(d,p) Polarization Measurements of Excited-State Reactions*

W. P. JOHNSON† AND D. W. MILLER
Department of Physics, Indiana University, Bloomington, Indiana
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A helium gas polarimeter has been built for use in conjunction with a heavy-particle magnetic spectrometer, which allows measurements to be made of the polarizations of proton groups corresponding to nearby nuclear states. The polarimeter was calibrated by measuring the left-right asymmetry of second-scattered recoil protons from a hydrogen target bombarded by 21.8-Mev alpha particles. The following (d,p) polarizations were measured at a deuteron energy of 10.8 Mev and a laboratory scattering angle of 12.5°, listed according to the residual nuclear state and using the quantization axis $\mathbf{n}=\mathbf{k}_d\times\mathbf{k}_p$. C^{13} ground state: -0.32 ± 0.05; C^{13} 3.09-Mev state: $+0.03\pm0.04$; Mg^{25} 3.40-Mev state: -0.05 ± 0.05; Ca^{41} 1.95-Mev state: $+0.014\pm0.043$; Ca^{41} 3.95-Mev state: -0.21 ± 0.05. The Mg result agrees within experimental errors with the polarization magnitude predicted by Martin *et al.* from $(d,p\gamma)$ angular correlation measurements made at a slightly different angle. If the two Ca states investigated are p-neutron states with $j=\frac{3}{2}$ and $\frac{1}{2}$, respectively, Huby *et al.* have shown that the ratio of the corresponding proton polarizations should be -0.5. The experimental ratio, which is subject to large error because of the near zero result for the 1.95-Mev state, is $-0.07_{-0.28}^{+0.18}$. This discrepancy may indicate the importance of spin-orbit forces in the distorting potentials.

I. INTRODUCTION

THE theory of the deuteron stripping reaction has enjoyed wide application to experimental nuclear physics. In its original formulations,[1,2] the qualitative features of the angular distributions of the emerging nucleons were predicted successfully by describing the incoming deuteron and outgoing nucleon by their plane-wave asymptotic limits. The forward peak of the experimental angular distributions in general agreed very well with the simple theory, and unambiguous assignments of the orbital angular momentum transfers were usually possible by such comparisons.

In an effort to account for the discrepancy between theory and experiment at angles beyond the first maximum of the angular distribution, several authors[3–5] tried to improve the stripping theory by using wave functions distorted by the nuclear and Coulomb potentials to describe the incoming and outgoing particles. One of the consequences of such a distorted-wave analysis is that the outgoing nucleons are expected to be polarized.[6,7] A number of measurements of the polarization of the protons produced in (d,p) reactions[8–14] have shown this to be true. Up until the present writing, the polarization has with two exceptions been found to to be in agreement with a semiclassical description[7] in which the distortion of the incident deuteron wave is greater than the distortion of the outgoing proton wave. Using the Basel sign convention for polarizations ($\mathbf{n}=\mathbf{k}_d\times\mathbf{k}_p$), this description results in the sign rule $P=\pm$ when the captured neutron has total angular momentum $j=l\pm\frac{1}{2}$. The two exceptions reported are the ground-state transitions in the reactions $B^{10}(d,p)$,[13] and $Ca^{40}(d,p)$.[11,13] An additional exception is suggested by the present work.

One of the difficulties with distorted-wave theories from an experimental standpoint is that the actual comparisons between theory and experiment require extensive computer calculations which are rather sensitive to the details of the distorting potentials chosen. Huby *et al.*[15] have presented a general treatment of distorted-wave theory in which they propose experimental tests which are independent of the details of the distortions. These tests concern the relation between the $(d,p\gamma)$ angular correlations and the proton polarizations; if satisfied they allow measurements of these quantities to establish experimentally the amount of distortion present in a particular reaction.

One crucial assumption made in the description by Huby *et al.* is that there are no spin-dependent forces present in the distorting potentials. That such forces should be of minor importance in stripping polarizations had also been suggested by the earlier work of Newns and Refai.[3] However, this point has been discussed by Austern,[16] who maintained that the spin-orbit force in the distorting potential should in general be important.

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† Now at the University of Colorado, Boulder, Colorado.
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[16] N. Austern, *Fast Neutron Physics*, edited by J. B. Marion and J. L. Fowler [Interscience Publishers, Inc., New York (to be published)], Part II, Chap. V.D.

Very recent theoretical calculations[17–19] indeed show this force to give a very sizable contribution. The results of the following discussion of the paper by Huby *et al.*[15] are therefore placed in some doubt because of the neglect of such forces. The present experiment was carried out in an attempt to verify the predictions of Huby *et al.* before these recent theoretical developments became known. Since the results appear to disagree rather seriously with one of the predictions of Huby *et al.*, they may indeed indicate experimental evidence for the importance of spin-dependent forces.

