5. The number of prompt neutrons emitted is much smaller than had been previously reported.

6. The total radiochemical fission cross sections at excitation energies of 37.7, 34.8, and 31.4 MeV are found to be 191.3, 72.4, and 10.5 μb, respectively, and are in satisfactory agreement with previously published instrumental values.


## ACKNOWLEDGMENTS

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# Polarization of Neutrons from the $D(d,n)He^3$ Reaction*

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Angular distributions of the polarization of neutrons from the $D(d,n)He^3$ reaction have been obtained at several deuteron energies from 1.9 to 3.7 MeV. The polarization at 45° c.m. ranged from −0.109±0.013 at 1.9 MeV to −0.027±0.015 at 3.7 MeV. Similar measurements presently available in the literature are reviewed and shown to fall into two conflicting sets, one of which is confirmed by the present measurement. All presently available angular distributions of the differential polarization have been fitted to the expansion $P_1(\theta)\sigma(\theta)=\Sigma_n a_n \sin 2n\theta$, and except for a previous measurement at 0.375 MeV, there is no evidence for terms of higher order than $n=2$ in the expansion. The coefficients of this expansion have been tabulated to permit interpolation of the differential polarization over deuteron energy and reaction angle.

## INTRODUCTION

A LARGE number of experiments concerning the properties of the $D(d,n)He^3$ reaction have been performed since this reaction was recognized as a very useful source of monoenergetic neutrons. Theoretical analyses of the experimental results have followed several approaches. The cross-section data for energies above 5 MeV have been interpreted in terms of a stripping interaction with considerable success.[1,2] Konopinski and Teller[3] analyzed the cross-section data below 2 MeV using the method of partial waves and were able to conclude that a large spin-orbit interaction is involved. Wolfenstein[4] noted that, if this is true, a polarization of the outgoing neutrons would be produced. Measurements of the predicted polarization ensued and now it is well established that indeed a polarization does exist. However, there is still some question as to the magnitude of the polarization. Below 2 MeV some of the discrepancies in the reported values can be attributed to the uncertainty in the properties of the polarization analyzers employed. Above 2 MeV the situation is not at all clear even though nine independent experiments have been conducted. Collecting all the polarization data reported for energies above 2 MeV and for reaction angles near 45° c.m. on a single graph illustrates a curious feature. From a glance at the graph one is inclined to divide the values into two groups of points, through each of which a smooth curve varying monotonically with energy can be drawn. These two curves indicate polarizations which differ by more than 0.20 over most of the energy range from 2 to 11 MeV and which in fact differ in sign from about 4.5 to 8 MeV. Since the usefulness of the $D(d,n)He^3$ reaction as a source of partially polarized neutrons depends on an accurate knowledge of the polarization, and, since any suitable theoretical interpretation of this reaction will be expected to explain the value of the neutron polarization, it appeared desirable to perform an experiment which could aid in determining which, if either, of the sets of data are reproducible.

Although the Duke electrostatic accelerator is limited to energies below 4 MeV, it appeared that the disagreement in the 2- to 4-MeV region was large enough that an accurate experiment would test the reliability of much of the reported data. (In the interim between reporting our results[5] prior to multiple-scattering calculations and submitting the present paper, two experiments by Bondarenko and Ot-Stanov[6] and Babenko *et al.*[7] also were conducted with this purpose in mind.)

* Work supported by the U. S. Atomic Energy Commission.
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[1] W. W. Daehnick and J. M. Fowler, Phys. Rev. **111**, 1309 (1958).
[2] M. D. Goldberg and J. M. LeBlanc, Phys. Rev. **119**, 1992 (1960).
[3] E. J. Konopinski and E. Teller, Phys. Rev. **73**, 822 (1948).
[4] L. Wolfenstein, Ann. Rev. Nucl. Sci. **6**, 43 (1956).
[5] F. O. Purser, J. R. Sawers, Jr., and R. L. Walter, Bull. Am. Phys. Soc. **8**, 320 (1963). J. R. Sawers, Jr., F. O. Purser, and R. L. Walter, *ibid.* **9**, 33 (1964).
[6] I. I. Bondarenko and P. S. Ot-Stanov, Zh. Eksperim. i Teor. Fiz. **47**, 97 (1964) [English transl.: Soviet Phys.—JETP **20**, 67 (1965)].
[7] N. P. Babenko, I. O. Konstantinov, A. P. Moskalev, and Yu. A. Nemilov, Zh. Eksperim. i Teor. Fiz. **47**, 767 (1964) [English transl.: Soviet Phys.—JETP **20**, 512 (1965)].

The following experiment was also conducted with the purpose of obtaining a better determination for this energy range of the coefficients in the series expansion

$$P_1(E_d,\theta_1)\sigma(E_d,\theta_1)=\sum_n a_n \sin 2n\theta. \qquad (1)$$

According to an analysis by Fierz,[8] knowledge of these coefficients can give information concerning the nature of the spin-orbit forces in this reaction.

