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Polarization of Neutrons from the $C^{12}(d,n)N^{13}$ Reaction for Deuteron Energies from 1.7 to 2.8 MeV*

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Six polarization distributions over the angular range from 10° (lab) to 135° (lab) have been obtained for neutrons produced in the $C^{12}(d,n)N^{13}$ (G.S.) reaction. The bombarding energy range covered was 1.74 to 2.76 MeV. A spin-precession solenoid and scattering from a helium analyzer were employed in conjunction with improved fast-coincidence circuitry. The polarization is appreciably negative at reaction angles less than 70° (lab) for all energies and ranges from -0.2 to -0.3 at the forward stripping peak. The consistency of this negative polarization with higher energy data is attributable to the predominance of the stripping mechanism over compound-nuclear effects. The reasonably high polarization near the stripping peak leads to a consideration of the reaction's utility as a source of polarized neutrons.

I. INTRODUCTION

Recently, Sawers, Purser, and Walter[1] observed only small changes in the neutron-polarization distributions of the $C^{12}(d,n)N^{13}$(g.s.) reaction between 3.5 and 4.0 MeV. In the angular range of the stripping peak, it was also observed that at each of the 11 energies investigated, the polarization was negative, around -0.20. Because of this latter feature and because of a strong similarity of the 3.5- to 4.0-MeV data to proton-polarization data obtained in the mirror reaction, it was concluded that a direct-interaction mechanism was primarily responsible for producing these polarization effects. To see whether such characteristics exist at lower energies where the resonances are more pronounced[2] and more closely spaced, Sawers *et al.*[3] conducted a study down to 1.8 MeV at 25° (lab) and obtained four-point angular distributions at several energies between 2.3 and 2.8 MeV. They found that the negative polarization persisted in this energy range in the stripping peak [$\sim$25° (lab)]. At the larger reaction angles though, the distributions are different in shape from the higher energy ones. Because of uncertainties in the size of the background in the latter experiment[3] (which had been conducted at this laboratory), some doubt existed about the exact magnitude of the polarization. It was suggested that more accurate methods be employed in recording and analyzing this low-neutron-energy data and that more complete polarization angular distributions be recorded. Other polarization work in this energy region was reported 9 years ago by Haeberli and Rolland[4] and last year by Hallowes.[5] Hallowes investigated the energy range from 1.1 to 1.8 MeV for 68° (lab) and also obtained an angular distribution at 1.73 MeV. Haeberli and Rolland report values for 20° (lab) at 2.0, 2.2, and 2.63 MeV. Theoretical work on the $C^{12}(d,n)$ reaction is limited and has been surveyed along with applicable $C^{12}(d,p)$ studies in Ref. 1.

As noted by Haeberli,[6] the $C^{12}(d,n)$ reaction looks suitable as a source of highly polarized neutrons. The monoenergetic nature of the reaction below 3.09 MeV, the high natural abundance of C^{12}, and the durability and ease of producing uniform, self-supporting carbon foils enhance the reaction's practicality as a source. Thus, a natural secondary reason for this study was to extend the reaction's usefulness as a source of low-energy polarized neutrons.

II. APPARATUS

Neutron production and detection were carried out in a manner quite similar to that in Ref. 1. A self-supporting carbon foil was bombarded by a deuteron beam from the Duke 4-MeV van de Graaff. The thickness of the foil was approximately 190 keV for 2.4-MeV deuterons. The neutrons produced in the foil were incident on a He^4-filled gas scintillation cell after having passed through a spin-precession solenoid. 90° spin precession was employed. The helium-scattered neutrons were detected in both "up" and "down" plastic scintillators located symmetrically about the helium cell in a vertical plane containing the solenoid axis. All three scintillators were viewed by phototubes from which "fast" and "linear" signals were derived. In contrast to the apparatus described in Ref. 1, all-transistorized electronics were used, permitting more reliable operation.