With the assumption that there are no spin-dependent forces present in the distorting potentials, Huby *et al.* show that the component of the polarization of the proton spin in the direction of the quantization axis $\mathbf{n}=\mathbf{k}_d\times\mathbf{k}_p$ is given by

$$P(\mathbf{k}_p,\mathbf{k}_d)=\frac{1}{3}\left[\frac{\theta_{l+\frac{1}{2}}^2}{l+1}-\frac{\theta_{l-\frac{1}{2}}^2}{l}\right]\frac{\langle m\rangle}{(\theta_{l+\frac{1}{2}}^2+\theta_{l-\frac{1}{2}}^2)},\qquad(1)$$

for the case in which only one value of l is necessary to describe the orbital angular momentum of the captured neutron. In this equation, the θ_j^2 represent the reduced widths corresponding to total angular momentum transfer $j=l\pm\frac{1}{2}$. The quantity $\langle m\rangle$ is the mean value of the orbital angular momentum l along the quantization axis, and is given by

$$\langle m\rangle=(\textstyle\sum_m m|B_{lm}|^2)/(\sum_m|B_{lm}|^2),\qquad(2)$$

where the matrix elements B_{lm} are the amplitudes for the absorption of a neutron with quantum numbers l and m. These B_{lm}, which are functions of the scattering angle, may be considered as unknown parameters to be fixed by the experiments, and serve as a common meeting ground with the theory which predicts them from the distorting potentials.

Equation (1) shows that upper limits are placed on the magnitude of the polarization given by $|P|\leqq\frac{1}{3}$ if $j=l-\frac{1}{2}$ and $|P|\leqq\frac{1}{3}[l/(l+1)]$ if $j=l+\frac{1}{2}$. Furthermore, if one takes the ratio of the polarizations of the protons corresponding to neutron capture to two levels with $j=l+\frac{1}{2}$ and $j=l-\frac{1}{2}$ in the same or neighboring nuclei, then for similar energies and corresponding proton directions Eq. (1) predicts that

$$P_{l+\frac{1}{2}}/P_{l-\frac{1}{2}}=-[l/(l+1)].\qquad(3)$$

For the special case $l=1$, a parameter λ defined by Huby *et al.* as

$$\lambda=2\left[\left|\frac{B_{1,-1}}{B_{1,1}}\right|+\left|\frac{B_{1,1}}{B_{1,-1}}\right|\right]^{-1}\qquad(4)$$

can be experimentally determined from the $(d,p\gamma)$ angular correlation. Furthermore, for this case the proton polarization is given by

$$P=\frac{2}{3}\frac{(-1)^{j-\frac{3}{2}}(|B_{1,1}|^2-|B_{1,-1}|^2)}{(2j+1)(|B_{1,1}|^2+|B_{1,-1}|^2)}=\pm\frac{2}{3}\frac{(1-\lambda^2)^{\frac{1}{2}}}{(2j+1)}.\qquad(5)$$

If λ is determined in the angular correlation measurements, it may be used to predict the magnitude (but not the sign) of the polarization using Eq. (5), and also to determine the magnitude of the ratio $B_{1,-1}/B_{1,1}$ or its reciprocal by Eq. (4). Polarization measurements can in addition then determine the magnitude of this ratio uniquely by the use of Eq. (5). Finally, it is then possible in principle for the theory to fix the scattering potentials so as to yield the observed ratio.

A measurement of the $(d,p\gamma)$ correlation for the reaction $Mg^{24}(d,p)Mg^{25*}$ (3.40 Mev) has been carried out for a deuteron bombarding energy of 15 Mev and proton angles of 15° and 45° by Martin *et al.*[20] at the University of Pittsburgh. From the values of λ obtained from their experimental correlation results, Eq. (5) predicts polarizations $|P(15°)|=0.096\pm0.026$ and $|P(45°)|=0.101\pm0.019$. In the present experiment, a measurement is reported of the polarization of the protons emitted in the identical reaction, but at an angle of 12.5° and for a lower bombarding deuteron energy (10.8 Mev).

In an attempt to check the prediction of Eq. (3), polarization measurements were also performed on two $l=1$ neutron capture states in the reaction $Ca^{40}(d,p)Ca^{41*}$. The levels chosen were the states at excitation energies of 1.95 Mev and 3.95 Mev in Ca^{41}, which have been tentatively assigned[21] as $p_{\frac{3}{2}}$ and $p_{\frac{1}{2}}$ states, respectively. A $p_{\frac{3}{2}}$ state is also reported at 2.47 Mev, but it was not included in this study because its yield is only about one-third that of the 3.95-Mev state.