## SURVEY OF EXISTING POLARIZATION DATA

Because of the inconsistencies in the reported polarization values, a brief description of all the previous work for deuteron energies above 2 MeV will be presented here. Before this is done, however, it should be pointed out that, in order to determine the polarization of a neutron beam, scattering from a suitable target must be employed. All of the measurements discussed below utilized scattering from helium as the polarization analyzer. In every case the analyzing power $P_2(\theta_2)$ was calculated from the $n$-He scattering phase shifts. For the neutron energies involved in the D($d,n$) studies, there exist two angular regions where the analyzing power is large, i.e., forward scattering angles near $\theta_2=75°$ c.m. and back scattering angles near $\theta_2=135°$ c.m. Each investigation was carried out using scattering angles near either one or the other of these angles. Since no correlation exists between the choice of analyzing angle and the aforementioned two sets of polarization results, the inconsistencies must be in the measured asymmetries themselves.

The earliest reported polarization measurements for this reaction above 2 MeV were performed by Daehnick.[9] For a deuteron energy of 8.2 MeV, he found that for the reaction angles $\theta_1=47°$ c.m. and 59° c.m. the neutron polarization $P_1(\theta_1)$ was near $-0.10$. By extrapolating the 0.9- to 1.8-MeV data of Levintov *et al.*,[10] Daehnick anticipated that for angles near 55° c.m. the polarization from 2 to 8 MeV was smoothly varying with energy, was negative, and was small in magnitude. Baicker and Jones[11] reported an experiment for deuteron energies from 2 to 4.5 MeV at a reaction angle of 40° lab (approximately 55° c.m.). Their results showed that the polarization in this energy region ranged from $-0.20$ to $-0.15$ and was generally consistent with the curve presented by Daehnick. Avignon, Deschamps, and Rosier[12] performed a one-point measurement to determine the polarization in the energy gap between the two earlier experiments. They found that $P_1$(40° lab) was $-0.16$ for a deuteron energy of 5.5 MeV, which agreed well with a linear interpolation of the data of the above experiments. A preliminary value of the polarization at $E_d=1.9$ MeV, which is consistent with the Baicker and Jones measurement at 2.0 MeV, has recently been reported by Miller.[13] Additional confidence in the validity of this group of data was found in the work of Trostin and Smotryaev.[14] These authors obtained values which showed that $P_1$ (45° c.m.) passed through zero near 8.5 MeV and increased to a value of 0.18 at 12 MeV. A graph of all of the available data for energies above 2 MeV and for reaction angles near 45° c.m. is presented in Fig. 1. A dashed curve has been drawn through the above-mentioned data which are represented by the solid symbols. If the dashed curve data were all that existed, one would conclude that the polarization does vary monotonically with energy and was probably known with considerable accuracy. Since the polarization should not vary strongly with angle for energies below 12 MeV, the fact that some of the measurements were performed at reaction angles differing somewhat from 45° c.m. is not of significance in the present discussion.

The most complete survey[15] of the D-D neutron polarization in this energy range was conducted by Dubbeldam and Walter (hereafter called DW). Five angular distributions and seven values of the polarization at 45° c.m. were obtained over the range from 1.9 to 11.0 MeV. Like the above data, these results are also consistent with a smooth extrapolation of the low-energy data reported by Levintov *et al.* However, over the entire energy range from 2 to 11 MeV, their data, which are represented by the open circles in Fig. 1, are statistically inconsistent with the data associated with the dashed curve. A solid line has been drawn through the DW data to indicate this discrepancy. In order to gain information about the $n$-He scattering phase shifts, May, Walter, and Barschall[16] used the partially polarized D-D neutrons at $E_d=8.4$ MeV with $\theta_1=45°$ c.m. By varying $\theta_2$, the $n$-He scattering angle, a relative measurement of the analyzing power of helium as a function of $\theta_2$ was obtained. The angular dependence of the analyzing power agreed well with that calculated using the Dodder-Gammel-Seagrave[17] (hereafter referred to as DGS) phase shifts for the $n$-He interaction. Some of the conclusions reached in this paper were that the experimental technique employed was a suitable method for measuring neutron polarizations and that $P_1$ (45° c.m.) was $0.26\pm0.02$. This value, which agreed very well with the DW data, is plotted in Fig. 1. Since the technique and much of the apparatus employed in this research was the same as that used in the DW experiment, this result gave some confidence in the DW data.