Pertinent to the problem of a background discussion is the manner in which data are recorded. The linear signal from the helium cell was supplied to each of the first two quadrants of a 400-channel analyzer. Gate pulses for the first quadrant were generated by coin-

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[1] J. R. Sawers, F. O. Purser, and R. L. Walter, Phys. Rev. **141**, 825 (1966).

[2] A. Elwyn, J. V. Kane, S. Ofer, and D. H. Wilkinson, Phys. Rev. **116**, 1490 (1959).

[3] J. R. Sawers, F. O. Purser, and R. L. Walter, in *Proceedings of he International Conference on Polarization of Nucleons, Karlsruhe, 1965* (to be published).

[4] W. Haeberli and W. W. Rolland, Bull. Am. Phys. Soc. **2**, 234 (1957). See also *Fast Neutron Physics Part II* (Interscience Publishers, Inc., New York, 1963), Chap. V. G.

[5] J. P. Hallowes, Jr., thesis, Nashville, Vanderbilt University, 1964 (unpublished).

[6] W. Haeberli (private communication). See also *Fast Neutron Physics Part II* (Interscience Publishers, Inc., New York, 1963), Chap. V. G.

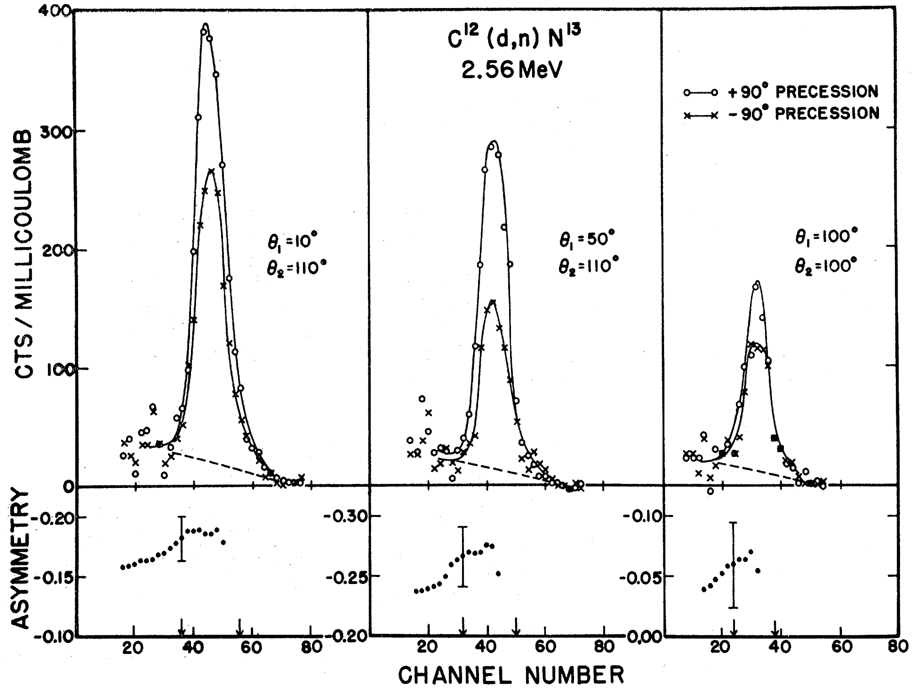

FIG. 1. Typical gated helium recoil spectra. The dashed lines indicate upper limit backgrounds which are discussed in the text. The lower portion of the figure shows the asymmetry as a function of lower bias channel. Arrows indicate the interval for which the asymmetries were calculated.

cidences between "fast" pulses from the "up" detector and the helium cell. Tunnel-diode discrimination and coincidence units[7] were employed to provide a resolving time (2τ) of 10 nsec. This was sufficient to give reasonable discrimination against coincidences caused by Compton-scattered photons. The cable lengths were conveniently adjusted by observing the time-of-flight spectrum of events occuring in the two scintillators. Gate pulses for the second quadrant were derived in the same manner, using the "fast" pulses from the "down" detector.

