Polarization of Protons from $B^{10}(d,p)B^{11}$, $C^{12}(d,p)C^{13}$, and Spin-Flip Stripping*

J. C. HENSEL AND W. C. PARKINSON
Harrison M. Randall Laboratory of Physics, University of Michigan, Ann Arbor, Michigan
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The polarization of proton groups corresponding to the ground and first excited states in the reactions $B^{10}(d,p)B^{11}$ and $C^{12}(d,p)C^{13}$ have been measured for an incident deuteron energy of 7.8 Mev. With the exception of the first excited state of B^{11}, the sign of the polarization for six known cases is consistent with the relation $P=(\pm)$ when $j_n=l_n\mp\frac{1}{2}$, the axis of quantization being defined by $\mathbf{n}=\mathbf{k}_p\times\mathbf{k}_d$. The anomalous polarization of the first excited state of B^{11} is interpreted as evidence for a spin-flip exchange process in the stripping reaction.

I. INTRODUCTION

THE deuteron stripping reaction, since the formulation of the Butler theory, has proved to be a valuable tool for the nuclear spectroscopist because it usually allows the determination of the orbital angular momentum l_n carried into the nucleus by the captured nucleon. The total angular momentum transfer $j_n=l_n\pm\frac{1}{2}$, however, remains indeterminate within $\pm\frac{1}{2}$ unit. A measurement of the polarization of the protons (or neutrons) can provide the additional information necessary to specify the value of j_n.

Calculations of the polarization have been reported by Newns,[1] Messiah and Horowitz,[2] and Cheston[3] with refinements added by Hittmair[4] and Sawicki.[5] Since the polarization vanishes in the simple Born approximation in which plane waves are assumed for the incoming deuterons and outgoing protons, the distinguishing feature of these calculations with respect to the sign and magnitude of the polarization is the choice of proton scattering potential. In the semiclassical model of Newns, which assumes a nucleus opaque to protons, and the hard-sphere nuclear model of Messiah and Horowitz, the polarization is a direct consequence of the proton alignment by the stripping process and has as its maximum value $|P|=\frac{1}{3}$. The sign predicted by both models is $P=(\pm)$ when $j_n=l_n\pm\frac{1}{2}$ for capture into a unique orbital. The sign is here defined relative to the axis of quantization $\mathbf{n}=\mathbf{k}_p\times\mathbf{k}_d$ where $\mathbf{k}_p$ and $\mathbf{k}_d$ are the wave vectors of outgoing protons and incoming deuterons, respectively.

In the calculation of Cheston the incoming deuterons are assumed to be scattered by a hard-sphere potential and the outgoing protons by an attractive optical-model potential plus a spin-orbit potential. Explicit calculations have been made only for the reaction $C^{12}(d,p)C^{13}{}_0$ at a deuteron energy of 3.29 Mev, where the subscript 0 indicates that the residual nucleus is left in its ground state. For this particular case the sign is opposite that predicted by Newns and by Messiah and Horowitz and the magnitude remains below $\frac{1}{3}$ for the angular range calculated (0° to 40°). In general, however, even though the sign and limiting value are not evident, the spin-orbit potential can presumably give rise to a polarization greater than $\frac{1}{3}$.

Measurements of polarization in stripping have been reported for the reaction $C^{12}(d,p)C^{13}{}_0$ at a deuteron energy of 4.0 Mev by Hillman[6] and for the groups from $C^{13}{}_0$, $C^{13}{}_{(3.86\text{ Mev})}$, $Si^{29}{}_{(4.93\text{ Mev})}$, and $Si^{29}{}_{(6.38\text{ Mev})}$ (the subscript referring to the energy of excitation in Mev of the residual nucleus) at a deuteron energy of 11.9 Mev by Juveland and Jentschke.[7] The polarization from $C^{13}{}_0$ was measured at several angles and the results indicate an angular dependence which increases to $|P|\sim0.5$ near 70°. Such a large polarization is significant in that it cannot be produced by a spin-independent scattering potential alone.

The purpose of the present investigation was to determine the polarization of several proton groups from the reactions $B^{10}(d,p)B^{11}$ and $C^{12}(d,p)C^{13}$ and in particular to determine the sign of the polarization with respect to the sign of coupling $j_n=l_n\pm\frac{1}{2}$ of the captured nucleon. Should a definite relationship exist, polarization measurements would then permit the determination of the total angular momentum transfer j_n. Further, it is to be hoped that as additional data become available, the nature of the nuclear interactions will become more evident and a successful theory of polarization in stripping will evolve.

The polarization measurements for the first excited state of B^{11}, of particular interest because of their implications with regard to the exchange and spin-flip processes in the stripping reaction, are discussed in Sec. V.

II. EXPERIMENTAL METHOD AND APPARATUS

The polarization of the protons was determined by an He^4 analyzer,[8] the protons being elastically scattered at an energy near the $p_{\frac{3}{2}}$ resonance of Li^5.

* This work was supported in part by the U. S. Atomic Energy Commission.
[1] H. C. Newns, Proc. Phys. Soc. (London) **B66**, 477 (1953).
[2] J. Horowitz and A. M. L. Messiah, J. phys. radium **14**, 731 (1953).
[3] W. B. Cheston, Phys. Rev. **96**, 1590 (1954).
[4] O. Hittmair, Z. Physik **144**, 449 (1956).
[5] J. Sawicki, Phys. Rev. **106**, 172 (1957).
[6] P. Hillman, Phys. Rev. **104**, 176 (1956).
[7] A. C. Juveland and W. Jentschke, Bull. Am. Phys. Soc. Ser. II, **1**, 193 (1956). The values quoted in this reference have been superseded by those given by Juveland [thesis, University of Illinois, 1956 (unpublished)].
[8] M. Heusinkveld and G. Freier, Phys. Rev. **85**, 80 (1952); M. J. Scott and R. E. Segel, Phys. Rev. **100**, 1244 (1955); A. C.