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[8] M. Fierz, Helv. Phys. Acta **25**, 629 (1952).
[9] W. W. Daehnick, Phys. Rev. **115**, 1008 (1959).
[10] I. I. Levintov, A. V. Miller, E. Z. Tarumov, and V. M. Shamshev, Nucl. Phys. **3**, 237 (1957).
[11] J. A. Baicker and K. W. Jones, Nucl. Phys. **17**, 424 (1960).
[12] P. Avignon, Y. Deschamps, and L. Rosier, J. Phys. Radium **22**, 414 (1961).
[13] T. G. Miller, Bull. Am. Phys. Soc. **9**, 153 (1964).
[14] I. S. Trostin and V. A. Smotryaev, Zh. Eksperim. i Teor. Fiz. **44**, 1160 (1963) [English transl.: Soviet Phys.—JETP **17**, 784 (1963)].
[15] P. S. Dubbeldam and R. L. Walter, Nucl. Phys. **28**, 414 (1961).
[16] T. H. May, R. L. Walter, and H. H. Barschall, Nucl. Phys. **45**, 17 (1963).
[17] J. D. Seagrave, Phys. Rev. **92**, 1222 (1953).

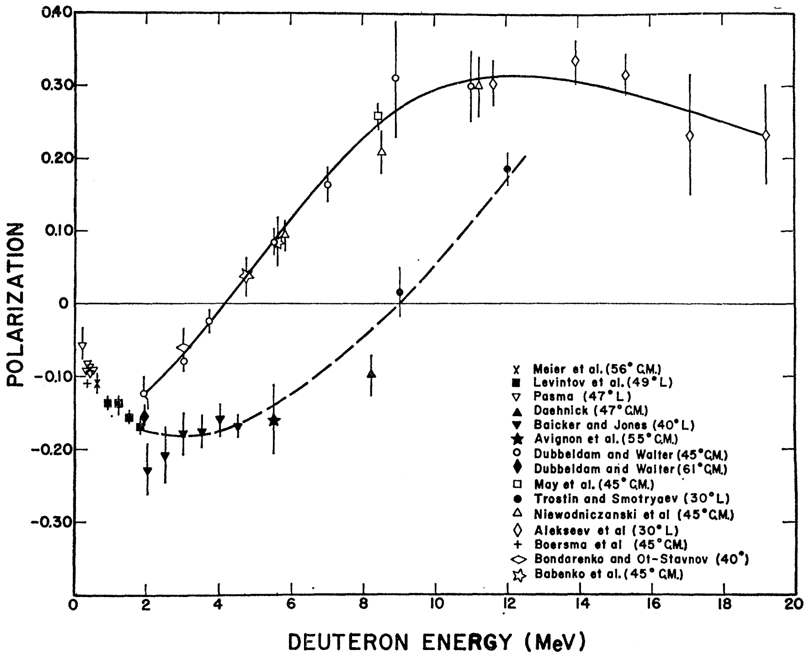


FIG. 1. $D(d,n)He^3$ neutron polarization measurements at reaction angles indicated. L = lab system; CM = c.m. system.

Support for the higher energy data reported by DW was given in papers recently published by Niewodniczanski, Szmider, and Szymakowski,[18] and by Alekseev *et al.*[19] The first group measured the three values of $P_1$ (45° c.m.) from 5.9 to 11.3 MeV which are represented by the open triangles in Fig. 1. It can be seen that the agreement with the energy dependence signified by the solid curve is good. Although the technique employed in this experiment was basically the same as that of the DW experiment, one important difference is worth mentioning. The former group purposely worked with $\theta_2 = 135°$ c.m. where $P_2 \simeq +0.98$ as compared to the choice by DW of $\theta_2 = 78°$ c.m. where $P_2 \simeq 0.65$. This test along with the results of May *et al.* appears to eliminate the possibility that the gross discrepancies in the D-D results arise because of uncertainties in the helium-analyzing power. Alekseev *et al.*, also using a similar technique, have reported polarization measurements from 11.6 to 19.2 MeV including an angular distribution at 11.6 MeV. Shown by the open diamonds in Fig. 1, it can be seen that their values join smoothly to those forming the previous basis for the solid curve although consistent agreement with an extension of the dashed curve can not be ruled out.

Since the present experiment was performed, Bondarenko and Ot-Stanov[6] and Babenko *et al.*[7] have presented results for deuteron energies between 3.0 and 5.6 MeV which also agree with the DW data.

[18] H. Niewodniczanski, J. Szmider, and J. Szymakowski, J. Phys. Radium **24**, 871 (1963).

[19] N. V. Alekseev, U. R. Arifkhanov, N. A. Vlasov, V. V. Davydov, and L. N. Samoilov, Zh. Eksperim. i Teor. Fiz. **45**, 1416 (1963) [English transl.: Soviet Phys.—JETP **18**, 979 (1964)].

