Polarization of Protons from Deuteron Stripping Reactions*

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(Received 19 July 1963; revised manuscript received 23 October 1963)

The proton polarization angular distributions from the following reactions have been measured: $C^{12}(d,p)C^{13*}$(3.09 MeV, $l_n=0$); $Mg^{24}(d,p)Mg^{25}$(g.s., $l_n=2$, and 0.58 MeV, $l_n=0$); $Be^9(d,p)Be^{10}$(g.s., $l_n=1$, and 3.37 MeV, $l_n=1$); $Si^{28}(d,p)Si^{29*}$(1.28 MeV, $l_n=2$). The incident deuteron energy was 15 MeV. Carbon and helium were used as polarization analyzers. The results are discussed in terms of distorted-wave theory. In addition to the polarization measurements, the differential cross section of deuterons elastically scattered from aluminum, silicon, and beryllium has been determined.

I. INTRODUCTION

IN the past few years (d,p) stripping reactions have become an extremely useful tool in nuclear structure studies. The reason for this lies in the great success with which distorted-wave calculations are able to predict (d,p) differential cross sections. This enables one to extract from differential cross-section measurements, spectroscopic information like the orbital angular momentum transfer of the captured neutrons, and spectroscopic factors (reduced widths) of the states formed. In light of these facts it is intriguing to investigate some of the other predictions of the distorted-wave theory, like for instance the polarization of protons emitted in (d,p) reactions. The polarization is a quantity which is much more sensitive to interference effects from mechanisms other than the stripping process and therefore, polarization measurements provide a more rigorous test of the reaction mechanism than differential cross-section measurements.

Moreover, the proton polarization predicted by the distorted-wave theory depends strongly on the optical-model parameters used in the distorting potentials of the deuterons and protons. The influence of spin-orbit terms is particularly strong and polarization measurements should provide information about these parameters.

In addition to the orbital angular momentum transfer, which can be extracted from differential cross-section measurements, polarization experiments are expected to differentiate between the two possible values for the total angular momentum transfer $j_n=l_n\pm\frac{1}{2}$ for a given l_n. The simple sign rule originally predicted by Newns[1] is expected to be inadequate because of the importance of spin-dependent forces. It is therefore of some interest to investigate whether there are any other systematic differences in the polarization patterns which would enable polarization measurements to be used to determine j_n values. This question is discussed further in Sec. IVB.

In contrast to the optical potential of protons, which is known quite well from the analysis of a large number of elastic differential cross section and polarization measurements, the deuteron optical potential is rather uncertain. In a meaningful distorted-wave theory this potential, too, should be determined from the analysis of elastic differential cross section measurements. In order to make such an analysis possible, the (d,d) differential cross section of aluminum, silicon, and beryllium which had not been determined previously was measured.

II. EXPERIMENTAL

A. Apparatus

The experimental arrangement was similar to that used previously by Isoya *et al.*[2,3] Major changes were made in the electronic set up.

The protons are momentum analyzed by a 60° homogeneous field spectrometer before entering the polarimeter. The polarization is determined in the usual manner, i.e., by measuring the right-left asymmetry of the elastically scattered protons from an analyzer by means of two counter telescopes. The counter telescopes consist each of a proportional counter and a CsI scintillation counter. The pulses from the two scintillation counters are gated by the proportional counter pulses and then analyzed into different subgroups of a Nuclear Data 512 channel analyzer. This arrangement allowed a clean separation of the elastic from the inelastic proton group in the cases where C^{12} was used as an analyzer. A typical pulse-height spectrum is shown in Fig. 1. Background runs were taken by rotating the carbon target out of the proton beam.

In order to calibrate the analyzing power of the carbon targets in regions where the polarization of carbon is not well known, a high-pressure helium cell was built,[4] similar to the one described in Ref. 5. The cell is of cylindrical shape, 1.6 cm in diameter and the energy loss in He is 200 keV for 14-MeV protons.

The two counter telescopes accept horizontal scattering angles between 40 and 55° and have a vertical angular spread of ±25°.

* This work was supported by the U. S. Office of Naval Research and the National Science Foundation.
† Present address: Oak Ridge National Laboratory, Oak Ridge, Tennessee.
[1] H. C. Newns, Proc. Phys. Soc. (London) **A66**, 477 (1953).
[2] A. Isoya and M. J. Marrone, Phys. Rev. **128**, 800 (1962).
[3] A. Isoya, S. Micheletti, and L. H. Reber, Phys. Rev. **128**, 806 (1962).
[4] H. W. Woodcock, M. S. thesis, University of Pittsburgh, 1962 (unpublished).
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B. Determination of the Analyzing Power $\langle P_2 \rangle$

A 45-mg/cm² carbon target was used to measure the polarization of the protons leading to the first excited state (3.09 MeV) of C^{13}. For the other reactions a 130-mg/cm² target was employed, except for the $Be^9(d,p)Be^{10}$ 3.37-MeV state measurement, which was performed using the helium cell.