III. PROCEDURE

Polarization distributions were obtained in 200 keV steps from 1.74 to 2.76 MeV for an angular range from 10° (lab) to 135° (lab). Running times were selected to give generally better than ±0.03 statistical accuracy in the asymmetry value at each angle. As described above, gated helium-recoil spectra comprised the raw data. A background spectrum arising from accidental coincidences was recorded at each point by means of inserting a delay in the "fast" helium circuitry. Other background was determined by measuring the difference between real and accidental coincidences, when the solenoid core was plugged with a composite paraffin and lead insert. These differences were small, i.e., typically 5% of the counts of interest, and thus were measured only at a few angles at each energy. Interpolation was used to obtain values at the intermediate angles.

Examples of a bothersome, nonsubtracting background are indicated in Fig. 1, where gated helium-recoil spectra associated with the "up" detector are presented for three measurements at a deuteron energy $E_d = 2.56$ MeV. The crosses and open circles exhibit the spectra obtained with the spin vector rotated through 90° in opposite directions. The tail below the peak which showed up in every measurement was usually statistically consistent with zero polarization. Possible causes for these lower energy recoil pulses are: (i) multiple scattering of neutrons in the helium scintillator, (ii) elastic and inelastic neutron scattering in the iron cell surrounding the helium, (iii) the fraction of gamma interactions which were not separated by the coincidence, and (iv) neutrons which interacted with the collimator walls. Estimates indicate that none of these sources particularly dominate and hence, these tails are likely due to many causes. An attempt to minimize the effect of this background was made by analyzing the data in a fashion similar to Andress *et al.*[8] The asymmetry in the peak region of the recorded spectra was computed as a function of the lower channel bias. The results for the three cases in Fig. 1 are displayed in the lower portion of the figure. As the lower-bias or lower-cutoff channel is decreased, more background is included and the asymmetry falls in magnitude. We have taken the height of the plateau as the true value of the asymmetry and the statistics associated with the included counts as the uncertainty. Because this technique does not eliminate the effect of all the background counts under the peak, our quoted asymmetries

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[7] Supplied by Chronetics, Inc., Yonkers, New York.

[8] W. D. Andress, F. O. Purser, J. R. Sawers, Jr., and R. L. Walter, Nucl. Phys. **70**, 313 (1965).