II. EXPERIMENTAL METHOD

A. Experimental Arrangement

Measurements were made by the familiar double-scattering method. In this case the protons were polarized in the (d,p) reaction in the first target, and the analysis was performed by measuring the left-right asymmetry in the scattering from a second target of helium. If P_1 and P_2 are the proton polarizations resulting from the interactions of *unpolarized* particles with the first and second targets, respectively, then

$$P_1P_2=(R-L)/(R+L),\qquad(6)$$

where R and L are the total number of counts in the right and left counters, respectively. The polarizations P_1 and P_2 are taken to be positive in each case when the respective polarization vectors are in the direction of $\mathbf{k}_{\text{in}}\times\mathbf{k}_{\text{out}}$.

In order for the counting rates after second scattering

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to be high enough for the experiment to be performed with reasonable economy, the second target must be as thick as possible. However, a thick target is incompatible with good energy resolution. If the polarization of the proton group corresponding to excitation of a single nuclear level is to be measured, it should be well resolved from groups corresponding to neighboring states.[22] In order to get around the opposing requirements of a thick second target and reasonable energy resolution, a heavy-particle magnetic spectrometer was used in the present investigation to separate the proton groups from the first target. The analyzing polarimeter, consisting of a helium target made as thick as feasible, was then placed at the spectrometer exit where it was required only to determine the polarization and not the energy separation of different groups. This technique has been used before[8] but with reduced energy resolution.

Unfortunately, determining P_2 for the analyzer is actually complicated by the interposition of the spectrometer between the first and the second targets. Because of the particular geometry of the spectrometer system, it becomes possible for the proton spin vector to precess in the magnetic field of the spectrometer in such a way as to replace part of the transverse polarization of the protons by a longitudinal polarization which is unobservable. This has the effect of adding a third factor that is not well known to the product P_1P_2. All polarizations measured in the present work were therefore obtained at a laboratory observation angle of 12.5°, which with the existing physical layout of the experimental apparatus is the only angle for which no depolarization occurs. Fortunately, for most of the reactions studied, this angle corresponds fairly closely to the peaks of the observed angular distributions. The analyzing power of

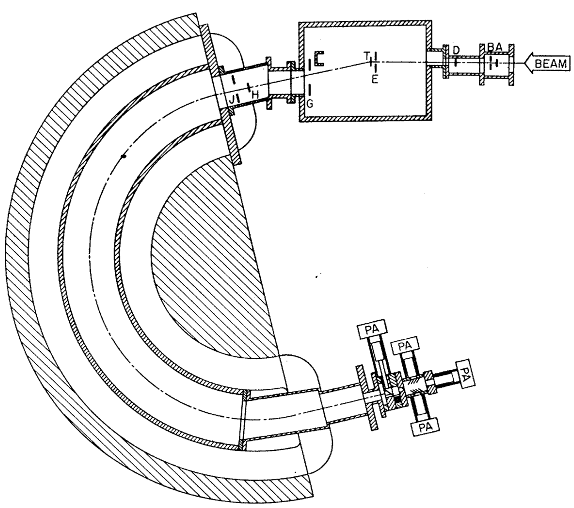

FIG. 1. Cross-sectional view of the experimental arrangement. The polarimeter is located just beyond the focus of the 20-in. radius double-focusing magnetic spectrometer.

[22] This requirement of course limits the thickness of the first target, regardless of the second scattering (analysis) measurement.

the polarimeter P_2 was found by substituting α-p elastic scattering as the polarizing reaction, in which case P_1 is known from the phase-shift analyses of this interaction. As a further check of the equipment, the reactions $C^{12}(d,p)C^{13}$ to the ground and first excited states were studied, since these polarizations have already been measured for several deuteron energies and laboratory angles at other laboratories.[8–10,12]

The experimental arrangement of the cyclotron and the magnetic spectrometer itself was the same as that used previously.[23,24] The polarimeter was connected to the exit of the spectrometer by a rotating, vacuum-tight joint, so that the polarimeter could be rotated 360° about its symmetry axis. A cross-sectional view of the target chamber, spectrometer, and polarimeter is shown in Fig. 1. Partially polarized protons from the (d,p) reaction in the target chamber were momentum analyzed by the spectrometer before entering the polarimeter. The protons were then scattered in the polarimeter, which consisted of a gas cell containing high-pressure helium, and detected by two scintillation counters placed symmetrically opposite one another.

Because of the high neutron flux near the deuteron beam and the close proximity of the polarimeter to the first scattering chamber, it was initially found that the number of background counts was comparable to the number of scattered protons, even with a concrete block and paraffin hut surrounding the polarimeter. This difficulty was overcome by placing a 2-mil plastic scintillator (hereafter referred to as the "dE/dx counter") in front of the entrance to the polarimeter, and requiring a pulse in one of the side counters to be in coincidence with a pulse from the dE/dx counter before the former was recorded. The proton energies involved in this investigation were in the range of 10–16 Mev, so that only about 0.6 Mev was lost in the dE/dx counter.