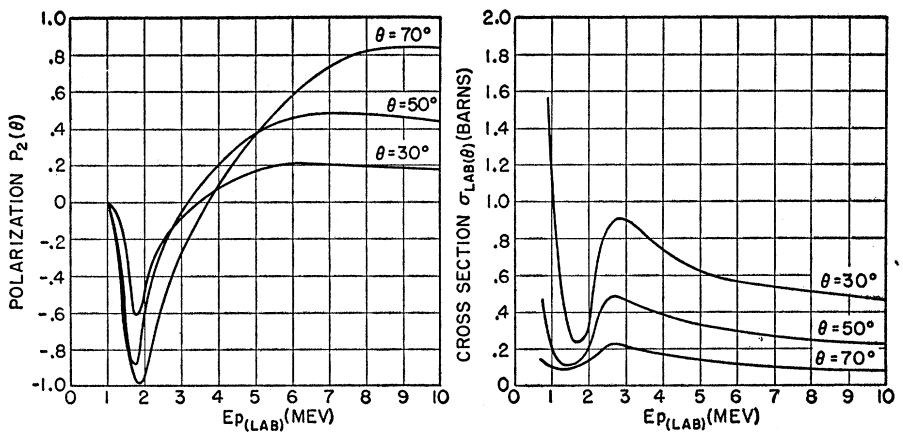

FIG. 1. The differential cross section $\sigma(\theta)$ and polarization $P_2(\theta)$ for $p-\alpha$ scattering calculated from experimental phase shifts up to and including d waves.

The differential cross section $\sigma(\theta,\phi)$ for the elastic scattering of a proton beam of polarization $\mathbf{P}_1$ is[9]

$$\sigma(\theta,\phi)=\sigma_0(\theta)[1+\mathbf{P}_1\cdot\mathbf{n}_2P_2(\theta)], \tag{1}$$

where $\sigma_0(\theta)$ is the cross section for a nonpolarized beam and $\mathbf{n}_2P_2(\theta)$ is the polarization produced in the outgoing beam by the scattering of a nonpolarized beam. The unit vector $\mathbf{n}_2$ representing the plane of the second scattering is defined by

$$\mathbf{n}_2 \sin\theta=\mathbf{k}_{p2}\times\mathbf{k}_{p1}, \tag{2}$$

where $\mathbf{k}_{p1}$ and $\mathbf{k}_{p2}$ are unit vectors in the direction of the incoming and outgoing proton momenta. If the polarization $\mathbf{P}_1$ is normal to $\mathbf{k}_{p1}$, then both its magnitude and direction are determined by a measurement of the asymmetry

$$e=\mathbf{P}_1\cdot\mathbf{n}_2P_2(\theta)=P_1P_2(\theta)\sin\phi, \tag{3}$$

provided $P_2(\theta)$ is known, and where the azimuthal angle ϕ is referred to an axis parallel to $\mathbf{P}_1$.

The differential cross section $\sigma(\theta)$ and $P_2(\theta)$ for the $p-\alpha$ scattering, computed using the method of Lepore[9] and the phase shifts compiled by Juveland and Jentschke,[8] are plotted in Fig. 1 for a number of scattering angles $\theta_{\rm lab}$ over the energy range $E_{p(\rm lab)}=1$ to 10 Mev. The scattering angle $\theta_{\rm lab}=50°$ used in the measurements is a compromise between a high cross section at low angles and a high polarization at angles near 90°. An incident proton energy of 7.0 Mev was selected since at that energy the polarization curve is relatively flat. The scattering angle and energy chosen determine the parameter $P_2=+0.48$.

The over-all experimental arrangement is shown in Fig. 2. The 7.8-Mev deuteron beam from the cyclotron was focused through a $\frac{3}{8}$-in. circular stop onto the target in the first scattering chamber. Protons from the (d,p) reaction scattered at an angle θ_1 were defined by a second $\frac{3}{8}$-in. circular stop and slowed to an energy of 8.5 Mev by lead and aluminum absorbers before entering the quadrupole lenses. The lead foils were used at the small scattering angles to stop the deuterons and prevent reactions in the aluminum. The protons focused by the lenses passed through a $3\frac{1}{2}$-in. diam. aperture in a paraffin shield and were bent by the field of the low resolution analyzer magnet through an angle of 17°. The proton beam was further collimated by a $\frac{1}{2}$-in. circular stop and slowed by foils to a mean energy of 7.0 Mev before entering the second scattering chamber which contained helium at a pressure of 20 atmospheres. Those protons elastically scattered from the helium into a solid angle of 0.04 steradian at the angle $\theta_{\rm lab}=50°$ were detected in eight nuclear emulsions arranged azimuthally around the direction of the incoming beam at regular intervals of 45°. Since the protons from the stripping reaction are polarized normal to the scattering plane, the vector $\mathbf{n}_1=\mathbf{k}_p\times\mathbf{k}_d$ for positive θ_1 has been chosen as a "vertical" direction to which the azimuthal angle ϕ in the second scattering is always referred. The nonscattered protons were collected in a proportional counter telescope which served as a monitor.