## EXPERIMENTAL PROCEDURE

In the present experiment, deuterons from the Duke electrostatic accelerator bombarded a target consisting of two atmospheres of deuterium gas contained in a thin-walled stainless-steel cylinder 2.5 cm long. The beam entered through nickel foil windows of from 2 to 3 μm thickness and was stopped in a thick silver backing. Deuteron beam currents of about 2 μA were used. Neutrons emitted in the horizontal plane at a reaction angle $\theta_1$ were collimated to a 3° cone with a shield composed of brass and lithium-loaded paraffin and were incident upon helium contained in a thin-walled, high pressure gas scintillation cell similar to those described by Shamu[20] and DW. The distance from the neutron source to the helium analyzer was 1 m. Neutrons scattered from the helium to the right or left through an angle $\theta_2$ of 132° c.m. were detected with rectangular plastic scintillators 2.5 cm×5 cm×5 cm. With a detector-to-helium-cell distance of 16 cm, the neutron detectors subtended an angle of approximately 16° at the scattering center. To minimize in-scattering, the plastic scintillators were shielded by only 0.5 cm of lead which helped to reduce the gamma radiation background.

Desired scattering events were determined by requiring coincidences between α recoils in the helium cell and proton recoils in the plastic scintillators. For this a fast-slow coincidence system with a measured time resolution of 10 nsec was used. A single-channel analyzer employed in the manner reported by DW to select only those helium recoil pulses corresponding to neutron scattering through angles near 132° c.m. served

[20] R. E. Shamu, Nucl. Instr. Meth. **14**, 297 (1962).

TABLE I. Results of experiment.

| $E_d$ (MeV) | $\theta_{lab}$ | $\theta_{c.m.}$ | $E_n$ (MeV) | $\epsilon$ | $\epsilon'$ | $\bar{P}_2$ | $P_1$ | $\sigma$ (mb/sr) | $P_1\sigma$ (mb/sr) |
|---|---|---|---|---|---|---|---|---|---|
| 1.9 | 17.2 | 22.0 | 5.00 | −0.0152 | −0.0112 | 0.976 | −0.012±0.013 | 19.10 | −0.220±0.241 |
| | 23.7 | 30.0 | 4.89 | −0.0315 | −0.0254 | 0.976 | −0.026±0.012 | 14.33 | −0.373±0.178 |
| | 35.8 | 45.0 | 4.62 | −0.1110 | −0.1060 | 0.975 | −0.109±0.013 | 7.85 | −0.853±0.100 |
| | 40.0 | 50.0 | 4.51 | −0.1430 | −0.1430 | 0.974 | −0.142±0.013 | 6.70 | −0.949±0.088 |
| | 49.0 | 61.0 | 4.24 | −0.1630 | −0.1630 | 0.971 | −0.166±0.016 | 5.44 | −0.902±0.085 |
| | 54.6 | 67.5 | 4.06 | −0.1510 | −0.1510 | 0.969 | −0.155±0.015 | 5.35 | −0.828±0.080 |
| | 61.0 | 75.0 | 3.85 | −0.1100 | −0.1100 | 0.964 | −0.114±0.016 | 5.32 | −0.607±0.087 |
| 2.5 | 35.0 | 45.0 | 5.14 | −0.1100 | −0.1100 | 0.976 | −0.108±0.013 | 6.82 | −0.737±0.091 |
| | 40.0 | 51.3 | 4.98 | −0.1410 | −0.1410 | 0.976 | −0.142±0.014 | 5.62 | −0.800±0.080 |
| 3.0 | 17.5 | 23.1 | 6.08 | −0.0054 | +0.0000 | 0.972 | 0.000±0.010 | 20.19 | 0.000±0.206 |
| | 24.0 | 31.6 | 5.91 | −0.0204 | −0.0134 | 0.973 | −0.014±0.010 | 13.39 | −0.185±0.138 |
| | 34.5 | 45.1 | 5.57 | −0.0695 | −0.0636 | 0.975 | −0.065±0.013 | 6.19 | −0.404±0.079 |
| | 42.0 | 54.5 | 5.29 | −0.1255 | −0.1233 | 0.976 | −0.126±0.021 | 4.79 | −0.605±0.099 |
| | 49.0 | 63.2 | 4.99 | −0.1080 | −0.1080 | 0.976 | −0.111±0.014 | 4.54 | −0.503±0.061 |
| | 55.0 | 70.4 | 4.72 | −0.0858 | −0.0858 | 0.976 | −0.089±0.013 | 5.04 | −0.448±0.066 |
| | 72.0 | 90.0 | 3.95 | +0.0025 | +0.0025 | 0.965 | +0.003±0.016 | 6.76 | +0.018±0.115 |
| 3.7 | 22.5 | 30.0 | 6.59 | +0.0030 | +0.0100 | 0.972 | +0.010±0.012 | 14.90 | +0.159±0.183 |
| | 34.0 | 45.0 | 6.16 | −0.0310 | −0.0260 | 0.972 | −0.027±0.015 | 5.31 | −0.142±0.082 |
| | 40.0 | 53.0 | 5.90 | −0.0690 | −0.0660 | 0.973 | −0.068±0.013 | 3.97 | −0.269±0.053 |
| | 45.5 | 60.0 | 5.63 | −0.0770 | −0.0790 | 0.974 | −0.081±0.016 | 3.79 | −0.307±0.062 |
| | 52.0 | 67.5 | 5.30 | −0.0600 | −0.0620 | 0.976 | −0.064±0.020 | 4.79 | −0.302±0.093 |
| | 58.0 | 75.0 | 4.98 | −0.0270 | −0.0280 | 0.976 | −0.029±0.016 | 5.48 | −0.157±0.090 |