The polarization was obtained using the well-known relation

$$P_1\langle P_2 \rangle = \frac{(N_{RR}/N_{RL})-1}{(N_{RR}/N_{RL})+1}, \qquad (1)$$

where P_1 is the polarization to be measured. $\langle P_2 \rangle$ is the polarization which would arise from the elastic scattering of unpolarized protons from the analyzing target, averaged over the angular interval accepted by the counter telescopes and the energy range within which the scattering from the analyzing target occurs. N_{RR} and N_{RL} are the number of particles scattered twice in the same sense (right-right or left-left) and in opposite senses (right-left and left-right), respectively.

$\langle P_2 \rangle$ has been calculated for the helium cell and the two carbon targets, using polarization and cross-section data from many sources.[5-20] The details of this calculation are described elsewhere.[3,21]

Because of disagreement in the polarization data of carbon below 14 MeV, it was necessary to perform calibration measurements for the 45-mg/cm² carbon target in this region. 16-MeV protons emitted at 10° from the $C^{12}(d,p)C^{13}$ ground-state reaction were used. The polarization of these protons was known to be 0.30±0.05 from previous measurements.[2] Polyethelene absorber were employed to degrade their energy. In order to make sure that the absorbers did not introduce any asymmetries, the polarization of these energy-degraded protons was redetermined at several energies with the helium analyzer. The results of the $\langle P_2 \rangle$ calculation for the helium and carbon analyzers and of the calibration measurements are shown in Fig. 2.

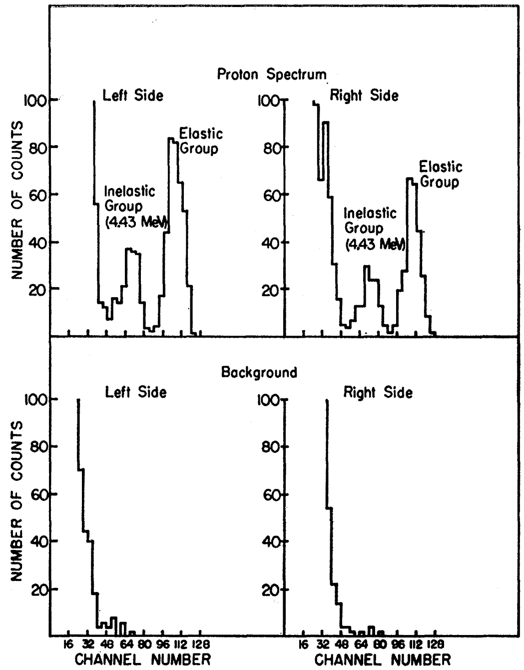

FIG. 1. Top portion: spectra of protons from the $C^{12}(d,p)C^{13}$(g.s.) reaction at 10° after scattering from a carbon target. Bottom portion: background spectra obtained by removing the second carbon target.

C. Instrumental Asymmetries

Detailed calculations of possible instrumental asymmetries have been carried out. The effects considered were: (1) beam-intensity variation over the width of the analyzing target; (2) beam-intensity variation over the angular spread of the proton beam incident on the analyzing target; (3) misalignment of the polarimeter axis with respect to the beam axis.

The result of this analysis showed that the instrumental asymmetries are at most 1%. The details of this calculation are given in Refs. 2 and 21.

D. Elastic Cross-Section Measurements

In addition to the polarization measurements, angular distributions of elastically scattered deuterons were obtained in 5° steps from 10 to 90° for aluminum, silicon, and beryllium. The experimental arrangement was identical to the one used by Jolly *et al.*[22]

III. RESULTS

The results of the polarization and elastic cross-section measurements are given in Tables I to VI. For those elements, in which the (d,d) differential cross

[6] W. Morrow and W. Haeberli (private communication).
[7] L. Rosen, P. Darriulat, H. Faraggi, and A. Garin, Nucl. Phys. **33**, 458 (1962).
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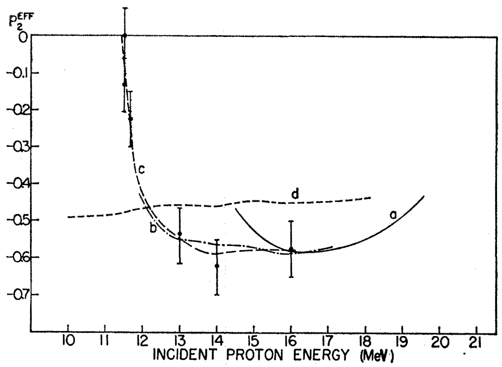