The first scattering chamber, constructed with a number of exit ports for measurements at different scattering angles, carried a proportional counter telescope mounted at 90° to the deuteron beam to assist in alignment of the system and adjustment of the focusing and analyzer magnets.

The enriched boron target (92% B^{10}) was prepared by painting a slurry of finely powdered boron suspended in acetone on a backing of 0.0001-in. thick gold foil. The target thickness of 13 mg/cm^2 corresponded to 500 kev deuteron energy loss at 7.8 Mev. The carbon target was prepared by spraying Aquadag suspended in alcohol onto a 0.0001-in. gold foil to a thickness of 8 mg/cm^2 corresponding to 300 kev deuteron energy loss. The targets were mounted in the scattering chamber with their plane inclined at 20° with respect to the deuteron beam.

To determine whether proton groups due to impurities

Juveland and W. Jentschke, Z. Physik **144**, 521 (1956); L. Rosen and J. E. Brolly, Jr., Phys. Rev. **107**, 1454 (1957).

[9] J. V. Lepore, Phys. Rev. **79**, 137 (1950).

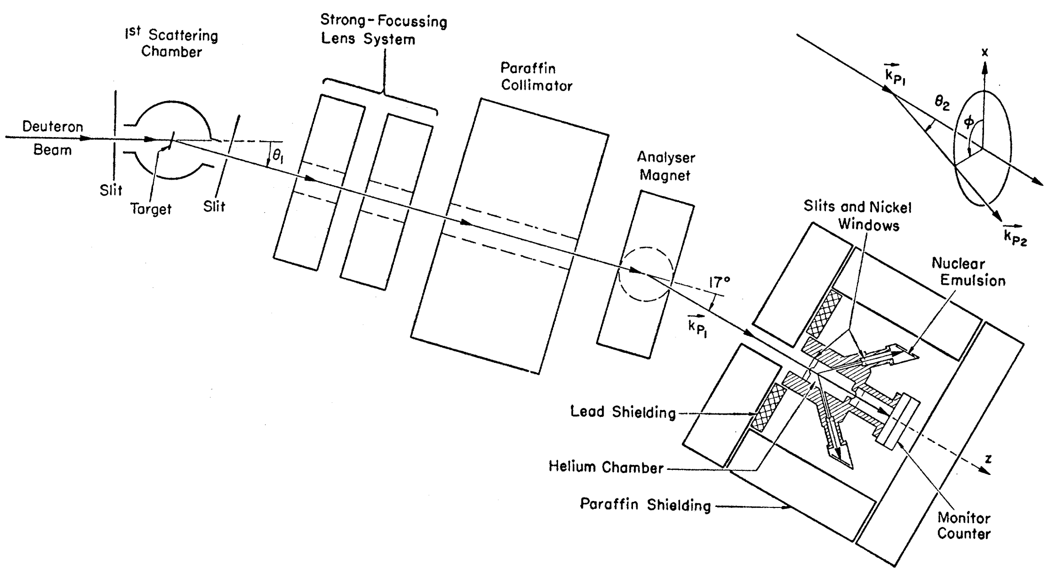

FIG. 2. The geometrical arrangement of the apparatus shown in cross section in the plane of the first scattering. The x axis of the coordinate system at the second scattering is directed perpendicularly out of the paper.

might be present to interfere with the weak group (which we call $B^{11}{}_1$) from the first excited state of B^{11}, a thin target of enriched boron was prepared by evaporation onto gold leaf, and the proton spectra obtained at 15° using the medium resolution magnetic analyzer.[10] With 30 kev resolution no groups were found within the energy region covered, 1000 kev below to 400 kev above the peak, that could be assigned to impurities except for a group 800 kev below with an intensity of 5% of the $B^{11}{}_1$ group which was identified as the ground state of Si^{29}.

The strong-focusing quadrupole lenses between the first and second scattering chamber permitted a large amount of shielding to be used between the two chambers with minimum loss of solid angle, the effective solid angle being increased by a factor of 50. Their design and operation was conventional except that the current through the second section was adjusted to permit focusing with unequal object and image distances. A small object distance affords maximum solid angle for the given (3 in.) lens aperture, but is limited by the onset of astigmatism at small object distances, the astigmatism preventing uniform illumination of the entrance slit at the second scattering chamber.

The magnet used as a low resolution analyzer was a 1/7 scale model of the 42-in. cyclotron and was altered to produce a uniform field of 700° gauss in the $1\frac{3}{8}$-in gap. In passing through the magnet the proton beam was deflected through 17°. The resolution of the combined focusing and analyzer magnet system was about 1 Mev, sufficient to separate the low-lying states of C^{13} and B^{11}. Because of the energy spread due to the thick targets, no advantage was to be gained in using a higher resolution.

The entrance and exit windows of the helium scattering chamber which contained helium at 20 atmos. pressure were 0.001-in. nickel foils $\frac{1}{2}$ in. in diameter. A series of circular slits at the entrance and within the chamber prevented multiple scattering of protons into the detectors from the windows, chamber walls, and slit edges. To minimize possible instrumental asymmetry due to misalignment of the beam, the nuclear plates were mounted as far from the helium chamber as was consistent with a reasonable solid angle. The space between the helium volume and the plates was evacuated to minimize the proton energy loss after the second scattering. The entire polarimeter was surrounded by a thick paraffin shield to reduce the neutron background and a lead shield to prevent fogging of the emulsions by gamma rays. The use of

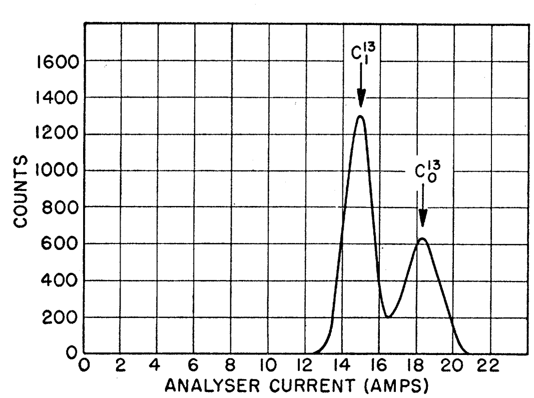

FIG. 3. The proton spectrum for $C^{12}(d,p)C^{13}$ with focusing magnets off.