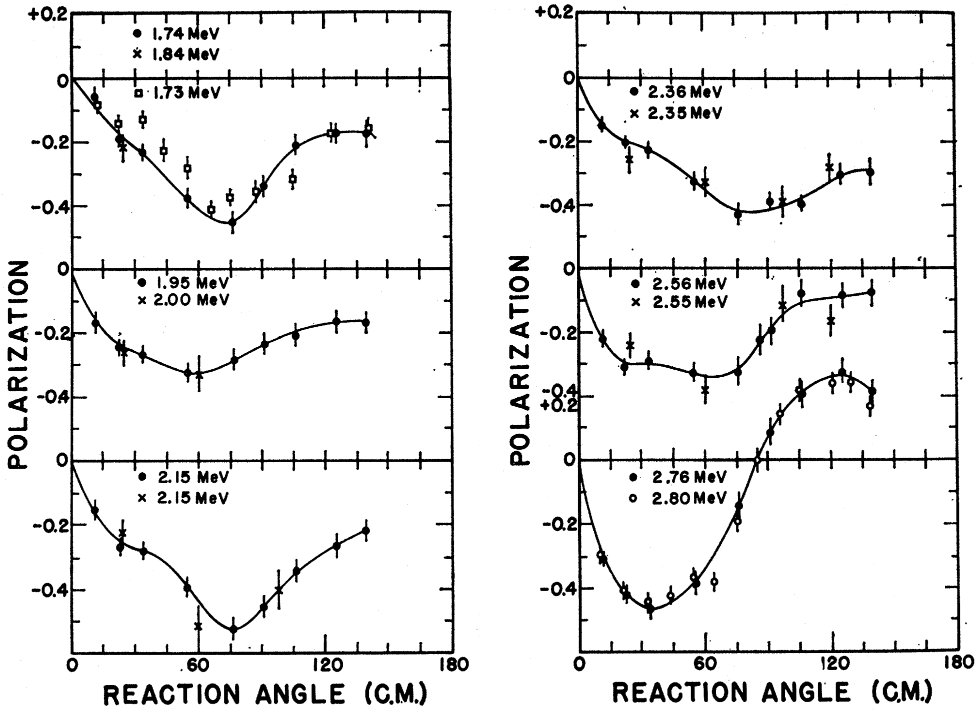

FIG. 2. Center-of-mass polarization distributions for the $C^{12}(d,n)$ reaction at the energies indicated. The data represented by the open circles, the squares, and the crosses are taken from Refs, 1, 5, and 11, respectively. The present data are represented by the solid circles. The curves exhibit the trend of the latter data.

are lower limits if the remaining background is unpolarized as expected. By studying the shapes of the spectra and taking the background to be a linear function of pulse height in the region of the peak, an estimate of the percentage of background entering into the asymmetry value has been obtained. Examples of such choices, which probably are upper limits of background, are shown as the dashed lines of Fig. 1. These backgrounds were integrated over the intervals from which the asymmetries were taken and were typically 10%. (For the three cases shown, backgrounds were 8% at 10°, 5% at 50°, and 12% at 100°.) Because the true shape of this background is not known, no corrections for this were made to the asymmetries.

Throughout the experiment the "up" and "down" detectors were positioned at scattering angles where the analyzing power P_2 of helium was close to the maximum for the respective neutron energy. The values for $\bar{P}_2$ were based on the Dodder-Gammel[9] phase shifts and were taken from a graph prepared by Sawers.[10] Included in the Monte Carlo calculation by Sawers are the effects of (i) the size of the He cell and the plastic scintillators, (ii) multiple scattering, including the rotation and depolarization parameters for the polarization vector, (iii) the transmission through the He to random scattering centers inside the cell, and (iv) the efficiency of detecting the scattered neutrons. The values of the effective analyzing power are listed in Table I.

IV. RESULTS

The results of this work are given in Table I and Fig. 2. Included in Table I are values for the measured asymmetry $P_1\bar{P}_2$, the effective analyzing power $\bar{P}_2$

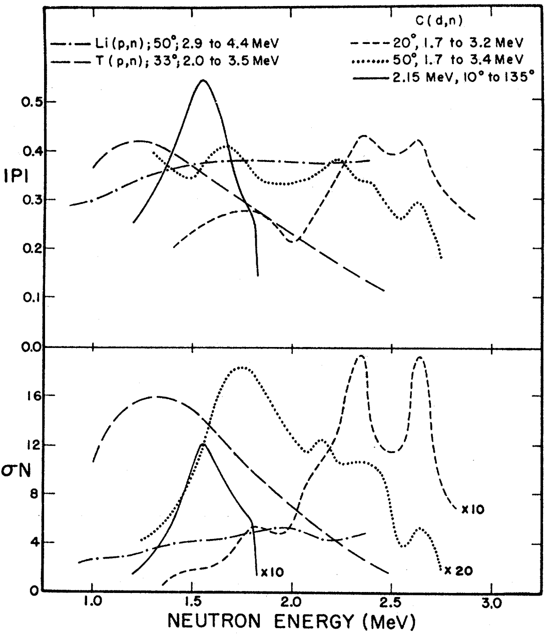

FIG. 3. Polarized neutron source considerations of the $C^{12}(d,n)$, $T(p,n)$, and $Li^7(p,n)$ reactions. (a) Absolute value of $P(E_n)$. (b) Figures of merit for the above reactions. The symbols σ and N represent the laboratory reaction cross section and the number of atoms per cm^2 per keV energy loss, respectively. The scale is arbitrary.

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[9] D. C. Dodder and J. L. Gammel, Phys. Rev. 88, 520 (1952).
[10] J. R. Sawers (to be published).