FIG. 2. Effective analyzing power $\langle P_2\rangle$ for the carbon and helium analyzers. Curve (a) is the calculated analyzing power for the 130-mg/cm² carbon target. The experimental points are the calibration measurements made for the 45-mg/cm² carbon target. Curve (b) is the analyzing power for the 45-mg/cm² carbon target calculated from other experimental data. Curve (c) was drawn to represent the most "probable" values for the $\langle P_2\rangle$ for the 45-mg/cm² carbon target. Curve (d) is the calculated analyzing power for the helium cell.

TABLE I. $C^{12}(d,p)C^{13*}$(3.09 MeV).

$\theta_{c.m.}$ (deg)	P_1	$\sigma(d,d)$[a] (mb/sr)
11.1	-0.026 ± 0.040	3540
16.7	$+0.033\pm0.042$	1220
22.3	-0.110 ± 0.048	530
27.8	-0.160 ± 0.049	224
33.3	-0.121 ± 0.042	32.8
39.0	-0.051 ± 0.034	6.81
44.2	-0.158 ± 0.038	12.9
49.7	-0.101 ± 0.041	20.4
60.4	-0.060 ± 0.089	15.8
71.0	$+0.243\pm0.179$	6.40
81.4	-0.090 ± 0.305	6.10
85.0		6.20
90.0		4.98
95.0		3.14

[a] See Ref. 23.

TABLE II. $Be^9(d,p)Be^{10}$(g.s.).

$\theta_{c.m.}$ (deg)	P_1	$\theta_{c.m.}$ (deg)	$\sigma(d,d)$ (mb/sr)
11.2	-0.006 ± 0.031	10.2	2440
16.9	$+0.007\pm0.024$	16.3	1020
22.5	-0.004 ± 0.031	22.3	324
28.0	-0.013 ± 0.034	28.3	184
33.6	-0.052 ± 0.036	34.3	35
39.1	-0.184 ± 0.042	40.3	7.8
44.6	-0.122 ± 0.049	46.1	15.0
48.0	-0.219 ± 0.060	52	18.2
55.5	-0.198 ± 0.041	57.7	15.6
58.7	-0.134 ± 0.069	63.4	9.4
62.0	-0.050 ± 0.061	69.0	5.8
66.2	-0.108 ± 0.060	74.5	3.7
76.8	-0.077 ± 0.090	79.9	3.4
87.1	-0.081 ± 0.125	85.3	3.7
		90.5	2.3

section was not measured in the present experiment, the results of Low[23] are quoted.

[23] C. A. Low, M.S. thesis, University of Pittsburgh, 1961 (unpublished).

TABLE III. $Be^9(d,p)Be^{10*}$(3.37 MeV).

$\theta_{c.m.}$ (deg)	P_1
11.4	$+0.166\pm0.090$
17.1	$+0.026\pm0.095$
22.7	-0.096 ± 0.090
28.4	-0.063 ± 0.120
34.0	-0.101 ± 0.135
39.6	-0.230 ± 0.105
45.2	-0.137 ± 0.100
56.2	-0.351 ± 0.119
67.0	-0.017 ± 0.198
82.8	$+0.163\pm0.221$

TABLE IV. $Mg^{24}(d,p)Mg^{25}$(g.s.).

$\theta_{c.m.}$ (deg)	P_1	$\sigma(d,d)$[a] (mb/sr)
10.5	$+0.004\pm0.057$	
14.6	-0.029 ± 0.057	
15.7	-0.000 ± 0.053	
17.8	-0.039 ± 0.053	
21.0	-0.068 ± 0.044	979
22.0	-0.004 ± 0.056	810
24.0	-0.029 ± 0.060	557
25.1	$+0.042\pm0.055$	462
28.3	$+0.095\pm0.054$	257
31.4	$+0.029\pm0.044$	64.0
36.6	$+0.112\pm0.054$	60.3
41.8	$+0.079\pm0.055$	68.2
52.2	-0.178 ± 0.065	32.8
57.5	-0.266 ± 0.092	11.0
62.5	-0.227 ± 0.068	4.05
68.0	-0.171 ± 0.090	4.50
75.0		4.58
85.0		3.58
95.0		0.825

[a] See Ref. 23.

The polarization errors quoted are statistical only. A systematic error may be contained in the analyzing power $\langle P_2\rangle$. This uncertainty $\langle\Delta P_2\rangle/\langle P_2\rangle$ is believed to be less than 10%. Such an error would influence the absolute magnitude of the measured polarization but not the shapes of the polarization patterns. The absolute value in the differential cross section of elastically scattered deuterons is believed to be accurate to within 20%.