A cross-sectional view of the stainless steel polarimeter is shown in Fig. 2. The partially polarized proton beam from the first target entered from the left, passing through a $\frac{5}{16}$-in.-diam collimator (b) in front of the dE/dx scintillator (a). Following the dE/dx counter, the energy of the protons was degraded, if necessary, by a set of seven metal foils. In this way the proton energy at the second scattering was adjusted to about 9 Mev for all of the reactions under study. These foils, covering particle ranges from 1 to 285 mg/cm² of aluminum, could be inserted independently into the path of the protons. The degradation of the proton energy presumably affected their polarization only a negligible amount,[25] but the number of particles entering the polarimeter was reduced by multiple scattering in these foils. For all background runs, an eighth foil made of $\frac{1}{16}$-in. copper was inserted between the dE/dx counter and the

[23] V. K. Rasmussen, D. W. Miller, and M. B. Sampson, Phys. Rev. **100**, 181 (1955).
[24] G. B. Holm, J. R. Burwell, and D. W. Miller, Phys. Rev. **118**, 1247 (1960).
[25] L. Wolfenstein, Phys. Rev. **75**, 1664 (1949).

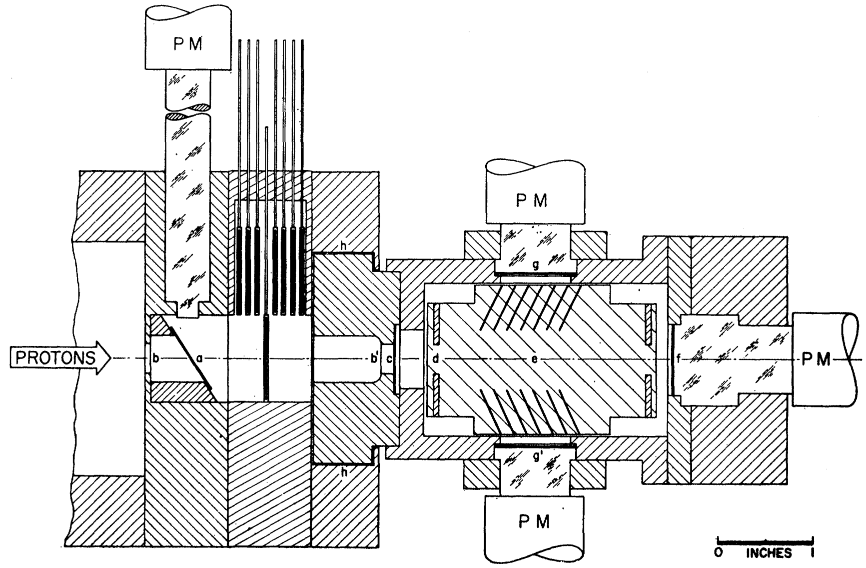

FIG. 2. Enlarged view of the polarimeter, showing the four scintillation counters employed in the present experiment. Details concerning these counters, apertures, absorbers, etc., are given in the text.

polarimeter to stop the protons before they entered the polarimeter. The observed background then presumably corresponded to chance coincidences between protons in the dE/dx counter and neutron-induced charged particles in the side counters.

At the main entrance to the gas cell two more $\frac{5}{16}$-in.-diam collimators (b′ and d) were located. Between these a 1-mil nickel window (c) sealed the 10 atm of helium pressure in the polarimeter from the spectrometer. The scattering volume (e) was viewed by the side counter through a series of collimating vanes set at an angle of 65° with respect to the symmetry axis of the polarimeter, using a design similar to that reported by Brockman.[26] The 20-mil brass vanes defined the detector solid angle and target thickness, thus making the effective scattering volume large without a sacrifice in angular resolution. A scattering angle of $65°\pm6°$ was chosen since contour maps of proton polarization produced in p-α scattering versus proton energy and scattering angle[9,27] indicated that at 65° the polarization is roughly independent of energy over the range from 7 to 18 Mev.

A fourth scintillation counter (f), referred to as the "center counter," was located at the back of the polarimeter and used to monitor protons passing straight through the gas cell without scattering.

To register proton counts from the two side counters, it was necessary in this experiment to record the pulse spectrum in a multichannel analyzer because the background counts increased rapidly near the low-energy end of the scattered proton spectrum. However, only one 20-channel pulse-height analyzer was available at the time this experiment was performed. Splitting this into two 10-channel analyzers without altering the internal wiring led to the circuit shown in block-diagram form in Fig. 3. The circuitry for all four counters is shown in this figure.

One counter, say the left, was assigned channels 11–20 and surplus, while the other (right) counter was assigned channels 1–10. The left counter was prevented from counting below channel 11 by the proper setting of the pulse-height selector on the left amplifier. Preventing the right counter from counting above channel 10 was accomplished by shutting off the entire 20-channel analyzer with an anticoincidence gate from a separate (model 153) amplifier whose input was in parallel with the right amplifier. If the signal from the right counter was above channel 10, this gate was also counted in a separate right-surplus scaler.