to minimize the background. All photomultipliers were shielded with Mumetal and soft-iron cylinders to eliminate magnetic field effects.

By using two neutron detectors and by taking measurements alternately to the right and to the left of the deuteron beam axis, effects due to time variations in neutron beam intensity and differences in detector efficiencies are minimized. This method has been described in the review article by Haeberli.[21] The asymmetry $\epsilon$ in the flux of neutrons scattered from the helium analyzer is related to the experimentally determined counting rates by

$$\epsilon=\frac{(F/F')^{1/2}-1}{(F/F')^{1/2}+1},$$

where $F$ is the ratio of the counting rate of the right detector to that of the left detector when the analyzing system is on the right of the deuteron beam axis (Basel convention). $F'$ is the same ratio at the identical reaction angle to the left.

A possible error associated with the determination of the 0° reaction angle is encountered if the right and left detector systems have efficiencies which vary differently with neutron energy, as would be the case if they were biased differently. Since the neutron energy depends upon emission angle, the relative efficiencies of the two detectors therefore could be different for the measurement of $F$ and $F'$. In the present experiment, 0° reaction angle was determined to within ±0.5° by measuring the yield of the D$(d,n)$ reaction on the right and left of the deuteron beam axis. It was calculated that errors arising from the possible differences in our detector efficiencies are negligible for a ±0.5° uncertainty.

A second instrumental asymmetry is introduced at all angles for which the reaction cross section varies appreciably with reaction angle because of an effective shift of scattering center within the helium cell caused by the nonuniform irradiation of the cell. This effect was calculated and applied to the measured asymmetries. The maximum correction was 0.007 and the uncertainty in these corrections is negligible compared with the final accuracy of the results.

As an initial check that no unforeseen asymmetry was inherent in the experimental arrangement, the polarization at 90° c.m. was measured for $E_d=3.0$ MeV. Within a statistical uncertainty of about ±0.01, the asymmetry was found to be consistent with zero polarization as expected from symmetry considerations when the bombarding particle and the target nucleus are identical.

Background originating from drive in deuterons or other reactions in the target system was measured with the target evacuated and was found to be less than 1% of the counts recorded with the deuterium gas present. Random-coincidence counting rates were measured by delaying one input to the fast coincidence circuits. They contributed at most 5% of the total counts for any measurement.

The polarization $P_1$ of the D-D neutrons is related to the measured asymmetry $\epsilon$ by the formula

$$\epsilon=P_1(E_d,\theta_1)\bar{P}_2(E_n,\theta_2), \tag{2}$$

where $\bar{P}_2(E_n,\theta_2)$ is the averaged analyzing power of the helium scatterer. The $\bar{P}_2$ used in (1) were based on the DGS phase shifts and were obtained by weighting $P_2$ with the $n$-He differential cross section calculated from

[21] W. Haeberli, in *Fast Neutron Physics*, edited by J. B. Marion and J. L. Fowler (Interscience Publishers Inc., New York, 1963), Part II, Chap. V.G.

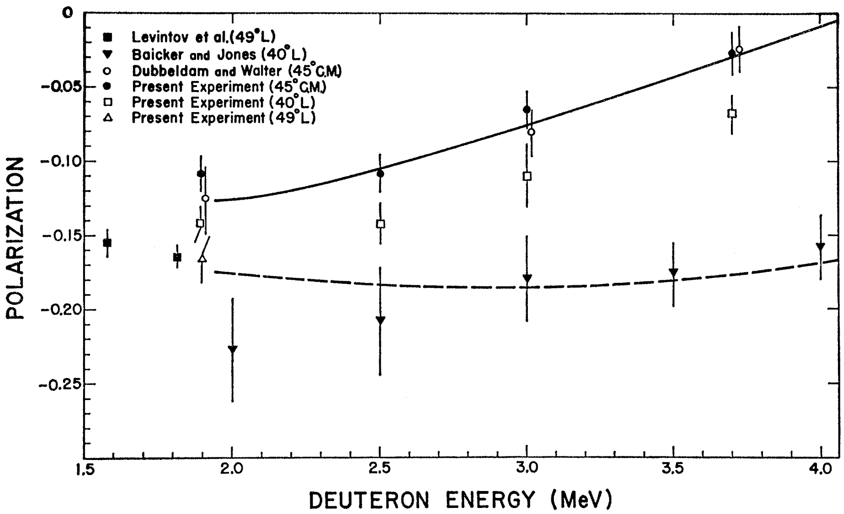


FIG. 2. Polarization of the $D(d,n)He^3$ neutrons in the 1.5- to 4.0-MeV region for angles near 45° c.m. L = lab system; CM = c.m. system.