Figure 3 shows the results of the polarization measurement. For comparison the corresponding (d,p) differential cross sections taken from various sources are also displayed. In Fig. 4 are the (d,d) differential cross-section results.

IV. DISCUSSION

Before the advent of computer programs for distorted-wave calculations, several authors[1,24] have pointed out that the distorted-wave theory imposes some limitations on the polarization of protons emitted from (d,p) reactions. These "selection rules" may serve

[24] R. Huby, M. Y. Rafai, and G. R. Satchler, Nucl. Phys. **9**, 94 (1958/59).

TABLE V. $Mg^{24}(d,p)Mg^{25*}$(0.58 MeV).

$\theta_{c.m.}$ (deg)	P_1
10.5	$+0.094\pm0.044$
15.7	$+0.213\pm0.051$
21.0	$+0.057\pm0.062$
26.2	-0.206 ± 0.048
28.3	-0.235 ± 0.053
31.4	-0.136 ± 0.046
33.5	-0.133 ± 0.052
36.6	-0.162 ± 0.040
40.7	-0.200 ± 0.056
41.8	-0.189 ± 0.050
46.9	-0.357 ± 0.089
57.0	$+0.060\pm0.088$
58.0	-0.091 ± 0.088
62.5	-0.223 ± 0.060
72.7	-0.099 ± 0.064

TABLE VI. $Si^{28}(d,p)Si^{29*}$(1.28 MeV).

$\theta_{c.m.}$ (deg)	P_1	$\theta_{c.m.}$ (deg)	$\sigma(d,d)$ (mb/sr)
10.4	-0.178 ± 0.058	8.7	14000
15.6	-0.128 ± 0.062	14.0	3260
17.7	-0.181 ± 0.051	19.4	1320
20.8	-0.055 ± 0.051	24.7	310
25.0	-0.143 ± 0.055	30.0	88
28.0	-0.158 ± 0.055	35.3	54
31.2	$+0.019\pm0.059$	40.6	56
36.3	$+0.108\pm0.066$	45.8	42
42.5	$+0.160\pm0.075$	51.1	21
51.8	-0.169 ± 0.083	56.3	8.1
57.0	-0.306 ± 0.092	61.5	5.3
62.0	-0.244 ± 0.104	66.6	7.7
72.2	$+0.354\pm0.143$	71.8	8.7
		76.9	7.1
		82.0	2.2
		87.0	2.1
		92.0	1.6

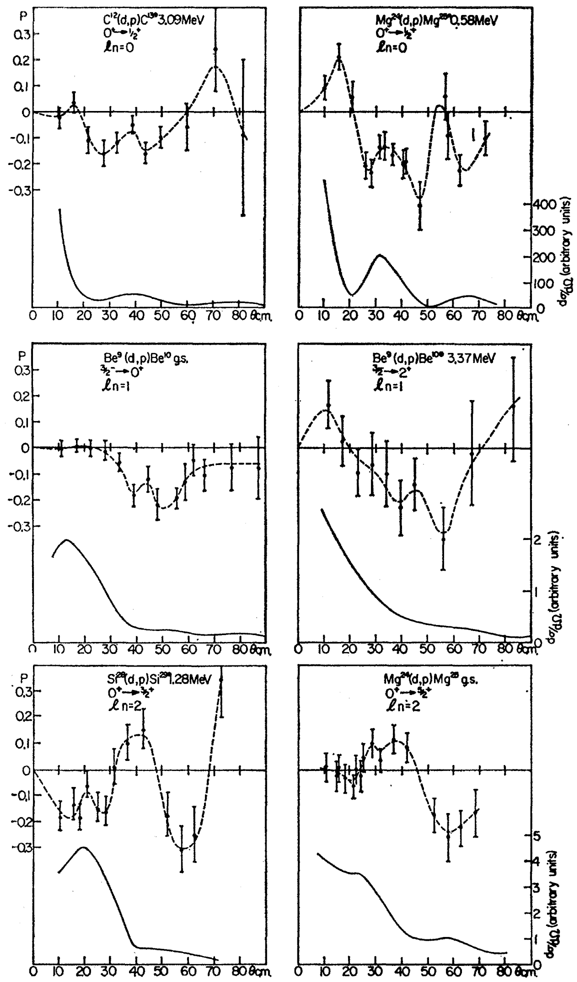

FIG. 3. Polarization and (d,p) differential cross section as a function of the center-of-mass scattering angle. The error bars indicate statistical uncertainties only. The dashed curves have no theoretical significance. The cross sections are from the following references:

$C^{12}(d,p)C^{13*}$ 3.09 MeV	J. N. McGruer, E. K. Warburton, and R. S. Bender, Phys. Rev. **100**, 235 (1955).
$Mg^{24}(d,p)Mg^{25*}$ 0.58 MeV	S. Hinds, R. Middleton, and G. Parry, Proc. Phys. Soc. (London) **71**, 49 (1958).
$Be^{9}(d,p)Be^{10}$ g.s. $Be^{9}(d,p)Be^{10*}$ 3.37 MeV	K. B. Rhodes, Ph.D. thesis, University of Pittsburgh, 1959 (unpublished).
$Si^{28}(d,p)Si^{29*}$ 1.28 MeV	A. G. Blair and K. S. Quisenberry, Phys. Rev. **122**, 869 (1961).
$Mg^{24}(d,p)Mg^{25}$ g.s.	See Ref. 34.

as a qualitative guide in the following discussion and are summarized in Table VII.

A. Reactions with $l_n=0$

1. $Mg^{24}(d,p)Mg^{25*}$(0.58 MeV)

This reaction corresponds to a transition from a 0^+ to a $\frac{1}{2}^+$ state and thus $l_n=0$. Figure 3 clearly shows that the polarization is different from zero and thus demonstrates the necessity of $\mathbf{l\cdot s}$ terms in the distorting potentials. This conclusion is only true if one assumes that the dominating reaction mechanism is the stripping process. A check on the validity of this assumption is provided by comparing the present data with the measurements carried out by Isoya *et al.*[2] at the same deuteron energy for the reactions; $Al^{27}(d,p)Al^{28}$(g.s.) and $Si^{28}(d,p)Si^{29}$(g.s.) (see Fig. 5). All three reactions correspond to a neutron orbital angular-momentum transfer of zero. The striking similarity in the angular

TABLE VII. Selection rules for the proton polarization in (d,p) reactions.

If l_n is:	and if the spin-orbit ($\mathbf{l\cdot s}$) term in the optical potential is	then the following restrictions are placed on the proton polarization
0	0	0
0	$\neq 0$	$\lvert P\rvert \leq 1$
$\neq 0$	0	$\lvert P\rvert \leq \frac{1}{3}l_n/(l_n+1)$ for $j_n=l_n+\frac{1}{2}$ $\lvert P\rvert \leq \frac{1}{3}$ for $j_n=l_n-\frac{1}{2}$
$\neq 0$	$\neq 0$	$\lvert P\rvert \leq 1$

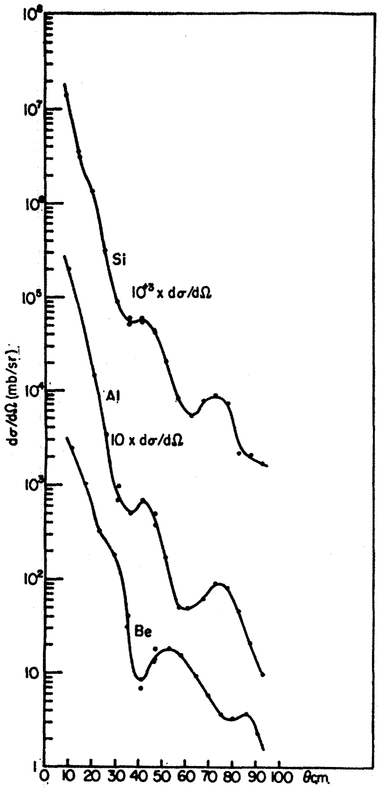

FIG. 4. The (d,d) differential cross section from silicon, aluminum, and beryllium at 15 MeV. The solid curve has no theoretical significance.

distributions of the polarization suggests that all three reactions proceed by the same mechanism (i.e., stripping). Some preliminary distorted-wave calculations have been performed by R. C. Johnson in collaboration with R. H. Bassel, R. M. Drisko, and G. R. Satchler by means of the latter's code Julie. In Fig. 5, the results of this calculation are compared with the present measurements on magnesium, as well as with the results obtained by Isoya *et al.*[2] on silicon and aluminum.

In the region of the first stripping peak the agreement is quite good, predicting correctly sign and magnitude of the polarization. Also the angle at which the polarization changes sign appears at about the right position. Around the second stripping peak, the sign of the polarization is correct but the magnitude of the theoretical polarization is appreciably larger than the measured values for magnesium and aluminum. A more detailed analysis by the Oak Ridge group is in progress.

