Polarization of Neutrons from the $N^{14}(d,n)O^{15}$(g.s.) Reaction*

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Four angular distributions of the polarization of the neutrons produced in the $N^{14}(d,n)O^{15}$(g.s.) reaction have been measured for deuteron energies from 3.1 to 3.7 MeV. The polarization is generally negative for angles less than 70° c.m. and positive for larger angles. These features and other similarities have been observed in a few deuteron-induced stripping reactions which proceed via orbital momentum transfers of one unit. The significance of this observation is discussed.

I. INTRODUCTION

MEASUREMENTS of polarizations of nucleons produced in single nucleon transfers have been performed over a wide range of energies for a large number of targets. For energies above 10 MeV, appreciable effort has been spent in attempts[1] to describe the polarization of the protons produced in (d,p) reactions with distorted wave, direct reaction theories. In a few cases, moderate success has been achieved in fitting the experimentally observed polarization data. Comparatively little effort has been expended on calculations of polarizations at lower energies because (i) there has been a paucity of (d,p) and (d,n) polarization data for targets with $Z>7$ and (ii) there has been insufficient evidence that direct reactions should describe polarization effects at the lower energies where compound nucleus formation interferes to an undetermined extent. In selecting reactions in which the polarization is produced predominantly by direct mechanisms, one demands that the polarization distributions have only small variations with energy or perhaps a systematic variation with energy (such as is seen in optical-model scattering). The only existing data below 10 MeV for $Z>2$ which meet this restriction for a sizable energy range are those of the $C^{12}+d$ reactions. As was first pointed out by Sawers *et al.*,[2] there are regions in the $C^{12}(d,n)$ reaction which exhibit this phenomenon. In fact, these authors noted the similarity of the $C^{12}(d,n)$ reaction in the 3.4- to 4.0-MeV region to the $C^{12}(d,p)$ polarization distribution obtained by averaging the data from 5 to 15 MeV. Successive $C^{12}(d,n)$ experiments by Morgan *et al.*[3] and $C^{12}(d,p)$ experiments by Blue *et al.*[4] showed basically identical distributions for data averaged over the 4.6- to 5.0-MeV region. Hodgson *et al.*[5] have reported an attempt to describe the (d,n) polarization using a distorted-wave Born-approximation (DWBA) code with the inclusion of a compound-nucleus contribution. At best, the predictions can be classed as "qualitatively successful." Preliminary attempts to fit either the $C^{12}(d,n)$ or the $C^{12}(d,p)$ polarizations around 5 MeV using DWBA code JULIE have been unsuccessful so far.[6]

It has been noted in an earlier report[7] that in other (d,n) reactions which proceed by an orbital angular momentum transfer of one unit, one finds at selected energies an angular dependence of the polarization function similar to that which persists in the $C^{12}+d$ reactions. The suggestion made therein was that even at low energies, the polarization produced at selected energies in other low Z, (d,n) reactions is caused predominantly by the direct reaction mechanism. This observation also gives added impetus to a theoretical analysis of the $C^{12}+d$ polarizations using direct reaction codes.

Because of the similarities there is reason to believe that a valid direct reaction code which even ignores compound-nucleus contributions might do reasonably well in describing the selected polarization distributions for energies as low as 3 MeV. In order to obtain more experimental data to determine the energy dependence of the polarization function and to look for other similar features, a program has been initiated to study other (d,n) reactions which proceed with an orbital angular momentum transfer of one unit, i.e., $l=1$. The $N^{14}(d,n)$ reaction was considered because the trend of the polarizations observed by Büsser *et al.*[8] indicated that at energies just above their highest energy, 2.9 MeV, the distribution would exhibit features similar to those seen in the $C^{12}+d$ reactions. The experiment discussed here is a measurement of the polarization distributions at four energies between 3.1 and 3.7 MeV.

II. APPARATUS AND PROCEDURE

A deuteron beam from the Duke 4-MeV Van de Graaff, after passing through a Ni window $<3\ \mu$

