proposed by Butler[7] through the use of plane- and distorted-wave Born approximations. The $^{12}C(d, n)^{13}N$ reaction is also a source of polarized neutrons.[8–10] The employment of this reaction as a standard neutron source for calibration of neutron detector efficiencies as a function of neutron energy is likewise of importance.[11] The utilization of this reaction for the production of an accurately known flux of monoenergetic neutrons (the neutrons are monoenergetic for deuterons below 3 MeV, since the threshold for neutron emission to the first excited state in ^{13}N is 3.09 MeV) has been ineffective because of the absence of an accurate measurement of the total cross section for the reaction. Additional reactions, such as $^{9}Be(\alpha, n)^{12}C$ and $^{13}C(\alpha, n)^{16}O$ reactions, have also been proposed as alternative sources of monoenergetic neutrons; however, the easy availability of carbon of high purity emphasizes the usefulness of the $^{12}C(d, n)^{13}N$ reaction.

It appeared desirable to determine the absolute total cross section for the $^{12}C(d, n)^{13}N$ reaction so that it could be coupled with existing[11] angular-distribution data to allow a relatively simple but absolute calibration of fast neutron detector efficiencies. A thin-target excitation function for deuteron bombarding energies between 1.2 and 4.5 MeV and a thick-target yield curve between 2 and 5 MeV were obtained and compared for the purpose of analyzing the results accurately.

II. EXPERIMENT

Natural-carbon targets were employed throughout the experiment since, in performing neutron detector calibration experiments, it would not be difficult to acquire natural-carbon targets. Although no resonances due to the $^{13}C(d, n)^{14}N$ reaction were observed in the excitation function, up to 4% of the yield at certain energies is due to the bombardment of the ^{13}C in the natural-carbon target. The $^{13}C(d, n)^{14}N$ yield was estimated from the results of Marion *et al.*[6] The thin targets used in the experiment were prepared by electron bombardment of carbon onto platinum backings. Two were accurately weighed (before and after the evaporation) on a microbalance, giving areal densities of 80.0 ± 0.5 and 92.0 ± 0.5 $\mu g/cm^2$. The cross sections derived from these weighings were also verified by comparison with thick-target yield measurements as will be discussed below. The thick target consisted of a piece of reactor grade (AGOT) graphite. The targets were located in the center of the 4π graphite-sphere neutron detector which has been previously described.[12] Corrections were made for the small change in efficiency of the detector with neutron energy. Above a bombardment energy of 3 MeV, corrections were also applied to the efficiency for the fractional populations of the ground and first excited states of ^{13}N.

The calibration of the 4π detector was performed by comparison with the NBS II Ra-Be standard through an intermediate local Pu-Be source.[13] The deuteron beam was supplied by the ORNL 5.5-MV Van de Graaff accelerator. For the thin-target measurements, the carbon target was mounted normal to the beam on the end of a thin stainless-steel tube by means of a greaseless Viton O ring. Two in-line liquid-nitrogen