[10] Bach, Childs, Hockney, Hough, and Parkinson, Rev. Sci. Instr. **27**, 516 (1956).

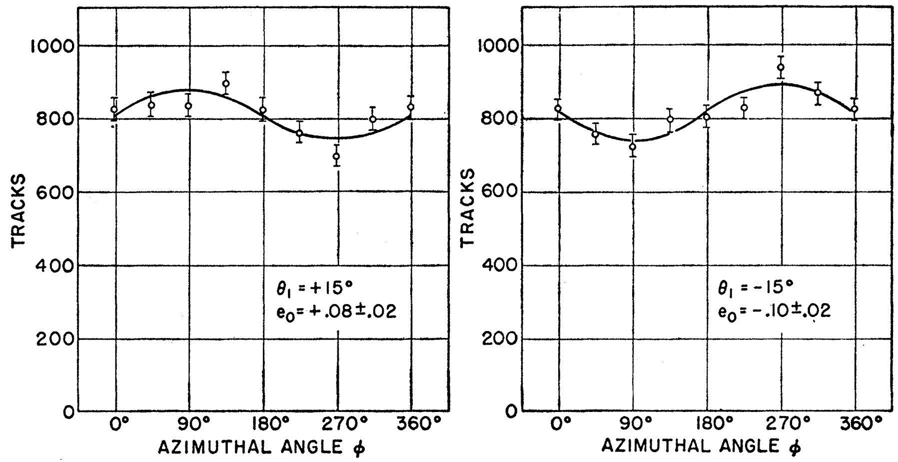

FIG. 4. The azimuthal asymmetry in the second scattering of protons from $C^{12}(d,p)C^{13}{}_0$ at $\theta_{lab}=15°$.

nuclear emulsions (100 μ Kodak NTB) afforded additional discrimination against the neutron background and was found necessary for weak proton groups. For strong groups, however, counters proved satisfactory. Two proportional counter telescopes were mounted 180° apart in azimuth and at a polar angle $\theta_{lab}=50°$ on a scattering chamber (not illustrated) constructed so as to allow rotation in angle ϕ about the axis of the incoming protons, thus permitting data to be taken simultaneously at two angles. By rotating the scattering chamber in steps of 45° an angular distribution, rather than just a "left-right" ratio, was obtained.

To reduce geometrical asymmetries the apparatus was carefully aligned using x-ray film to determine the beam pattern and position. Calculations show that under the most adverse conditions the maximum asymmetry from geometrical misalignment could be $e_0=0.05$ but with reasonably good alignment should be $e_0 \leq 0.01$.

In taking the data several runs were usually made without disturbing the geometry except for the necessary changes in targets, foils, and nuclear plates. The fact that no systematic skewness was observed in any series of runs indicates good stability of the apparatus.

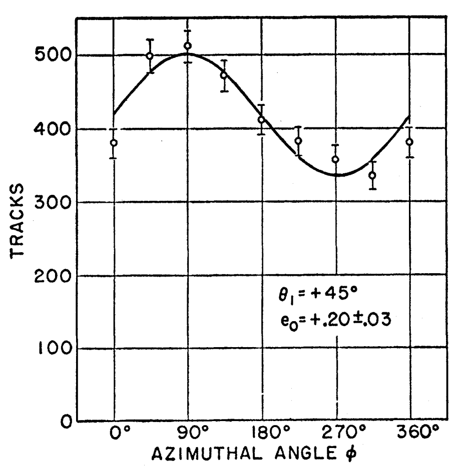

FIG. 5. The azimuthal asymmetry in the second scattering of protons from $C^{12}(d,p)C^{13}{}_0$ at $\theta_{lab}=45°$.

Geometrical asymmetries were further minimized by measuring the polarization at both (+) and (−) scattering angles. The asymmetry due to polarization reverses with the sign of θ_1 since the axis of quantization $\mathbf{n}_1=\mathbf{k}_p \times \mathbf{k}_d$ reverses. Geometrical asymmetries, on the other hand, are in general independent of the sign of θ_1 and are essentially removed by making measurements at both plus and minus angles.

After development the entire areas of the plates were scanned in 0.5-mm wide strips using an 8-mm oil immersion objective and 10× eyepieces. The tracks were judged carefully with regard to length, angle, and density. Background plates, exposed under identical conditions but with the helium chamber evacuated, were scanned in the same manner. The background was found to be negligible for all but the longest runs (30 hours) for which it approached 5% of the total count.

Using the method of least squares the resulting angular distribution was fitted by a curve $N=a+b\sin\phi$ from which the asymmetry amplitude $e_0=b/a$ was determined. The uncertainty associated with the data represents the standard deviation for counting errors only. By collecting the data at the eight angles the standard deviation in e_0 is improved by only slightly more than $1/\sqrt{2}$ compared to a "left-right" measurement but does provide additional information in the form of the phase of the sine curve. The lack of phase shift indicates a negligible amount of polarization rotation by magnetic fields or spurious asymmetries.