TABLE I. Polarization distributions for neutrons resulting from the $C^{12}(d,n)N^{13}$(g.s.) reaction.

E_d (MeV)	θ_1 (lab) (deg)	E_n (MeV)	θ_2 (lab) (deg)	$P_1\bar{P}_2$	$\bar{P}_2$	P_1	ΔP_1
1.74	10.5	1.42	100	−0.041	0.714	−0.057	0.028
	20.5	1.40	100	−0.141	0.712	−0.198	0.027
	30.5	1.38	90	−0.172	0.716	−0.241	0.026
	50.5	1.30	90	−0.285	0.726	−0.392	0.025
	70.5	1.20	90	−0.349	0.734	−0.475	0.031
	85.5	1.13	90	−0.264	0.733	−0.360	0.032
	100.5	1.05	80	−0.170	0.784	−0.217	0.029
	120.5	0.97	80	−0.148	0.811	−0.183	0.028
	135.5	0.80	80	−0.152	0.803	−0.190	0.038
1.95	10.5	1.62	100	−0.129	0.730	−0.177	0.028
	20.5	1.61	100	−0.185	0.730	−0.254	0.026
	30.5	1.58	100	−0.202	0.730	−0.277	0.027
	50.5	1.49	100	−0.243	0.725	−0.336	0.031
	70.5	1.38	90	−0.209	0.716	−0.292	0.033
	85.5	1.29	90	−0.179	0.728	−0.246	0.032
	100.5	1.21	90	−0.161	0.733	−0.219	0.032
	120.5	1.12	90	−0.130	0.732	−0.177	0.033
	135.5	1.06	80	−0.136	0.780	−0.175	0.030
2.15	10.5	1.82	110	−0.113	0.744	−0.152	0.031
	20.5	1.80	110	−0.201	0.740	−0.272	0.027
	30.5	1.77	110	−0.211	0.732	−0.288	0.026
	50.5	1.67	100	−0.299	0.731	−0.409	0.028
	70.5	1.55	100	−0.391	0.720	−0.544	0.033
	85.5	1.45	100	−0.338	0.720	−0.469	0.035
	100.5	1.36	90	−0.254	0.719	−0.353	0.032
	120.5	1.26	90	−0.200	0.726	−0.275	0.032
	135.5	1.19	90	−0.162	0.734	−0.221	0.033
2.36	10.5	2.03	110	−0.115	0.772	−0.149	0.020
	20.5	2.00	110	−0.160	0.769	−0.207	0.020
	30.5	1.97	110	−0.177	0.765	−0.232	0.023
	50.5	1.86	110	−0.248	0.750	−0.331	0.026
	70.5	1.73	100	−0.323	0.731	−0.442	0.031
	85.5	1.62	100	−0.294	0.732	−0.404	0.023
	100.5	1.52	100	−0.295	0.728	−0.406	0.024
	120.5	1.40	90	−0.220	0.710	−0.310	0.036
	135.5	1.33	90	−0.217	0.721	−0.301	0.039
2.56	10.5	2.22	110	−0.182	0.798	−0.231	0.023
	20.5	2.20	110	−0.248	0.791	−0.314	0.021
	30.5	2.16	110	−0.232	0.788	−0.295	0.022
	50.5	2.04	110	−0.267	0.775	−0.345	0.029
	70.5	1.90	110	−0.249	0.754	−0.330	0.041
	80.5	1.82	110	−0.170	0.742	−0.229	0.048
	85.5	1.78	110	−0.147	0.736	−0.200	0.039
	100.5	1.67	110	−0.059	0.731	−0.081	0.044
	120.5	1.54	100	−0.064	0.728	−0.087	0.039
	135.5	1.47	100	−0.057	0.720	−0.079	0.040
2.76	10.5	2.42	110	−0.256	0.813	−0.315	0.020
	20.5	2.39	110	−0.346	0.810	−0.426	0.023
	30.5	2.35	110	−0.386	0.807	−0.478	0.023
	50.5	2.22	110	−0.308	0.797	−0.386	0.034
	70.5	2.07	110	−0.115	0.778	−0.148	0.041
	85.5	1.94	110	0.066	0.761	0.086	0.042
	100.5	1.82	110	0.158	0.743	0.213	0.043
	120.5	1.68	100	0.211	0.732	0.289	0.037
	135.5	1.60	100	0.162	0.730	0.222	0.037