Biedenharn and Satchler[25] have suggested that in a (d,p) reaction with zero orbital angular momentum transfer the proton polarization should be approximately proportional to the derivative of the differential cross section. The experimental data show that this rule gives roughly the angle at which the polarization changes the sign the first time but fails to be valid beyond the first stripping peak. For instance at the second stripping peak the polarization should change sign again but does not. However in all three cases there seems to be a decrease in the magnitude of the polarization in this region. The calculations do not reproduce these dips. In summary, the experimental data as well as explicit distorted-wave calculations show that the derivative rule is not an adequate approximation. The fact that the polarization changes sign at the first stripping minimum can be derived from much more general considerations than the ones which are necessary in order to derive the derivative rule.

2. $C^{12}(d,p)C^{13*}$(3.09 MeV)

The Chalk River group[26,27] has performed differential cross-section and polarization measurements in the 5- to 10-MeV region. They found the angular dependence of the polarization to be extremely energy dependent. In the same energy region they observed strong fluctuations in the magnitude of the differential cross section but the shape of the angular distribution did not change significantly. They concluded that the contribution from compound nucleus formation is significant and cannot be neglected. This is not surprising for an element as light as carbon with a bombarding energy around 8 MeV.

The present polarization measurements on the $C^{12}(d,p)C^{13*}$(3.09 MeV) reaction have been carried out at 15 MeV where one might expect the stripping process to be more dominant. In order to gain any evidence as to whether this is indeed the case, one would need to measure the energy dependence of the polarization around 15 MeV or investigate the polarization of some (d,p) reactions with $l_n=0$ in some nuclei in the same mass region. Preliminary distorted-wave calculations by the Oak Ridge group did not bear any resemblance with the experimental data.

B. $l_n>0$

The (d,p) reactions investigated in this category are summarized in Table VIII.

Thus far no systematic distorted-wave analysis has been performed for these cases.

TABLE VIII. Summary of reactions studied with $l_n>0$.

Reaction	Initial state	Final state	l_n	j_n
$Si^{28}(d,p)Si^{29*}$(1.28 MeV)	0^+	$\frac{3}{2}^+$	2	$\frac{3}{2}$
$Mg^{24}(d,p)Mg^{25}$(g.s.)	0^+	$\frac{5}{2}^+$	2	$\frac{5}{2}$
$Be^9(d,p)Be^{10}$(g.s.)	$\frac{3}{2}^-$	0^+	1	$\frac{3}{2}$
$Be^9(d,p)Be^{10}$(3.37 MeV)	$\frac{3}{2}^-$	2^+	1	$\frac{1}{2}, \frac{3}{2}$

[25] L. C. Biedenharn and G. R. Satchler, Helv. Phys. Acta, Suppl. VI, 372 (1961).

[26] E. Almqvist, J. E. Evans, and J. A. Kuehner, in *Proceedings of the International Symposium on Direct Interactions and Nuclear Reaction Mechanisms, Padua*, edited by E. Clementel and C. Villi (Gordon and Breach, Science Publishers Inc., New York, 1963), p. 629.

[27] J. E. Evans, J. A. Kuehner, and E. Almqvist, Phys. Rev. 131 1632 (1963).