III. EXPERIMENTAL RESULTS

The spectrum of Fig. 3, obtained by varying the analyzer field with the focusing magnets turned off, shows the proton groups $C^{13}{}_0$ and $C^{13}{}_1$ from the ground and first excited states in the reaction $C^{12}(d,p)C^{13}$. The particles were detected by the double-proportional

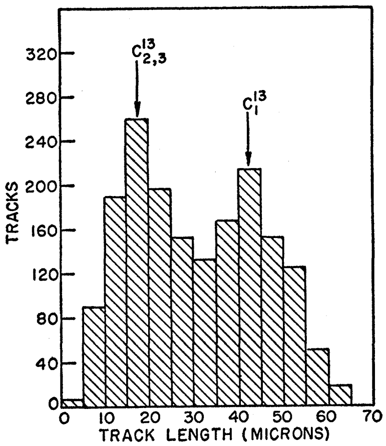

FIG. 6. The proton spectrum obtained by track-length analysis in nuclear emulsions.

monitor counter at the end of the helium scattering chamber. The scattering angle was $\theta_1=15°$, and the spectrum was taken with 65 mg/cm^2 of aluminum absorber in front of the counter to cut out the proton groups from the second and higher excited states and the scattering deuterons.

In measuring e_0 for the group from $C^{13}{}_0$, three steps were taken. First, the absorber foils were transferred from the test position in front of the monitor counter to a point preceding the helium chamber and adjusted to reduce the proton energy to 7.0 Mev at the second scattering. Second, the analyzer magnet was peaked on the proton group $C^{13}{}_0$. Finally, the focusing magnets were turned on and adjusted to their optimum operating point.

The data obtained at the angles, $\theta_1=\pm 15°$, are shown in Fig. 4 and those obtained at the scattering angle $\theta_1=+45°$, under similar conditions except for a reduction of absorbers and adjustment of magnets owing to the kinematic decrease of energy at the larger angle, are shown in Fig. 5.

An identical procedure was employed for the proton group from $C^{13}{}_1$. However, the resolution of the analyzer did not permit the separation of $C^{13}{}_1$ from $C^{13}{}_{2,3}$. All three groups were admitted into the helium scattering chamber and the resolution was effected at the detectors. At $\theta_1=-15°$, the two counter telescopes were used as detectors, and absorbers were placed in front of the counters to cut off the lower energy $C^{13}{}_{2,3}$ groups. Photographic plates were used at $\theta_1=+15°$ and $+45°$; and since the $C^{13}{}_{2,3}$ protons could not be removed by absorbers and still leave the $C^{13}{}_1$ protons with sufficient energy to traverse the full thickness of the emulsion, the groups were resolved by track-length analysis. The spectrum in histogram form is shown in Fig. 6. The results of the measurement of e_0 for the $C^{13}{}_1$ proton group at $\theta_1=\pm 15°$ are shown in Fig. 7 and at $+45°$ in Fig. 8. No asymmetry measurements were obtained for the unresolved $C^{13}{}_2$ and $C^{13}{}_3$ groups because the shortness of the tracks did not permit reliable scanning.

The proton spectrum for the enriched boron target, Fig. 9, was obtained as for the carbon target and shows the groups from $B^{11}{}_0$, $B^{11}{}_1$, and the unresolved $B^{11}{}_{2,3}$ levels. The results of the measurements of e_0 for the $B^{11}{}_0$ protons at $\theta_1=\pm 15°$ are shown in Fig. 10.

The spectrum obtained when the absorbers and magnets were adjusted to discriminate in favor of the $B^{11}{}_1$ group is shown in Fig. 11. The higher excited states were cut off by absorbers in front of the helium chamber. The admixture of ground state protons was reduced considerably by setting the analyzer on the low-energy side of the $B^{11}{}_1$ peak. This procedure, however, results in a nonuniform illumination of the entrance slit of the polarimeter. The edges of the entrance slit lie at the points labelled a and b in Fig. 11, and the proton distribution function corrected for the finite slit width is plotted as a dashed line under the spectrum. Because the proton intensity varies almost linearly between a and b the correction factor was easily calculated and found to be $e_0=+0.03$. Since the protons were deflected to the "left" by the analyzer for both angles $\theta_1=\pm 15°$, the sign of the correction term does not change and is to be subtracted from the measured asymmetries. Any uncertainty in the correc-

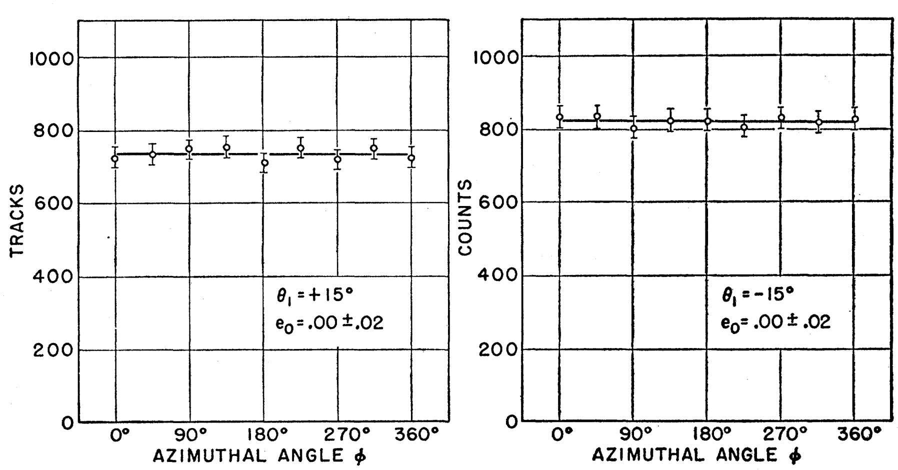

FIG. 7. The azimuthal asymmetry in the second scattering of protons from $C^{12}(d,p)C^{13}{}_1$ at $\theta_{lab}=15°$.