the above phase shifts and numerically integrating over the scattering geometry involved. The scattering angle chosen ($\theta_2 = 132°$ c.m.) is in the region where $P_2$ exhibits a broad maximum and is relatively insensitive to neutron energy. The results of May *et al.*[16] and those of Austin, Barschall, and Shamu[22] have shown that $P_2$ is probably determined quite accurately from the DGS phase shifts for the neutron energies of interest to this experiment, particularly for angles near 132° c.m. It is difficult to attach a definite uncertainty to $P_2$, and it may be possible that the present uncertainties in $P_2$ could lead to a change in the uncertainty in $P_1$ given in the next section by as much as 0.02 where the magnitude of $P_1$ is largest. Naturally this contribution to the uncertainty would be less for the other values of $P_1$ in proportion to the magnitudes of the polarization, giving no contribution where $P_1 = 0.0$. The effect upon the analyzing power $\bar{P}_2$ of multiple scattering within the helium analyzer, including the effect of rotation of the polarization vector, was considered. For the neutron energy range covered by the experiment it is estimated that multiple scattering would decrease $\bar{P}_2$ by less than 0.01 with the uncertainty in this estimate being approximately 50% of the correction. In view of the possible error in $P_2$ associated with the DGS phase shifts and since the maximum correction due to multiple scattering would result in values of $P_1$ well within the statistical errors given in the next section, this correction was not applied to the data.

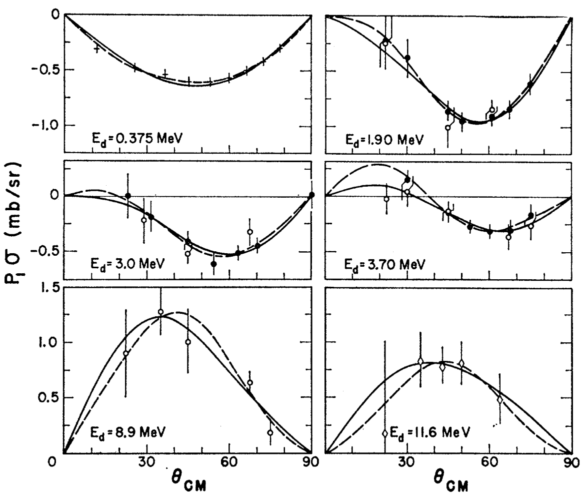


FIG. 3. Angular distributions of the differential polarization. The solid and dashed curves are two- and three-term fits to the expansion (1), respectively. Present data are represented by the solid circles, the data of Ref. 15 by the open circles. The data at 0.375 MeV are from Ref. 24 and at 11.6 MeV are from Ref. 19. L = lab system; CM = c.m. system.

## RESULTS

The results of the experiment are compiled in Table I. The errors listed for the asymmetry $\epsilon$ are the standard deviations for the total number of counts recorded for each measurement. The asymmetry $\epsilon'$ shown has been corrected for the above-mentioned shift-of-center asymmetry. The deuteron energy $E_d$ is the mean deuteron energy in the gas target. Neutron energies and cross-section data were obtained by interpolation from the tabulation by Fowler and Brolley.[23]

The variation of polarization with deuteron energy over the energy range covered by the present experiment is shown in Fig. 2. Data points due to other experiments in this region have been shown for comparison. The solid and dashed curves have been taken from Fig. 1. Agreement with the 45° c.m. DW data and the lack of agreement with those reported by Baicker and Jones for this energy interval at 40° lab is obvious.

The angular distribution data for the differential polarization obtained in the present experiment at 1.9,

[22] S. M. Austin, H. H. Barschall, and R. E. Shamu, Phys. Rev. **126**, 1532 (1962).

[23] J. E. Brolley and J. L. Fowler, in *Fast Neutron Physics*, edited by J. B. Marion and J. L. Fowler (Interscience Publishers Inc., New York, 1960), Part I., Chap. IC.