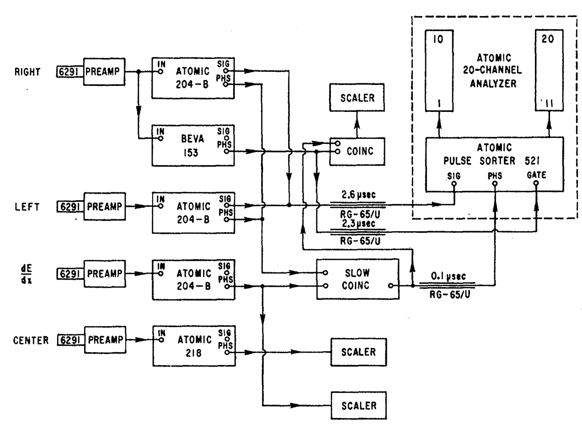

FIG. 3. Block diagram of the electronics associated with the four counters used in the present experiment. The right and left counters were displayed in 10 channels each of a 20-channel analyzer by appropriate discrimination and gating, as indicated in this diagram.

[26] K. W. Brockman, Jr., Phys. Rev. **110**, 163 (1958).
[27] G. C. Phillips and P. D. Miller, Phys. Rev. **115**, 1268 (1959).

B. Experimental Procedure

The "first targets" were made as thick as could be done conveniently without causing the proton groups corresponding to states of the residual nuclei to overlap (calcium was an exception, as will be discussed in Sec. II.C.)

The calcium and magnesium targets were prepared by rolling pieces of the oxide-free natural metal to thicknesses of approximately 10 mg/cm². A carbon target 10 mg/cm² thick was prepared by applying a layer of colloidal graphite in alcohol solution to a glass plate, and then lifting off the self-supporting layer following evaporation of the alcohol. Solid targets containing hydrogen were made by sandwiching two $\frac{1}{2}$-mil layers of polyethylene between three layers of gold leaf.

A complete data run consisted first of aligning the deuteron beam on the center axis of the first target, and then using the spectrometer and the center counter to obtain the momentum spectrum of the proton group corresponding to the nuclear level of interest in the residual nucleus. Typical momentum spectra obtained in this way are shown in Figs. 4–6. The spectrometer was then set to focus protons at the peak of the spectrum, and a polarization data run and a background run were taken using the side counters. Lengths of the data and background runs were chosen so that the whole procedure could be repeated about every 2 hr. After all reactions had been studied, the polarimeter was rotated 180° about its axis, and all the measurements were repeated.

In order to keep the energy of the protons at the center of the helium target the same for all reactions studied, in each case the spectrum of the center counter was separately displayed on the full 20-channel analyzer. With a helium pressure of 131±2 psi gauge, the foil combination was adjusted to give the same pulse height to within ±2%. Allowing for the differences in helium pressure, the energies of the protons from the several reactions should not have differed by more than ±3% at the center of the polarimeter.

C. Data Analysis and Corrections

The raw data consisted of 10 to 30 individual pairs of 10-channel spectra for the right and left counters for each level studied. These were accumulated when possible into one graph for each counter. Background data were also accumulated into one graph, and normalized to the same total beam charge striking the Faraday cup. The background was then subtracted from the raw data, and the statistical error was calculated for each point. A spectrum of the data after background subtraction for the $C^{12}(d,p)C^{13}$ ground-state reaction is shown in Figs. 7 and 8. The proton peak in both counters shows a low-energy tail which was present in all the data taken but often erratic in its energy distribution. This tail was presumably due to multiple scattering from the collimators and the vanes defining the polarimeter scattering angle, and was therefore not included when calculating P_1P_2. The point of demarcation between the peak and the tail was decided upon visually, and in all but one case the choice seemed to be clear cut. Its selection did introduce some uncertainty, but the error was estimated to be less than 0.3% in the total count for each counter.

Due to the finite extent and shape of the spectrometer acceptance angle, one counter can receive more counts than the other, even in the absence of polarization. This

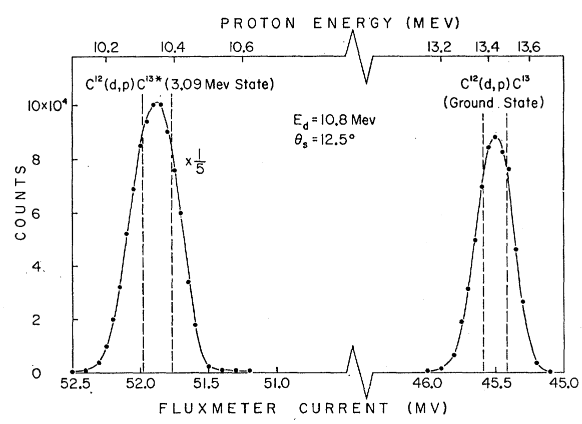

FIG. 4. Momentum spectrum of protons corresponding to the ground and first excited states of C^{13}, whose polarizations were measured in the present work to compare with previous results. The dashed lines represent the maximum momentum interval accepted by the polarimeter apertures during an actual polarization run.