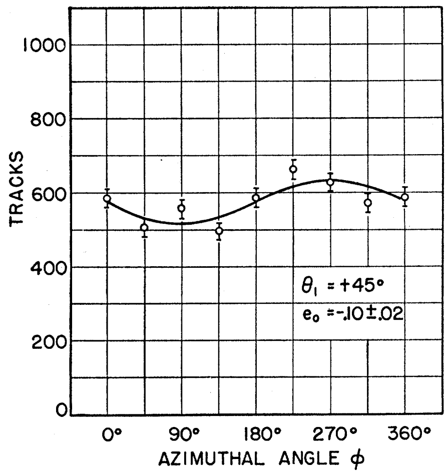

FIG. 8. The azimuthal asymmetry in the second scattering of protons from $C^{12}(d,p)C^{13}{}_1$ at $\theta_{lab}=45°$.

tion tends to cancel when the two measurements are averaged. In view of the somewhat uncertain nature of the correction, however, a higher standard deviation has been assigned to the final result. The uncorrected data for the asymmetry measurement from the group $B^{11}{}_1$ are plotted in Fig. 12.

The results of our measurements are summarized in Table I. The polarization was calculated from the asymmetry amplitude e_0 using Eq. (2) and the value $P_2=+0.48$.

IV. DISCUSSION

A striking feature of the results summarized in Table I is the correlation of the sign of the polarization in column 6 with the coupling sign of l_n and s_n in forming the total angular momentum j_n of the captured neutron. The values for l_n and j_n listed in columns 3 and 4 are taken from experimental results.[11] With the exception of $B^{11}{}_1$, an anomalous state discussed in

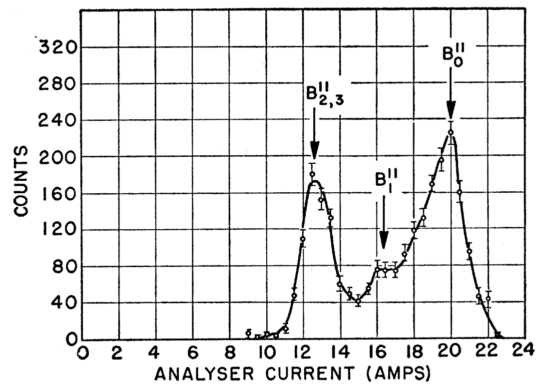

FIG. 9. The proton spectrum for $B^{10}(d,p)B^{11}$ with focusing magnets off.

TABLE I. Summary of present polarization measurements. Subscripts indicate the energy of excitation. $E_d=7.8$ Mev.

Final nucleus	l_n	j_n	$\theta_{1(lab)}$	Asymmetry e_0 (corrected)	Polarization P	Average polarization
$C^{13}{}_0$	1	$\frac{1}{2}$	+15°	+0.08±0.02	+0.17±0.04	+0.18±0.03
			−15°	−0.10±0.02	+0.20±0.04	
			+45°	+0.20±0.03	+0.41±0.05	+0.41±0.05
$C^{13}{}_{(3.09\ Mev)}$	0	$\frac{1}{2}$	+15°	0.00±0.02	0.00±0.04	0.00±0.03
			−15°	0.00±0.02	0.00±0.04	
			+45°	−0.10±0.02	−0.21±0.04	−0.21±0.04
$B^{11}{}_0$	1	$\frac{3}{2}$	+15°	−0.09±0.03	−0.18±0.05	−0.15±0.04
			−15°	+0.06±0.03	−0.12±0.05	
$B^{11}{}_{(2.14\ Mev)}$	1	$\frac{3}{2}$	+15°	+0.02±0.03	+0.04±0.05	+0.06±0.05
			−15°	−0.04±0.03	+0.08±0.05	

detail below, the signs are consistent with the relation $P=(\pm)$ when $j_n=l_n\mp\frac{1}{2}$, the axis of quantization being defined by $\mathbf{n}=\mathbf{k}_p\times\mathbf{k}_d$.

For an $l_n=0$ capture there can be no proton alignment from the "direct" stripping process, consequently, near the peak of the angular distribution the polarization might be expected to be small. The result $P=0.00\pm0.02$ for the protons from $C^{13}{}_1$ at $\theta=15°$ supports this conjecture.