TABLE II. Coefficients of the expansion $P_1(\theta)\sigma(\theta)=\sum_n a_n \sin 2n\theta$.

| $E_d$ | Two-term fit $a_1$ | Two-term fit $a_2$ | Three-term fit $a_1$ | Three-term fit $a_2$ | Three-term fit $a_3$ | Ref. |
|---|---|---|---|---|---|---|
| 0.375 | −0.627±0.016 | +0.037±0.014 | −0.627±0.014 | +0.023±0.013 | −0.036±0.013 | 24 |
| 1.90 | −0.82 ±0.14 | +0.18 ±0.15 | −0.81 ±0.12 | +0.18 ±0.13 | +0.19 ±0.12 | 15 |
| 1.90 | −0.82 ±0.06 | +0.25 ±0.06 | −0.78 ±0.07 | +0.30 ±0.08 | +0.06 ±0.07 | Present |
| 2.50 | −0.74 ±0.09 | +0.18 ±0.28 | Two-point angular distribution | | | Present |
| 3.00 | −0.47 ±0.08 | +0.03 ±0.12 | −0.40 ±0.10 | +0.12 ±0.14 | +0.12 ±0.11 | 15 |
| 3.00 | −0.41 ±0.05 | +0.21 ±0.05 | −0.38 ±0.06 | +0.23 ±0.07 | +0.04 ±0.06 | Present |
| 3.70 | −0.18 ±0.04 | +0.19 ±0.04 | −0.18 ±0.06 | +0.18 ±0.07 | −0.05 ±0.06 | 15 |
| 3.70 | −0.15 ±0.06 | +0.19 ±0.07 | −0.07 ±0.09 | +0.27 ±0.10 | +0.08 ±0.07 | Present |
| 7.00 | +0.64 ±0.08 | +0.16 ±0.09 | +0.68 ±0.08 | +0.22 ±0.10 | +0.09 ±0.08 | 15 |
| 8.90 | +1.12 ±0.13 | +0.26 ±0.10 | +1.12 ±0.13 | +0.16 ±0.17 | −0.13 ±0.17 | 15 |
| 11.6 | +0.81 ±0.11 | +0.09 ±0.19 | +0.73 ±0.21 | +0.03 ±0.23 | −0.11 ±0.21 | 19 |

3.0, and 3.7 MeV are indicated by the solid circles in Fig. 3. Angular distributions reported by Boersma *et al.*[24] at 0.375 MeV and by Alekseev *et al.* at 11.6 MeV have been included. The DW angular distribution data are indicated by the open circles in Fig. 3. Curves drawn are two- and three-term least-square fits to the data of expansion (1) for $P_1\sigma$. For the energies covered by the present work, the DW data were not considered in making the least-square fits. The coefficients of expansion (1) with their standard errors are tabulated in Table II. Three-term fits to the Boersma data and to the DW data at 1.9, 3.0, and 3.7 MeV were made using our program. In making the least-square fit to the Alekseev polarization data, D($d,n$)He[3] differential cross sections for this energy were obtained from the Legendre coefficients published by Goldberg and LeBlanc.[25] No three-term fit was made to the 2.5 MeV data of the present experiment since at this energy only a two-point angular distribution was obtained. The variation with energy of the coefficients for a two-term expansion is shown in Fig. 4.

## DISCUSSION

It can be shown quite generally[21] that the angular dependence of the polarization is of the form

$$P_1(\theta,E_d)=\frac{1}{\sigma(\theta,E_d)}\sum_{L=1}^{L\max} a_L(E_d)P_L{}^1(\cos\theta)\,, \qquad (3)$$

where the $P_L{}^1(\cos\theta)$ are the associated Legendre polynomials. For the present reaction involving two identical particles, only even $L$ values are allowed and the formula reduces simply to (1).

Beiduk, Pruett, and Konopinski,[26] in an analysis of differential-cross-section data, developed the formalism of approach cross sections. Their work, in which the reaction is dominated by the differences in barrier height seen by incoming deuterons of differing orbital angular momenta, has provided the basis for much of the subsequently reported work. In successfully fitting the available differential cross sections, these authors concluded that considerable spin-orbit interaction was necessary to explain the data; however, they were unable to determine whether the spin-orbit coupling provided by the tensor force was sufficient or whether internucleonic forces of the $\mathbf{l}\cdot\mathbf{s}$ form were present.

For energies up to 400 keV, Blin-Stoyle[27] obtained the formula

$$P_1(\theta,E_d)=\frac{cA(E)\sin 2\theta}{1+A(E)\cos^2\theta}\,, \qquad (4)$$

which is seen to be the $n=1$ term from formula (1). Here $c$ is an energy-independent factor and $A(E)$ is the first anisotropy coefficient derived from fitting the differential cross section. By including an outgoing barrier penetrability with the approach cross sections of Ref. 26, Blin-Stoyle was able to account for the large value of the measured proton polarization in the D($d,p$)T reaction at low energies in a manner consistent with the approach cross section formalism with the assumption of only tensor and central forces.