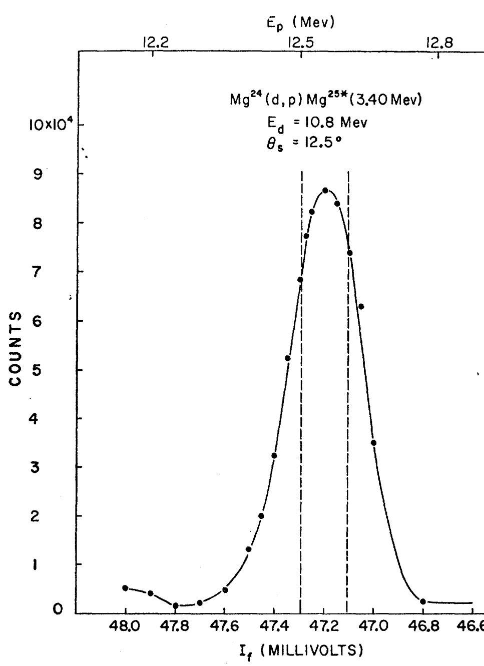

FIG. 5. Momentum spectrum of protons corresponding to the 3.40-Mev excited state of Mg^{25*}. The dashed lines have the same significance as in Fig. 4.

sort of an effect cannot be eliminated by rotation of the polarimeter through 180°. Therefore, the raw data had to be corrected for the variation of the proton angular distribution from the first target over the acceptance angle of the spectrometer, and for the double-trapezoid shape of the spectrometer acceptance angle.

Uncertainties in the magnitude of the product P_1P_2 arose from sources other than counting statistics. One such source of uncertainty was a possible motion of the deuteron beam spot on the first target; this would have tended to move the focus of the spectrometer off the symmetry axis of the polarimeter. If such a motion occurred over intervals of some hours, it was corrected each time a new momentum spectrum was taken with the spectrometer, since the spectrometer magnetic field was always adjusted to give a maximum proton flux in the polarimeter (as seen by the center counter). Possible motion of the beam spot during periods of time short compared to the length of the data run were assumed to be random with the result that the net asymmetry would be expected to be zero. A similar type of uncertainty arose from possible changes in the beam energy or from errors in adjusting the spectrometer to give the maximum proton flux in the polarimeter. These latter causes of uncertainty were found to be small compared to the uncertainty due to counting statistics.

In the case of calcium, the failure to resolve completely the proton groups corresponding to excitation of the 1.95- and 3.95-Mev states from proton groups corresponding to the excitation of neighboring levels

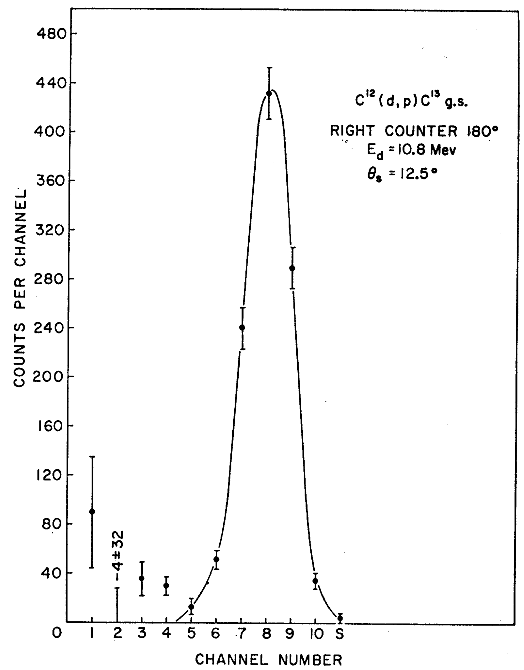

FIG. 7. Pulse height spectrum of C^{13} ground-state protons after second scattering in the helium gas cell into the right counter, as displayed in ten channels of the 20-channel analyzer. The "180°" does not refer to either first or second scattering angles, but is simply the angular setting of the polarimeter in its allowed 360° rotation about the axis of the proton beam leaving the spectrometer. Another complete run was taken in every case in the so-called "0°" polarimeter position to determine the asymmetry in counting efficiencies ("K" in Table II).

caused small uncertainties which were also found to be smaller than the statistical limits. A level at 2.014 Mev, which is probably formed by d-state neutron capture,[21]