for the scattering angle θ_2, the neutron polarization P_1 and the statistical uncertainty ΔP_1. Also tabulated is the neutron energy E_n. In Fig. 2 the crosses represent data of Sawers *et al.*,[11] who used a 100-keV target. The curves in Ref. 3 were obtained from these data. The crosses shown alongside of the 2.56-MeV data are averages of values obtained[11] at 2.50 and 2.60 MeV. The general agreement between the two sets of data implies that the unknown background in the experiment of Ref. 3 was probably not sizeable. Also shown are the results of the earlier experiment by Sawers *et al.*[1] at 2.80 MeV. The remarkable agreement is encouraging. The three polarization values published by Haeberli and Rolland[4] are not shown but are consistent with the present results also. Data obtained at 1.73 MeV by Hallowes[5] using a 100-keV target are represented by the squares in Fig. 2.

V. DISCUSSION

As mentioned previously, Sawers *et al.*[1] discuss the current status of the theoretical predictions in the $^{12}C(d,n)$ and $^{12}C(d,p)$ reactions. No calculations of the polarization have been published for this lower energy range. Presumably this situation exists because of the complicated reaction mechanism which causes pronounced structure even in the vicinity of the forward stripping peak. However, the observed polarization suggests that the direct mode of interaction which dominates the shape of the differential cross sections at all energies above 2.0 MeV also dominates the polarization at forward angles. In fact, for all energies studied in this experiment the polarization is negative at all angles less than 85° (lab). The positive polarization seen at angles greater than 95° (lab) at most of the energies above 2.6 MeV and presumed to be primarily caused by the direct mode is not exhibited at the lower energies. On the other hand, the fact that the polarization at all angles measured [10° (lab) to 135° (lab)] exhibits similar features for all energies between 1.7 and 2.4 MeV suggests that the direct mode is primarily responsible even at these lower energies. Although some recent attempts to predict the polarization in this reaction by Hodgson[12] have been unsuccessful, the persistent features of the pattern encourages one to pursue the theoretical analysis.

As a source of polarized neutrons, the $C^{12}(d,n)$ reaction is more favorable in many aspects than the other common sources. Several worthwhile features of carbon targets are mentioned in the Introduction. In contrast to perhaps all other neutron-producing reactions, this source gives a relatively high polarization where the differential cross section is at its maximum. Hence, in scattering experiments, the problem of neutron background is reduced by probably more than an order of magnitude compared to the $D(d,n)$ reaction, for example, where the polarization is largest near the minimum of the differential cross section. The $C^{12}(d,n)$ reaction is also convenient in that the polarization is sizeable and changes slowly as the neutron energy is varied by either changing the bombarding deuteron

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[11] J. R. Sawers, F. O. Purser, and R. L. Walter, Bull Am. Phys. Soc. **10**, 440 (1965).

[12] P. E. Hodgson (private communication).

energy and keeping the reaction angle fixed or by varying the reaction angle and keeping the deuteron energy fixed. In Fig. 3(a) we have plotted the magnitude of the polarization produced in the C(d,n) reaction for several conditions and for the Li(p,n) and the T(p,n) reactions at the angles indicated as a function of neutron energy. The ranges of bombarding energies are also given. A better figure of merit as a neutron source for scattering experiments is the product of the square of the polarization and the laboratory differential cross section $P^2\sigma$. But in making a valid comparison of reactions, one must include the energy loss in the target of the bombarding particle, which is appreciably different for 3-MeV deuterons in carbon and 4-MeV protons in tritium. Figure 3(b) is a comparison of $P^2\sigma N$, where N is the number of atoms per cm^2 per keV energy loss. Here it is clearer which of the measured reactions are most useful. However, one should bear in mind the following details: (i) protons are inherently "cleaner" in terms of neutron background, (ii) it is desirable to use reaction angles where one is not in a minimum of the differential cross section, (iii) tritium-gas targets require special care, and (iv) the Li$+p$ reaction is not monoenergetic in this region.