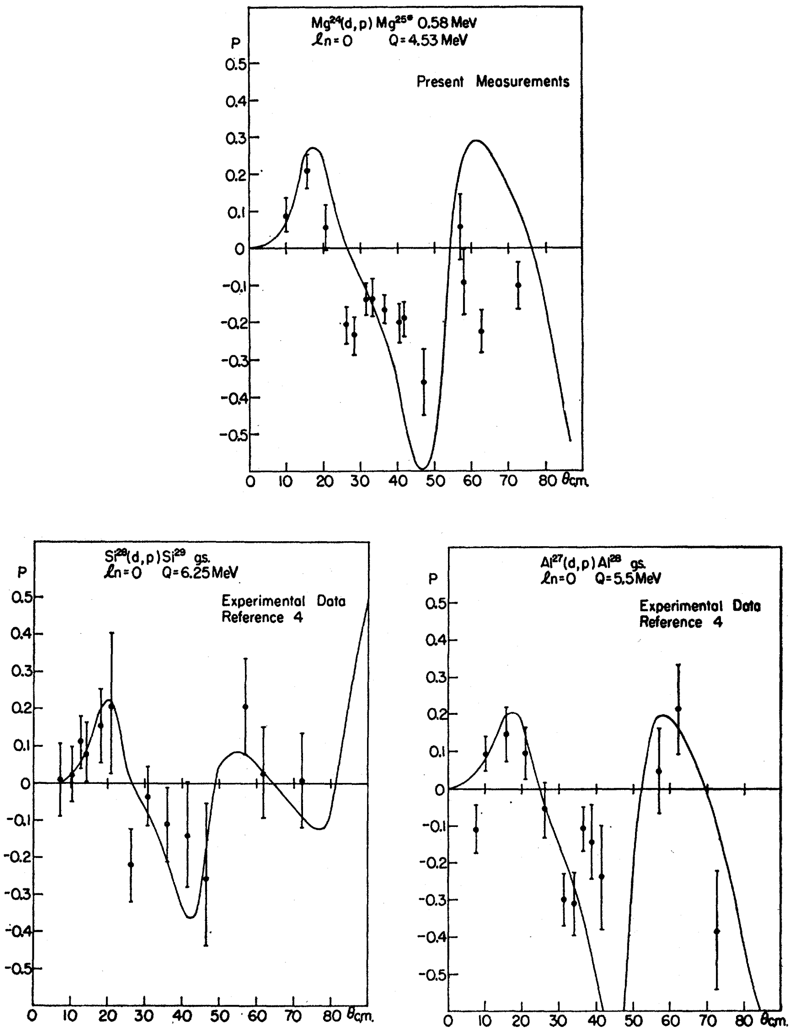

FIG. 5. Comparison of the polarization measurements on $Mg^{24}(d,p)Mg^{25*}$ (0.58 MeV), $Si^{28}(d,p)Si^{29}$ (g.s.) and $Al^{27}(d,p)Al^{28}$ (g.s.) reactions with preliminary distorted wave calculations performed by Bassel, Drisko, Johnson, and Satchler. All three reactions correspond to $l_n=0$.

On the basis of a semiclassical argument, Newns[1] and Tobocman[28] suggested that in the region of the first stripping peak the polarization for a $j_n=l_n+\frac{1}{2}$ transition should be of opposite sign to the polarization observed in a $j_n=l_n-\frac{1}{2}$ transition. Spin-orbit forces were neglected in the derivation of this rule. Huby *et al.*[24] have shown that if $\mathbf{l}\cdot\mathbf{s}$ terms are neglected, this rule follows directly from distorted-wave theory provided that the reactions under consideration have similar Q values and take place at the same energy and in the same mass region. It follows however, from the data on the $l_n=0$ reactions and from polarization measurements of elastically scattered protons that $\mathbf{l}\cdot\mathbf{s}$ terms must be taken into account. In the following, systematic differences in the polarization patterns between cases with $j_n=l_n+\frac{1}{2}$ and $j_n=l_n-\frac{1}{2}$ are investigated. Attention is focused around the first stripping peak, because one expects the differences to be most meaningful in this region.[29]

The first two reactions considered are $Si^{28}(d,p)Si^{29*}$ (1.28 MeV) with $l_n=2$ and $j_n=l_n-\frac{1}{2}$ and $Mg^{24}(d,p)Mg^{25}$ (g.s.) with $l_n=2$ and $j_n=l_n+\frac{1}{2}$.

In Si, relatively large negative polarization is found around the first stripping peak, whereas in Mg the polarization is very small and the sign rule does not seem to hold. The $Mg^{24}(d,p)Mg^{25}$(g.s.) differential cross section shows, however, a peculiar behavior around 15 MeV which casts some doubt upon the validity of the stripping assumption. At 10 MeV the differential cross section shows a pattern as expected from Butler theory for a $l_n=2$ transition with a minimum at 0°. At 15 MeV, however, the differential cross section no longer falls off at small angles.[30] Recent DWBA calculations have

[28] W. Tobocman, Technical Report No. 29, Case Institute of Technology, 1956 (unpublished).

[29] S. T. Butler, in *Proceedings of the Rutherford Jubilee International Conference*, edited by J. E. Burke (Heywood and Company, Ltd., Manchester, 1962), p. 492.

[30] E. W. Hamburger and A. G. Blair, Phys. Rev. **119**, 777 (1960).

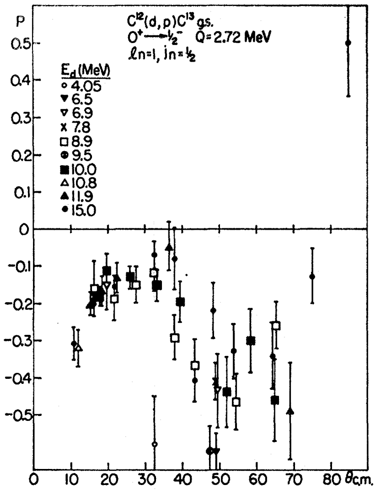

FIG. 6. Summary of experimental proton polarization measurements on the $C^{12}(d,p)C^{13}$(g.s.) reaction at various incident deuteron energies. The reaction corresponds to a $j_n=\frac{1}{2}$ case. The energy and the corresponding references are as follows:

E_d(MeV)	Reference
4.05	P. Hillman, Phys. Rev. **104**, 176 (1956).
6.5 9.5	J. E. Evans, J. A. Kuehner, and E. Almqvist (see Refs. 30 and 31).
6.9	B. Hird, J. A. Cookson, and M. S. Bokhari, Proc. Phys. Soc. (London) **72**, 489 (1958).
7.8	J. C. Hensel and W. C. Parkinson, Phys. Rev. **110**, 128 (1958).
8.9	M. S. Bokhari, J. A. Cookson, B. Hird, and B. Wessakul, Proc. Phys. Soc. (London) **72**, 88 (1958).
10.0	R. G. Allas and F. B. Shull, Phys. Rev. **116**, 996 (1959).
10.8	W. P. Johnson and D. W. Miller, Phys. Rev. **124**, 1190 (1961).
11.9	A. C. Juveland and W. Jentschke, Phys. Rev. **110**, 456 (1958).
15.0	A. Isoya, S. Micheletti, and L. H. Reber, Phys. Rev. **128**, 806 (1962).

indeed shown a rise in $d\sigma/d\Omega$ at 0° but no detailed fit has yet been performed.[31]

Another comparison can be made between the present $Be^0(d,p)Be^{10}$(g.s.) measurements and the data obtained by Isoya *et al.*[3] on the $C^{12}(d,p)C^{13}$(g.s.) reaction. The former corresponds to a transition with $l_n=1$ and $j_n=l_n+\frac{1}{2}$, whereas in the latter $l_n=1$ and $j_n=l_n-\frac{1}{2}$.

There is good evidence to believe, that in spite of the small mass number of the elements involved, both reactions go mainly via the stripping process. The differential cross section in both cases exhibits a pattern typical for stripping. But more important, the angular distributions of the polarization seem to be rather energy independent. In Fig. 6 is a summary of all experimental data on the $C^{12}(d,p)C^{13}$(g.s.) reaction. For angles less than 40° all the measurements between 4 and 15 MeV seem to agree within the experimental error bars.

For the $Be^9(d,p)Be^{10}$(g.s.) reaction there exist besides the present 15-MeV data, measurements carried out by Boschitz[32] at 21 MeV. The polarization pattern at 21 MeV is very similar to the one at 15 MeV, indicating that the polarization is a rather smooth function of energy. In the C^{12} reaction the polarization is relatively large and negative around the first stripping peak; in Be^9, however, it is zero within the error bars. This again indicates that the sign rules does not hold.

It is interesting to note, that for l_n values of one *and* two, a large negative polarization is observed at small angles if $j_n=l_n-\frac{1}{2}$ whereas for $j_n=l_n+\frac{1}{2}$ the polarization is small. If this distinct difference should prove to be systematic, it may be used for the determination of j_n values for a given l_n. Such a procedure is expected to be very reliable if states of the same l_n in the same nucleus are investigated.

C. $Be^9(d,p)Be^{10*}$(3.368 MeV)

This reaction corresponds to a transition from a $\frac{3}{2}^-$ to a 2^+ state; l_n is equal to one and j_n can now assume the values $\frac{1}{2}$ and $\frac{3}{2}$. There is considerable interest in the relative strength of the two reaction channels.[33]

In Fig. 3 one notices that the proton groups leading to the first excited state and ground state in Be^{10} exhibit a very similar angular dependence of the polarization. Essentially the same behavior was found at 21 MeV.[32] In both cases the polarization is very small for small angles. In the $Be^9(d,p)Be^{10}$(g.s.) reaction $j_n=\frac{3}{2}$. This, together with the evidence from Sec. IVB, indicates that the $Be^9(d,p)Be^{10*}$(3.37 MeV) reaction takes place predominantly through the $j_n=l_n+\frac{1}{2}=\frac{3}{2}$ channel. This is in contradiction to the conclusion reached by Hird and Strzalkowski[34] who measured the relative sign of the polarization of the two proton groups at 39.6° and at 50.7° for a bombarding energy of 6 MeV. Their reasoning was based on the sign rule.

ACKNOWLEDGMENTS

We are very much indebted to R. C. Johnson, R. H. Bassel, R. M. Drisko, and G. R. Satchler for the permission to show the results of their DW calculations prior to publication. We are also very grateful for many discussions and suggestions we received from R. C. Johnson, N. Austern, R. Drisko, and G. Satchler. We acknowledge the assistance of H. Woodcock who designed the helium cell and performed most of the measurements carried out with the helium cell. Thanks are due to A. J. Allen and J. H. McGruer for helpful criticism and encouragement in all phases of this work. We are very much indebted to the cyclotron staff, especially W. B. Leonard and J. DeFrancesco.

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