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† U.S. Atomic Energy Commission Postdoctoral Fellow under appointment from the Oak Ridge Associated Universities.
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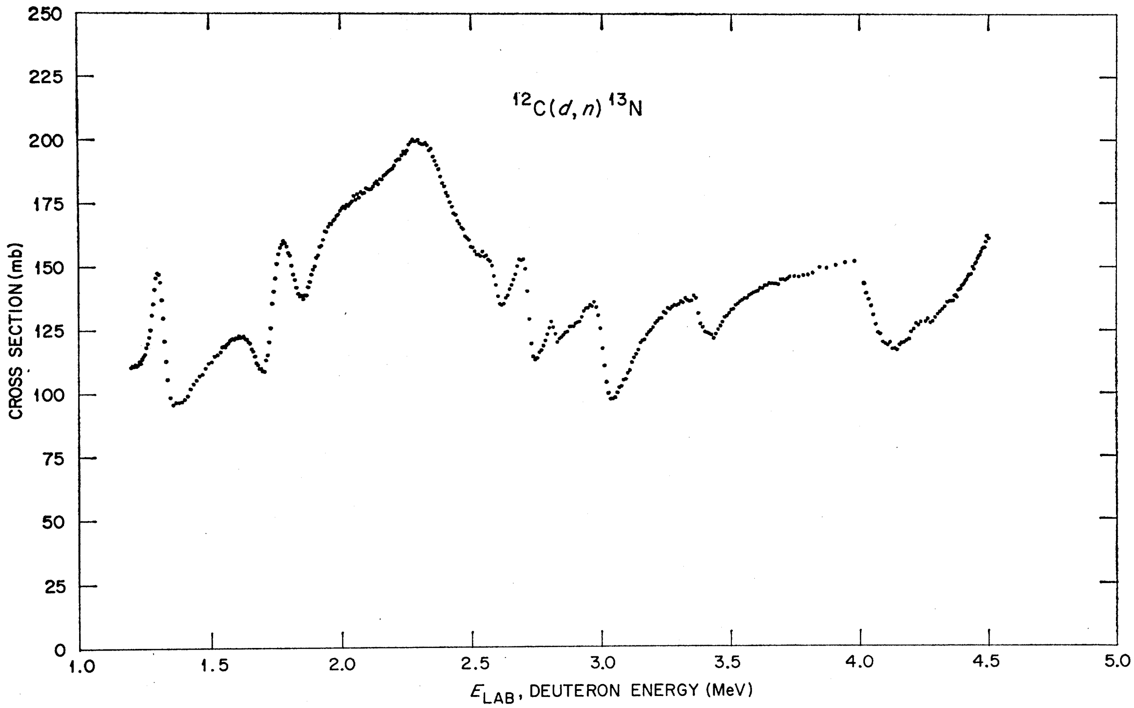

FIG. 1. Total cross section for the $^{12}C(d, n)^{13}N$ reaction from 1.2 to 4.5 MeV.

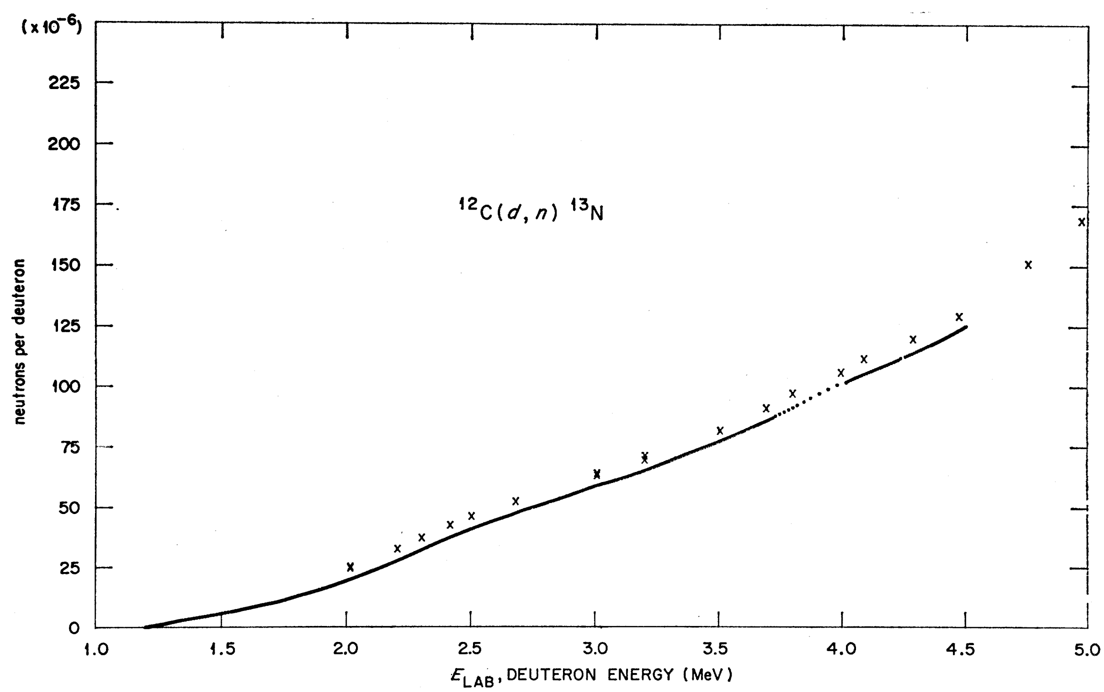

FIG. 2. Experimental thick-target yield (crosses) and the numerically integrated thin-target yield versus deuteron bombarding energy for the $^{12}C(d, n)^{13}N$ reaction. The lower value of the integrated thin-target yield is due to the neutron yield for $E_d < 1.2$ MeV, which was not measured and therefore was not included in the integration.