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Measurement of the C$^{12}(d,n)$N^{13} Cross Section for Energies from 3.8 to 5.0 MeV*

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Yield curves at 5°, 40°, 80°, 115°, and 150° were measured for the C$^{12}(d,n)$N^{13} (g.s.) reaction from 3.8 to 4.1 MeV in about 10-keV steps in search for a resonance about 40 keV wide, superimposed on a broader one. The existence of the narrower resonance near 3.91 MeV was suggested by Verba who previously measured and analyzed cross sections for the same reaction. No indication of this resonance was seen in earlier work at this laboratory on the same reaction or in studies of the mirror reaction. The results of the present experiment do not exhibit the structure which would be produced by the proposed 40-keV resonance. Thus, it appears that the calculation of Buck and Satchler concerning changes in polarization around an isolated resonance still is applicable to the 4.0-MeV resonance in the C$^{12}+d$ reactions. A second experiment was conducted in preparation for a polarization study at higher energies in the reaction. With a 50-keV target, a 5° yield curve was obtained up to 5.0 MeV. Only one broad peak was exhibited in the C$^{12}(d,n)$N^{13} (g.s.) reaction between 4.1 and 5.0 MeV. No sizable structure appeared for the reaction C$^{12}(d,n)$N^{13*} (2.37 MeV) in the 5° yield. Angular distributions of the neutrons for both reactions were measured at 105-keV intervals. All distributions showed strong stripping patterns.

I. INTRODUCTION

A SERIES of cross-section and polarization measurements concerning the C$^{12}(d,n)$N^{13} (g.s.) reaction have been performed at our laboratory in the past 2 years.[1] One region studied has been that near the resonance at a deuteron energy of 4 MeV. Our cross-section work and an earlier experiment by Bonner *et al.*[2] show a broad peak at this energy in the yield curves for 5°, and 0°, respectively. The work[2] on the mirror reaction C$^{12}(d,p)$C^{13} (g.s.) is also consistent with the existence of only a single, broad resonance. However, it is reasonable that structure which would be produced by a second, narrower resonance might not be pronounced at forward angles where the stripping contribution is large. Verba[3] made a thorough study of the C$^{12}(d,n)$ reaction cross section, both experimentally and theoretically, for the region from 3.8 to 4.2 MeV. At forward angles, his yield curves also showed a prominent, broad peak near 4 MeV but at larger angles, his data exhibited additional structure. The results of his analysis suggested the existence of a narrow resonance superimposed upon a much broader one. Besides the importance a second state has on the level diagram of N^{14}, the existence of a second level is of interest in that theoretical calculations have been performed on the assumption that the resonance at 4 MeV is isolated. Of particular significance is the calculation by Buck and Satchler[4] which treated the C$^{12}(d,p)$C^{13} (g.s.) reaction as having an isolated compound elastic resonance in

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[1] J. R. Sawers, Jr., F. O. Purser, Jr., and R. L. Walter, Phys. Rev. **141**, 825 (1966).

[2] T. W. Bonner, J. T. Eisinger, Alfred A. Kraus, and J. B. Marion, Phys. Rev. **101**, 209 (1956).

[3] J. W. Verba, thesis, University of Rochester, Rochester, New York, 1962 (unpublished). See also Bull. Am. Phys. Soc. **6**, 368 (1961).

[4] B. Buck and G. R. Satchler, in *Proceedings of the International Conference on Nuclear Structure* (University of Toronto Press, Toronto, Canada, 1960), p. 355.