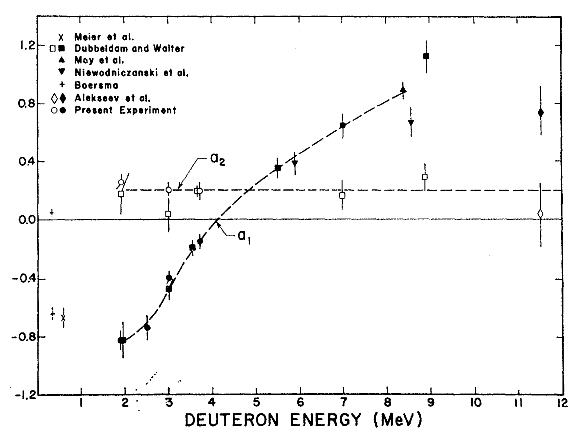


FIG. 4. Variation of the expansion coefficients with deuteron energy. Error bars are standard least-square errors. Only the coefficients from the two-term fit are plotted.

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In terms of the "approach" cross sections $\sigma_{l_1}$ for the reaction, if one assumes no contribution from incoming deuterons with $l_1 \geq 4$, the coefficient $a_L$ of formula (3) may be written

$$a_1(E) = a\sigma_1 + \alpha(\sigma_0\sigma_2)^{1/2} + \beta\sigma_2 + b(\sigma_1\sigma_3)^{1/2} + c\sigma_3, \quad (5a)$$

$$a_2(E) = \beta'\sigma_2 + b'(\sigma_1\sigma_3)^{1/2} + c'\sigma_3, \quad (5b)$$

$$a_3(E) = c''\sigma_3, \quad (5c)$$

where the coefficients of the various $\sigma_{l_1}$ terms are energy-independent. Here $l_1$ indicates orbital angular momentum of the incoming deuteron. Fierz,[8] who gives (5) for $l_1 \leq 2$, has pointed out that $\alpha$, $\beta$, and $\beta'$ must vanish if only central and tensor forces are present. Rook and Goldfarb[28] have also shown that only by including a nucleon-nucleon $\mathbf{l}\cdot\mathbf{s}$ force, is the singlet-triplet transition [indicated above by the $(\sigma_0\sigma_2)^{1/2}$ term] permitted to first order. By including the energy-dependent phase for this transition, these authors were able to explain the energy dependence of the measured neutron polarization[29] below 700 keV using only the first two terms in (5a). More recent data in this energy region[24,30] are consistent with their analysis.

## CONCLUSIONS

The results of the present experiment are in excellent agreement with the upper curve in Fig. 1. In addition, the angular distributions obtained tend to closely confirm those reported by Dubbeldam and Walter for the corresponding energies. Our results tend to discriminate equally against values lying near the dashed curve in Fig. 1. The source of the discrepancy is not obvious, but it is possible that the difference between the two sets of data indicated may be associated with the much higher backgrounds recorded for the measurements lying near the dashed curve. The signal-to-noise ratio for the present experiment and for the DW work was improved by roughly an order to magnitude over those measurements.

Data of the present experiment are inadequate for determining whether the nucleon-nucleon spin orbit force contributes to the reaction. For deuteron energies above 2.0 MeV sufficient terms are available in Eq. (5) to fit the energy dependence of the data with $\alpha$, $\beta$, and $\beta'$ equal to zero, i.e. without the inclusion of an $\mathbf{l}\cdot\mathbf{s}$ force. However, when one takes into account the reported results of Boersma[24] and others[29,30] at low deuteron energies, the energy dependence of the coefficients shown in Fig. 4 is difficult to account for on the basis of the approach cross-section formalism assuming only tensor and central forces. Considering the extreme simplicity of the assumptions of the approach cross-section model this is not surprising. On the other hand, if one accepts the terms in Eq. (5) due to the nucleon-nucleon $\mathbf{l}\cdot\mathbf{s}$ force, our results appear to be consistent with the low-energy data, an agreement which is possibly due merely to the increased degrees of freedom available. A more detailed investigation of the D$(d,n)$ polarization for deuteron energies from 1.0 to 2.0 MeV has been undertaken at this laboratory. Analysis of these data should be of value in determining the usefulness of the approach cross-section model for this energy range.

It appears that for deuteron energies between 1.9 and 7.0 MeV the two-term coefficients given in Table II and plotted in Fig. 4 may be used to calculate the differential polarization for use as a source of polarized neutrons at unmeasured angles and deuteron energies with some degree of confidence. Except for the measurement at 0.375 MeV, no terms of order higher than $\sin 4\theta$ are clearly present in any of the angular distributions available. While the absence of higher order terms at 8.9 and 11.6 MeV seems principally to be due to the inadequacy of the data to permit a statistically significant determination of the appropriate coefficients, below 7.0 MeV the contribution of the higher order terms to the polarization is negligible in comparison with that of the first two terms of the $\sin 2n\theta$ expansion.

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