The results of all published measurements of polarization in stripping are summarized in Table II. Each

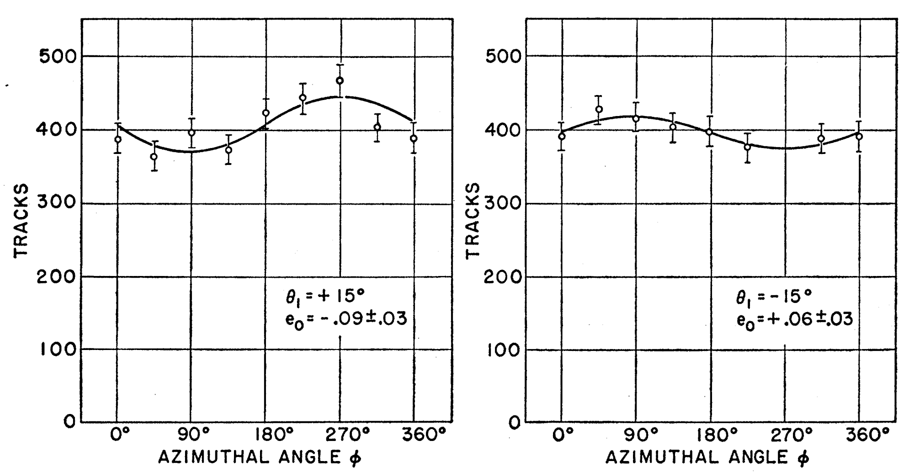

FIG. 10. The azimuthal asymmetry in the second scattering of protons from $B^{10}(d,p)$-$B^{11}{}_0$ at $\theta_{lab}=15°$.

[11] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955).

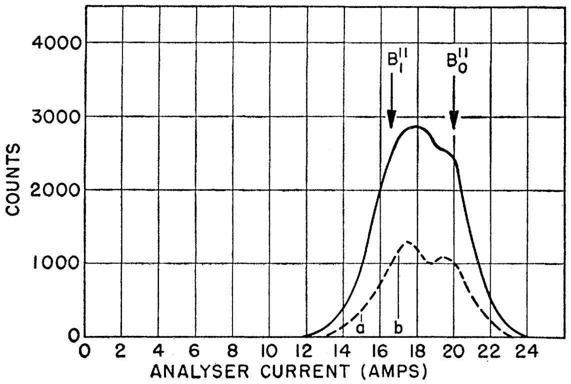

FIG. 11. The proton spectrum for $B^{10}(d,p)B^{11}$ with focusing magnets on is shown as a solid curve. The dashed curve is the proton distribution corrected for finite slit width with the points *a* and *b* marking the location of the edges of the entrance slit to the helium scattering chamber.

of the six "normal" states in B^{11}, C^{13}, and Si^{29} is consistent, near the stripping peak, with the sign rule suggested. While it is quite possible that the observed correlation is coincidental, should it prove to be a general rule, a measurement of the polarization in a stripping reaction would reduce the ambiguity in assigning a spin to the final nuclear state.

A knowledge of the angular dependence of the polarization should yield further specific information about the nuclear interactions in a (d,p) reaction. The polarization probably contains contributions from spin-independent interaction of the deuterons and protons with the initial and final nucleus, respectively, in addition to spin-dependent forces, exchange effects, and interference terms. Near the peak of the angular distribution where the "direct" stripping process usually predominates, a substantial contribution to the polarization would be expected from the alignment. Far from the peak, however, other polarization processes probably become significant and perhaps dominant. Further, at larger angles admixtures of other l values can result in the opposite sign of coupling and, consequently, reverse the sign of the stripping alignment contribution. The fact that at 45° the polarization for C^{13}_0 is larger than $\frac{1}{3}$ and the polarization for $C^{13}_{(3.09\ \mathrm{Mev})}$ is not zero presumably indicates the existence of processes other than "direct" stripping.

TABLE II. Summary of all polarization measurements referred to the quantization axis $\mathbf{n}=\mathbf{k}_p\times\mathbf{k}_d$. Subscripts indicate energy of excitation.

Final nucleus	E_d (Mev)	l_n	j_n	$\theta_{1(\mathrm{c.m.})}$	Polarization P	Reference
B^{11}_0	7.8	1	$\frac{3}{2}$	16.3°	−0.15±0.04	...
$B^{11}_{(2.14\ \mathrm{Mev})}$	7.8	1	$\frac{3}{2}$	16.4°	+0.06±0.05	...
C^{13}_0	4.05	1	$\frac{1}{2}$	32.5°	+0.58±0.13	a
C^{13}_0	7.8	1	$\frac{1}{2}$	16.5°	+0.18±0.03	...
C^{13}_0	7.8	1	$\frac{1}{2}$	49°	+0.41±0.05	...
C^{13}_0	11.9	1	$\frac{1}{2}$	15.5°	+0.20±0.04	b
C^{13}_0	11.9	1	$\frac{1}{2}$	18.5°	+0.17±0.04	b
C^{13}_0	11.9	1	$\frac{1}{2}$	22.5°	+0.13±0.04	b
C^{13}_0	11.9	1	$\frac{1}{2}$	36.5°	+0.05±0.06	b
C^{13}_0	11.9	1	$\frac{1}{2}$	68.8°	+0.49±0.13	b
$C^{13}_{(3.09\ \mathrm{Mev})}$	7.8	0	$\frac{1}{2}$	16.8°	0.00±0.03	...
$C^{13}_{(3.09\ \mathrm{Mev})}$	7.8	0	$\frac{1}{2}$	50°	−0.21±0.04	...
$C^{13}_{(3.86\ \mathrm{Mev})}$	11.9	2	$\frac{5}{2}$	37.0°	−0.04±0.05	b
$Si^{29}_{(4.93\ \mathrm{Mev})}$	11.9	1	$\frac{3}{2}$	14.5°	−0.10±0.03	b
$Si^{29}_{(6.38\ \mathrm{Mev})}$	11.9	1	$\frac{1}{2}$	14.5°	+0.06±0.04	b

[a] See reference 6.
[b] See reference 7.