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[1] D. W. Miller, in *Proceedings of the Second International Symposium on Polarization Phenomena of Nucleons* (Birkhauser Verlag, Basel, Switzerland, 1966), p. 410.
[2] J. R. Sawers, F. O. Purser, and R. L. Walter, Phys. Rev. **141**, B825 (1966).
[3] G. L. Morgan, R. L. Walter, C. S. Soltesz, and T. R. Donoghue, Phys. Rev. **150**, 830 (1966).
[4] K. J. Stout, R. A. Blue, and G. Marr, Bull. Am. Phys. Soc. **11**, 316 (1966). Also, R. A. Blue (private communication).
[5] P. E. Hodgson and D. Wilmore (to be published).
[6] R. Drisko, T. R. Donoghue, R. G. Seyler, G. L. Morgan, and R. L. Walter (private communication). For code JULIE, refer to R. H. Bassel, R. M. Drisko, and G. R. Satchler, Oak Ridge National Laboratory Report No. ORNL-3240 (unpublished).
[7] M. M. Meier, F. O. Purser, and R. L. Walter, Bull. Am. Phys. Soc. **12**, 87 (1967).
[8] F. W. Büsser, J. Christiansen, F. Niebergall, and G. Söhngen, Nucl. Phys. **69**, 103 (1965).

thick, was incident on a natural nitrogen-gas target. The pressure in the target cell was adjusted to produce an energy loss of less than 250 keV to deuterons traversing the cell. The polarimeter, which has been described previously,[2] utilized a 90° spin-precession solenoid through which reaction neutrons passed before bombarding a helium gas scintillation cell. Neutrons scattered through 120° (L) were detected in organic scintillators located in "up" and "down" positions in a vertical plane containing the solenoid axis.

Data were recorded by supplying the "linear" signal from the helium cell to each of the first two quadrants of a 400-channel analyzer. Gate pulses for the first quadrant were generated by a coincidence between the "fast" signal from the "up" detector and the "fast" signal from the helium cell. Gate pulses for the second quadrant were generated in the same manner, but utilized fast coincidence between helium cell and "down" detector. The resolving time of the fast-coincidence units was about 10 nsec. Background arising from random coincidences were recorded by inserting an 80-nsec delay in the helium side of the fast-coincidence circuitry.

Linear helium recoil spectra generated in this manner are shown in Fig. 1. Each of the spectra labeled "Left" is actually the sum of two spectra. The first is generated by "up"-helium coincidence gates with the solenoid current in the forward direction and the second is generated by "down"-helium coincidence gates with the solenoid current reversed. The "Right" designation corresponds to the opposite sum: "up"-helium, reverse current plus "down"-helium, forward current. Running times for these spectra were selected to give better than ±0.05 statistical accuracy in the asymmetry value at each angle. After subtraction of the random-coincidence spectra, which usually contributed a background of less than 3%, a nonsubtracting background remained on the low-energy side of the peak. Reflection of the high-energy half of the peak about its axis of symmetry provides an estimate of this background effect which is shown by the dashed line. Such an estimate indicates that this background is generally less than 10% in the region of interest. To diminish the effect of this background, the summation intervals from which the final asymmetries were calculated were chosen with a slightly higher bias than would be used for a symmetric, background-free peak. This background probably is associated with neutrons which interact with the helium cell after a few elastic or nearly elastic scatterings in the shielding. The trajectories of such neutrons are such that if their spins are processed at all, the effect would be small. Study of the spectra confirms this, i.e., it is found that the background tail is unpolarized within statistics.

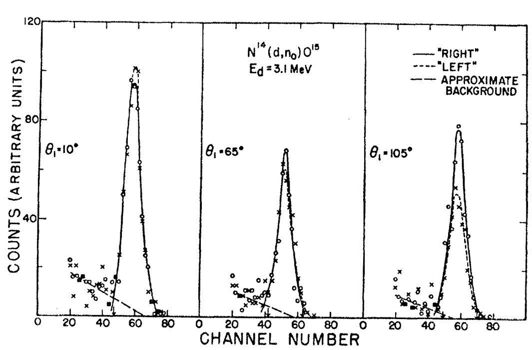

FIG. 1. Typical gated helium recoil spectra. Background estimations are discussed in the text. Arrows indicate summation intervals.

TABLE I. Polarizations for neutrons from the $N^{14}(d,n)O^{15}$(g.s.) reaction.