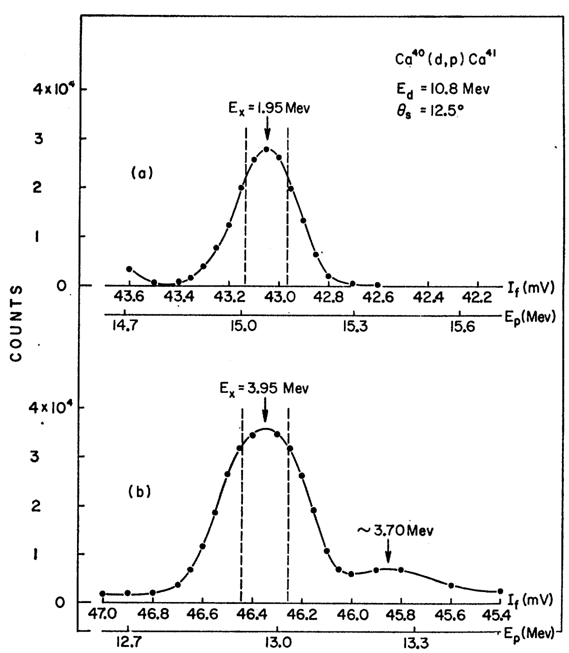

FIG. 6. Momentum spectra of protons corresponding to the 1.95- and 3.95-Mev levels of Ca^{41}. The momentum interval accepted by the polarimeter apertures during the polarization runs (as indicated by the dashed lines) included very small contributions from nearby unresolved states as discussed in the text.

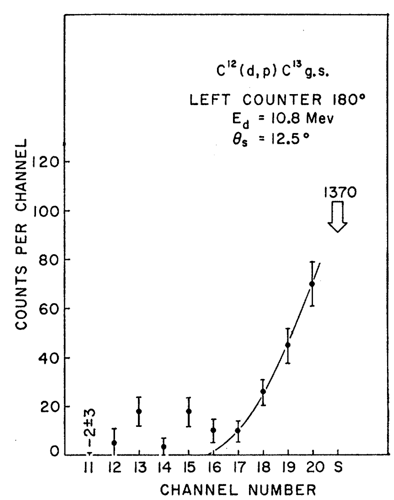

FIG. 8. Pulse-height spectrum of C^{13} ground-state protons after second-scattering into the left counter in the "180°" position, as explained in the caption of Fig. 7. Because the effective gains of the system were different for one set of 10 channels from the other, it was convenient to run the peak in the top 10 channels mostly in surplus, so that the tail could be examined carefully as shown here.

was estimated to have contributed about 1% to the total number of protons entering the polarimeter during the study of the 1.95-Mev state. For the 3.95-Mev level, there are six nearby unresolved states which contributed an estimated total of about 5% to the total proton counting rate. Only one of these unresolved states ($E_x=3.74$ Mev) has a forward-peaked angular distribution resembling a Butler curve,[21] but it is far enough removed in energy that it could only contribute a small fraction of the total 5%.

It should finally be emphasized that the chief defect in this experiment might be considered to be the failure to achieve a completely independent experimental measurement of the over-all asymmetry of the entire system. The rotation of the polarimeter through 180° measures only the asymmetry in counting efficiency of the side counters, but does not include any possible asymmetry due to the protons passing off axis through the polarimeter. It seems rather certain that (aside from the corrections already discussed) this effect cannot be large, because the spectrometer was always kept tuned for maximum counting rate in the center counter, and the axis of the polarimeter-center counter system was constructed to be accurately aligned. However, two attempts were made to measure any remaining asymmetries experimentally. In the first case elastic alpha particles were scattered from the first target through the entire spectrometer polarimeter system. Unfortunately, the alpha energy was so low after second scattering into the side counters that the alphas could not be separated from background. In the second attempt, the spectrometer was moved to a laboratory observation angle of 90°, while the polarimeter was left in its standard position. In this case, the second scattered protons would have corresponded to "up–down" scattering rather than "right–left" scattering, and no asymmetry should have been observed. However, the proton yield from available (d,p) reactions at 90° was too low to give a usable counting rate after the second scattering. Thus the best test of the over-all inherent asymmetry of the apparatus was given in the measurement of the polarization of the proton group corresponding to the 3.09-Mev state of C^{13*} as will be discussed in Sec. IV.

III. RESULTS

Polarization data for the calibration of the polarimeter using α-p scattering at the first target are shown in Table I. The result for P_2 is based upon an assumed value[28] of P_1 of -0.61 ± 0.03 obtained from the contour maps of Phillips and Miller[27] for a center-of-mass scattering angle for the inverse p-α scattering of 155° and proton energy of 5.5 Mev. The error listed for P_2 in Table I includes both statistical and estimated geometrical errors.

TABLE I. Results of the calibration of the polarimeter using partially polarized protons recoiling from a hydrogen target bombarded with 21.7-Mev alpha particles. The polarimeter analyzing power P_2 obtained in this way was then used for all measurements listed in Table II.