The observed sign of the polarization for C^{13}_0 is in agreement with the calculation of Cheston, and for all the data it is opposite that predicted by Newns[1] and by Messiah and Horowitz.[2] This suggests that an attractive scattering potential similar to that employed by Cheston rather than the repulsive potential assumed by the other authors is the more likely. Such an attractive spin-independent potential alone, however, cannot account for the observed polarization magnitudes greater than $\frac{1}{3}$. Since Cheston's calculations for C^{13}_0 have not as yet been extended to angles as large as $\theta_1=45°$, nor to energies as high as 7.8 Mev, they cannot be compared directly with experiment.

The results obtained for C^{13}_0 at $\theta_1=15°$ would appear to agree with the data of Jentschke and Juveland, although such agreement may not be significant in

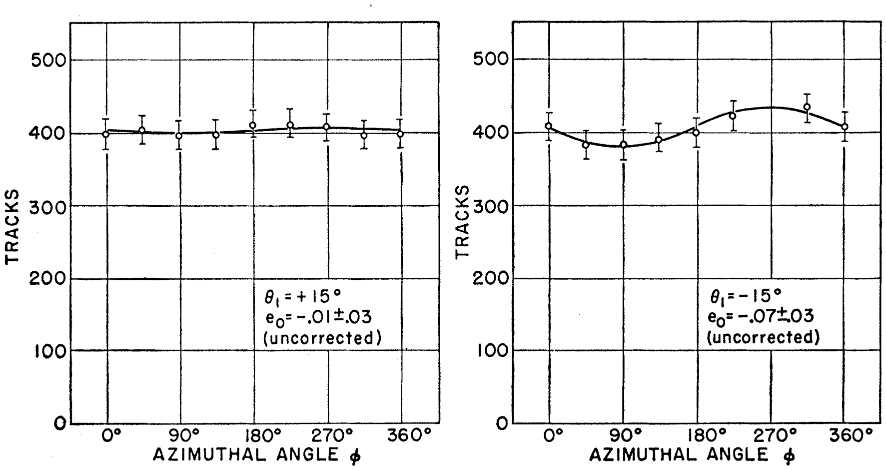

FIG. 12. The azimuthal asymmetry in the second scattering of protons from $B^{10}(d,p)$-B^{11}_1 at $\theta_{\mathrm{lab}}=15°$.

view of the difference in deuteron energy. The large polarization measured for $C^{13}{}_0$ at $\theta_1=45°$ is also consistent with the large values obtained by Hillman at 30° and Jentschke and Juveland at 68.5°.

V. SPIN-FLIP STRIPPING

Of the measurements reported here the only level whose spin and parity are uncertain is the first excited state of B^{11}, a fact which motivated its study. The conflict in the interpretation of the large amount of data available on this state has already been discussed by Wilkinson.[12] Briefly, the only conflicting evidence to the assignment of $J=\frac{1}{2}^-$ is the interpretation of the angular distributions from the reactions $B^{10}(d,p)B^{11}$ and $B^{10}(d,n)C^{11}$. The angular distribution obtained by Evans and Parkinson[13] for $B^{10}(d,p)B^{11}{}_1$ can be interpreted as a capture of a neutron with $l_n=1$. Since the spin of B^{10} is known to be $J=3^+$, the direct stripping process restricts the spin of the final state to $3/2^- \leq J \leq 9/2^-$. The interpretation of the angular distribution as $l_n=1$ was originally subject to some doubt due to the unusual shape of the curves. Recent high resolution measurements[14] reproduce the shape of these curves. Further, measurements of the mirror reaction $B^{10}(d,n)$-$C^{11}{}_1$ by Cerineo[15] and by Maslin, Calvert, and Jaffe[16] yield neutron angular distributions characteristic of $l_p=1$.

Although a direct Butler-type stripping process is forbidden, the conflicting evidence can be explained plausibly by assuming an exchange process[17] in which the spin orientation of the outgoing (observed) particle is reversed imparting an angular momentum change $\Delta S=1$ to the residual nucleus thus extending the range of possible character for the final states $B^{11}{}_1$ or $C^{11}{}_1$ to $\frac{1}{2}^- \leq J \leq 11/2^-$. None of the existing data are contradicted by this assumption, even though the exact nature of the mechanism responsible for the spin-flip is not clear. If the spin of $B^{11}{}_1$ is indeed $\frac{1}{2}^-$, then the stripping reaction must proceed either by an $l_n=3$ capture or by the spin-flip process with zero contribution from the direct (nonexchange) process. The angular distribution certainly suggests capture with $l_n=1$ and only a small amount of f-shell admixture ($l_n=3$). Additional support of the idea is supplied by the calculations of Evans and French,[17] for a spin-flip process with $l_n=1$, which predict an angular distribution not greatly different from that measured.[14] If the reaction does proceed via the spin-flip process the sign of the polarization of the outgoing protons should be just opposite that for the direct process.

The measured sign for the proton group from $B^{11}{}_1$ (Table I) is, in fact, just opposite that of $B^{11}{}_0$, thus supporting the spin-flip hypothesis and the assignment of $\frac{1}{2}^-$. The magnitude is significantly smaller than for $B^{11}{}_0$ or $C^{13}{}_0$ at the same scattering angle. This may be due to the incomplete separation in the experimental arrangement of the proton groups from the ground and first excited states, but it also suggests an interference between the polarization contributions from pure potential scattering which will reverse sign with spin-flip and from spin-dependent scattering which would not change sign. It might also be observed that for any reaction which can proceed by both the direct and the exchange spin-flip processes the magnitude of the polarization will be reduced.

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