E_d (MeV)	θ_1 (lab) (deg)	E_n (MeV)	P_1P_2	P_1[a]	ΔP_1
3.1	10	8.143	−0.015	−0.016	0.046
	20	8.100	−0.063	−0.068	0.048
	30	8.031	−0.140	−0.150	0.044
	45	7.884	−0.379	−0.405	0.048
	65	7.627	−0.018	−0.019	0.050
	85	7.336	0.220	0.233	0.041
	105	7.046	0.204	0.215	0.043
	135	6.688	−0.098	−0.103	0.043
3.3	10	8.344	0.034	0.037	0.046
	20	8.299	0.007	0.008	0.048
	30	8.227	−0.153	−0.165	0.044
	45	8.074	−0.332	−0.365	0.048
	65	7.806	0.126	0.135	0.050
	85	7.501	0.311	0.330	0.041
	105	7.199	0.260	0.275	0.043
	135	6.826	0.052	0.054	0.043
3.5	10	8.545	−0.064	−0.069	0.050
	20	8.499	−0.118	−0.127	0.042
	30	8.423	−0.123	−0.133	0.041
	45	8.263	−0.245	−0.264	0.045
	65	7.984	0.003	0.003	0.043
	85	7.666	0.213	0.227	0.039
	105	7.352	0.205	0.217	0.039
	135	6.965	0.084	0.088	0.049
3.7	10	8.746	−0.185	−0.200	0.051
	20	8.697	−0.183	−0.198	0.039
	30	8.619	−0.105	−0.114	0.038
	45	8.452	−0.126	−0.136	0.046
	65	8.162	−0.079	−0.085	0.042
	85	7.832	0.131	0.140	0.051
	105	7.506	0.206	0.219	0.039
	135	7.103	0.183	0.193	0.057

[a] The sign of the polarization is in accordance with the Basel convention.

The values for P_2 used in the calculation of the neutron polarization were calculated from the Hoop-Barschall phase shifts.[9] Included in the calculation were the size and geometry of helium cell and organic scintillators, and the variation of the efficiency with energy of the organic scintillators.

III. RESULTS AND DISCUSSION

The results of this work are presented in Table I and Fig. 2. Included in Table I are values for the neutron energy E_n, the measured asymmetry P_1P_2, the neutron polarization P_1, and the statistical uncertainty ΔP_1.

[9] B. Hoop and H. H. Barschall, Nucl. Phys. 83, 65 (1966).

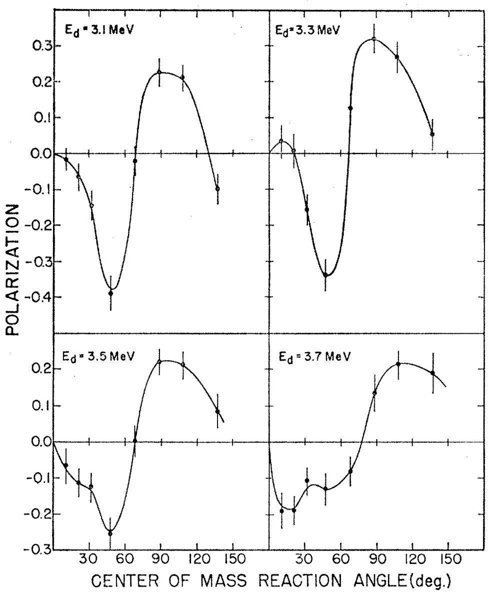

FIG. 2. Center-of-mass polarization distributions for the $N^{14}(d,n)O^{15}$(g.s.) reaction at the energies indicated. The curves exhibit the trend of the data.

$P_2(120°L)$ was approximately constant throughout the neutron energy region studied and was about 0.94.

In Fig. 3, the earlier work on this reaction is shown. The data at 1.32 MeV are that of Epstein *et al.*,[10] at 3.70 MeV, Babenko *et al.*,[11] and from 1.65 to 2.90 of Büsser *et al.*[8] It is the distribution at 2.90 MeV which is reminiscent of the $C^{12}(d,n)$ data and which stimulated the present work. The earlier data[11] at 3.7 MeV were obtained with a deuteron beam from a 6-MeV cyclotron which bombarded a gas target after penetrating a 2-MeV-thick foil. The average deuteron energy[11] was "assumed to be 3.7±0.3 MeV." It is difficult to evaluate the apparent disagreement between this set of data and the present results.

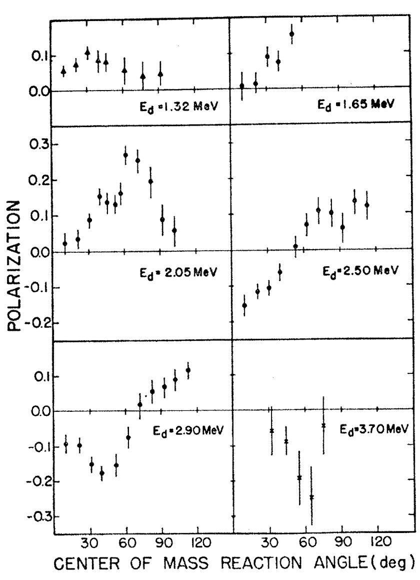

FIG. 3. Earlier polarization data for the $N^{14}(d,n_0)$ reaction. The data represented by triangles, solid circles, and crosses are taken from Refs. 10, 8, and 11, respectively.