TABLE I. Peaks observed in the excitation function for the $^{12}C(d, n)^{13}N$ reaction. The deuteron energies are those observed in the laboratory and have been corrected for target thickness.

Deuteron energy (MeV)	Excitation in ^{14}N (MeV) Present work	Previous measurement[a]
1.30	11.38	11.38
1.62	11.65	11.66
1.78	11.79	11.76
2.30	12.24	12.21, 12.29
2.55	12.45	12.40
2.69	12.57	12.51
2.81	12.67	12.67
2.97	12.83	12.82
3.36	13.14	13.17
3.99	13.68	13.70

[a] From Ref. 17.

cold traps were utilized in series to minimize the buildup of organic material on the target. No increase in yield due to the buildup of organic material or to d-D reactions was observed during the experiment. The platinum backing was air-cooled, and no collimators were located in the target room. Beam definition was accomplished with the aid of a strong-focus lens that had been calibrated through the use of a quartz viewer positioned on the end of the target holder. Backgrounds observed using a platinum blank at various bombarding energies were used for background corrections to the thin-target yield. Corrections were also made for room background and deadtime. The analyzing magnet calibration was obtained from the narrow resonance at 2.800 MeV [14] in the reaction $^{13}C(\alpha, n)^{16}O$.

The deuteron energies shown in Fig. 1 correspond to the deuteron energies at the center of the target. These were extracted using values of dE/dx obtained from the recent measurement of the atomic stopping power of carbon for α particles.[15] The stopping powers for α particles were then converted to stopping powers for deuterons by the usual methods.[16] These were inferred to have an accuracy of $\pm 2\%$ for deuteron energies greater than 1.5 MeV. This result is sufficiently accurate to carry out an independent determination of the target thickness by a comparison of the thin-target yield with the thick-target yield. The thin-target excitation curve was numerically integrated over energy. The integrated thin-target yield and the experimental thick-target yield are shown in Fig. 2. The energy lost by the deuterons in the target enters into the numerical integration as a division of the yield at each datum point by the energy lost in the target at that point. Since the energy lost in the target is proportional to the target thickness (in $\mu g/cm^2$), we see that the integrated yield is inversely proportional to the areal density of the target. In Fig. 2 it is seen that the slopes of the integrated thin-target yield and the experimental thick-target values are in excellent agreement. The downward shift of the integrated thin-target yield with respect to the thick-target yield is due to the fact that the contribution of the thin-target yield below 1.2 MeV was not used in the numerical integration. We consider this agreement to be a good verification of the target thickness, assuming that the dE/dx values are of the stated accuracy. The over-all accuracy of the values presented in Figs. 1 and 2 are estimated to be $\pm 3\%$ for natural-carbon targets.

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III. DISCUSSION

Table I lists the peaks that we observed in the $^{12}C(d, n)^{13}N$ reaction together with values from Lauritsen and Ajzenberg-Selove.[17] In Fig. 1 there appears to be some structure at 2.0 MeV. This is in the vicinity of the large resonance at 2.3 MeV which obscures its identity. Possibly this structure at 2 MeV is a result of a broad state in ^{13}N near 11.94 MeV corresponding to a deuteron bombarding energy of 1.95 MeV. From the data we estimate the c.m. width $\Gamma_{c.m.}$ to be 0.2 MeV.

In order to improve the accuracy of our measurement of the $^{12}C(d, n)^{13}N$ total cross section, it would have been necessary to have utilized enriched ^{12}C targets; however, we reiterate that for neutron flux calibration purposes it is advantageous to use natural carbon because it is readily accessible. One method of detector calibration would be through the use of a thick high-purity graphite target. The count rates obtained at two slightly different deuteron energies could be combined with angular-distribution data taken at the mean of the two energies to obtain an absolute calibration of the detector efficiency from the data given in Fig. 2. This method eliminates the necessity of a determination of target thickness and would be especially useful below 3 MeV, where, the $^{12}C(d, n)^{13}N$ neutrons are monoenergetic. In the region 3–4 MeV, the data given in Fig. 1 can be compared with those of Wylie *et al.*[11] (where only the ground-state neutron group was observed) to obtain the branching ratio for the ground- and first-excited-state neutron groups.

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