Figure 4 shows two yield curves[12] and a contour plot of the polarization for the $N^{14}(d,n)O^{15}$(g.s.) reaction between 1.0 and 4.0 MeV. The contour plot is based on the data of Figs. 2 and 3. Horizontal bars below the yield curves indicate the energy spreads associated with each bombarding energy at which polarization data were obtained. It is clear that none of these polarization measurements was designed to study changes which might be associated with the narrow structure in the yield.

The irregular variation of the contour plot and the considerable structure in the excitation function do not offer obvious aid in the selection of an energy region where the direct mechanism dominates. However, the differential cross sections indicate that the direct interaction is effective over the energy range shown in Fig. 4.

In Fig. 5, the reported angular distribution data for the $N^{14}(d,n)$ cross section are displayed. In this figure, the crosses refer to the data of Morita *et al.*,[13] the open circles, Rolland,[14] and the triangles Retz-Schmidt and Weil.[12] (To our knowledge the data of the last two reports have not been compared before and the cause of the differences is not apparent. It is doubtful that the slight differences in deuteron energies could account for the disagreement. One group[12] used pulse-shape discrimination to reduce background from γ interactions in their stilbene scintillator and the other[14] employed time-of-flight techniques to reduce background. It is

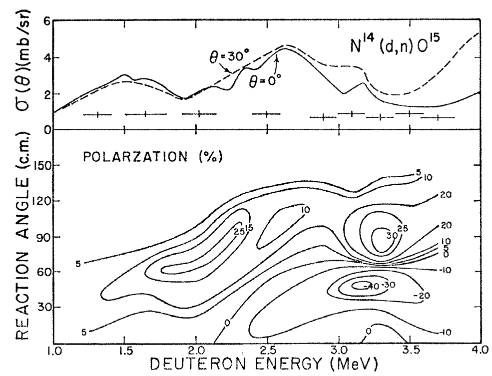

FIG. 4. Yield curves from Ref. 12 and polarization contour map for the energy region 1.0 to 4.0 MeV. The contour map is based on the data of Figs. 2 and 3.

[10] H. M. Epstein, D. F. Herring, and K. W. Jones, Phys. Rev. **136**, 131 (1964).

[11] N. P. Babenko, B. A. Bibichev, I. O. Konstantinov, A. P. Moskalev, and Yu. A. Nemilov, Yaderna Fiz. 1, 452 (1965) [English transl.: Soviet J. Nucl. Phys. 1, 323 (1965)].

[12] T. Retz-Schmidt and J. L. Weil, Phys. Rev. **119**, 1079 (1060).

[13] S. Morita, N. Kawai, Y. Goto, T. Maki, and M. Mukae, J. Phys. Soc. Japan **15**, 2170 (1960).

[14] W. Rolland, thesis, Duke University, Durham, North Carolina, 1963 (unpublished).

possible that the time uncorrelated background in the latter experiment was underestimated. Nevertheless, another measurement or reanalysis of the existing data will be necessary to clear up the discrepancy.) Except for angles $>120°$, the shapes of the cross-section curves in Fig. 5 do not change considerably even though the resonance structure is so strongly pronounced in the yield curves. The distribution at 4.4 MeV most resembles the $C^{12}(d,n)$ cross sections,[15] but even here the ratio of the forward stripping peak to the valley is lower by a factor of 2 or 3. Because the structure in the cross section is less pronounced and because empirically and theoretically[16] the size of the polarization is related to the size of the structure in the cross section, it would not be surprising to find lower polarizations in the $N^{14}(d,n)$ reaction than in the $C^{12}(d,n)$ case.

In Fig. 6, we show the $C^{12}(d,n)$ polarization obtained by averaging the data over the intervals from 3.5 to 4.1 MeV and from 4.6 to 5.0 MeV. Also included are averages of the $C^{12}(d,p)$ data for nearly the same energy intervals. It is the higher-energy patterns which resemble the average of the 5- to 15-MeV proton polarization data. Somewhat similar shapes have also been seen in the $l_p=1$, $N^{15}(d,n)$ reaction.[17] If one assumes that this shape is that produced by a direct reaction stripping mechanism, then it becomes apparent that for the present reaction, the distribution at 3.5 MeV compares favorably. In fact, the yield curves suggest that the resonance amplitude is small at this energy. On the other hand, the shape of the polarization at 2.9 MeV is also quite similar to that at 3.5 MeV, even though the former is in the region of a peak. Both the 2.9- and the 3.5-MeV distributions have been plotted for comparison in Fig. 6. Note that there is a scale factor of 2 between the two sides of this figure. Also shown is a curve representing the average over energy of the polarization results obtained in the present work.

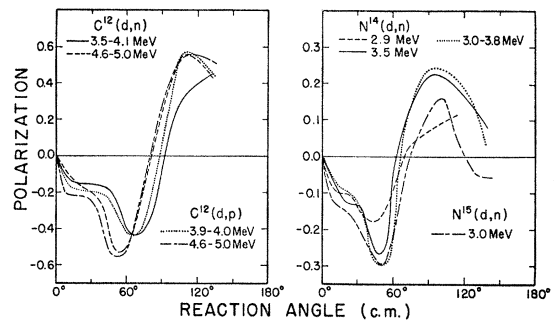

FIG. 6. Polarization distributions for the outgoing nucleon in several deuteron induced reactions. Averages over indicated energy intervals are shown for the $C^{12}+d$ reactions and for the $N^{14}(d,n)$ reaction.

The only other $l_p=1$ reactions for which a sizable amount of data exists above 3 MeV are the $B^{11}(d,n_0)$ and $B^{11}(d,n_1)$. The main reason these data have not been included in Fig. 5 is that the polarization distributions from 3 to 4 MeV[18] are unlike those at 9 MeV[19] and below 3 MeV.[20] A second reason is that there may be j-dependent effects which would cause the $j=\frac{3}{2}$, $B^{11}(d,n_0)$ polarization to differ from that of the $j=\frac{1}{2}$ reactions in Fig. 5. More work on the $B^{11}(d,n)$ reaction is necessary before they are used in the comparison.

Since a similar polarization pattern has now been observed in four $l=1$ reactions, it appears that at selected energies the $X^A(d,n)$ reactions for $11<A<15$ proceed via similar direct mechanisms, similar even to the extent that the polarization of the outgoing nucleons is produced in the same manner. Considering the basis of conventional direct-reaction theories, this fact may not be too surprising in itself. However, realizing the complexity of low-energy (d,n) reactions on low-A targets, it is probably significant in that one could now compare polarization predictions from direct-reaction codes which incorporate spin-orbit interaction with this pattern to further test the validity of the codes (at low energies with low-A targets). However, before this is tried at our laboratory, we intend to survey other (d,n) reactions to supplement the data and suggestions presented here.

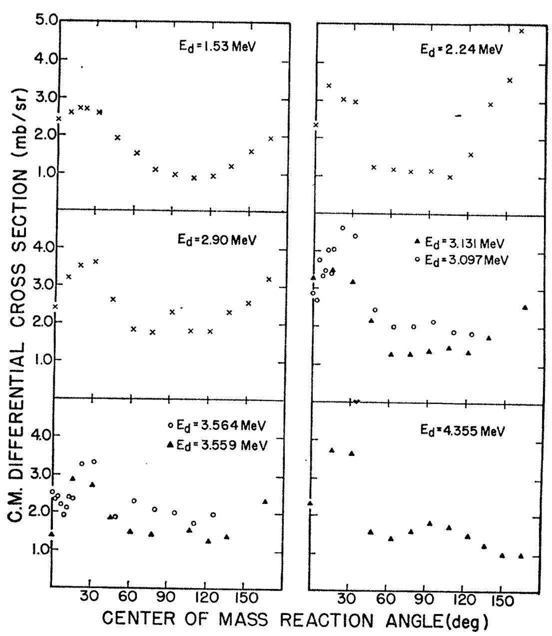

FIG. 5. Differential cross sections for the $N^{14}(d,n_0)$ reaction. The data represented by crosses, circles, and triangles are taken from Refs. 13, 14, and 12, respectively.

[15] See, for example, Ref. 2.

[16] L. J. Goldfarb, in *Proceeding of the Second International Symposium on Polarization Phenomena of Nucleons* (Birkhäuser Verlag, Basel, Switzerland, 1966).

[17] R. Brüning, F. W. Büsser, F. Niebergall, and J. Christiansen, Phys. Letters **21**, 435 (1966).

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[19] V. A. Smotryaev and I. S. Trostin, Zh. Eksperim. i Teor. Fiz. **46**, 1494 (1964) [English transl.: Soviet Phys.—JETP **19**, 1012 (1964)].

[20] J. Christiansen, G. Söhngen, F. W. Büsser, and F. Niebergall, in *International Congress on Nuclear Physics, Paris, 1964*, edited by P. Gungenborger (Centre National de la Recherche Scientifique, Paris, 1964), Vol. II, p. 921.