P_1P_2 (uncorrected)	Geometric correction	P_1P_2 (corrected)	P_2
$+0.416\pm0.015$	-0.009 ± 0.010	$+0.406\pm0.021$	-0.67 ± 0.05

Results of the polarizations from the (d,p) reactions are collected in Table II. The errors quoted for the *uncorrected* product P_1P_2 are only statistical. Geometric corrections quoted include the correction for the angular distribution of the protons [which is proportional to $[1/\sigma(\theta)]d\sigma(\theta)/d\theta$] and the correction for the trapezoidal shape of the spectrometer acceptance angle. The relative error for the geometric correction is large primarily because of the difficulty in obtaining an accurate angular distribution for angles less than 12.5°. All differential cross sections $\sigma(\theta)$ used in these corrections were extracted from the data of other authors, since the spectrometer employed in this experiment cannot readily be used for scattering angles less than 12.5°.

The quantity K in the fifth column of Table II represents the ratio of the effective counting efficiencies of the polarimeter side counters. It was obtained by taking the square root of the ratio of the asymmetries observed experimentally when the polarimeter was in its normal position and when it was rotated 180°. Although this correction was always applied to the data, it is shown in Table II explicitly to give an idea of the consistency of this result in various data runs.

The corrected value for P_1P_2 is shown in Table II together with the total estimated uncertainty (statistical and geometrical). All results for P_1 have been calculated using the value of P_2 given in Table I. The quoted uncertainty in P_1 was obtained from the rms sum of the percentage errors in P_2 of Table I and of the corrected P_1P_2 of Table II.

From the results for calcium, it is found that the ratio of the product polarizations for the proton groups corresponding to the 1.95- and 3.95-Mev states of $Ca^{41*}$is

$$P_1P_2(1.95)/P_1P_2(3.95)=(P_{l+\frac{1}{2}}/P_{l-\frac{1}{2}})_{l=1} = -0.07_{-0.28}^{+0.18}.$$

This ratio is clearly independent of the value chosen for P_2 in obtaining the absolute polarizations.

IV. DISCUSSION

α-p Scattering

This measurement was performed to provide a calibration of the analyzing power P_2 of the polarimeter. It also provided a check on the over-all consistency of the system, since both P_1 and P_2 can be estimated with fair accuracy from the polarization curves calculated by Juveland and Jentschke[9] and by Phillips and Miller.[27]

[28] The error quoted for P_1 is simply an estimate of the error in reading the contour map, and does not include any errors incurred in the original calculations of reference 27 of the polarizations for p-α phase-shift data.

TABLE II. Proton polarizations (P_1) obtained for all of the (d,p) reactions investigated in this work. The geometric correction and the relative counting efficiency K of the side counters are discussed in the text.

Final nucleus	Average $\theta_{c.m.}$	P_1P_2 (uncorrected)	Geometric correction	K	P_1P_2 (corrected)	P_1
C^{13} g.s.	13.3°	$+0.213\pm0.017$	$+0.003\pm0.020$	1.070	$+0.216\pm0.026$	-0.32 ± 0.05
C^{13} (3.09)	14.1°	$+0.040\pm0.015$	-0.059 ± 0.020	1.076	-0.019 ± 0.025	$+0.029\pm0.039$
Mg^{25} (3.40)	12.9°	$+0.043\pm0.018$	-0.010 ± 0.020	1.060	$+0.033\pm0.027$	-0.050 ± 0.042
Ca^{41} (1.95)	12.64°	-0.019 ± 0.018	$+0.010\pm0.020$	1.060	-0.009 ± 0.027	$+0.014\pm0.043$
Ca^{41} (3.95)	12.69°	$+0.129\pm0.020$	$+0.010\pm0.020$	1.061	$+0.139\pm0.028$	-0.21 ± 0.05

Assuming the value of $P_1=-0.61\pm0.03$, the measured value for P_2 of -0.67 ± 0.05 agrees within experimental errors with the value of -0.71 ± 0.03, obtained from the contour maps. Using the polarization curve of reference 7, it was also estimated that the value of P_2 should change by no more than ±0.01 over the ±300 kev uncertainty in the energy of the second scattering. The biggest source of uncertainty in the analyzing power P_2 of the polarimeter probably lies in the estimate of P_1 in the α-p scattering calibration; until the phase-shift calculations of the polarizations can be verified experimentally at our energy, it must be assumed that the value of P_1 taken from these phase shift analyses is correct.[29]

C^{13*} (3.09 Mev)

Previous measurements have been made of the polarization of this group by Hensel and Parkinson[8] and by Juveland and Jentschke.[9] Results of these two experiments and of the present work are given in Table III. At the forward angles, the present measurement agrees well with Juveland *et al.*, and within experimental errors with Hensel *et al.*, in spite of differences in deuteron energy and angle. This result is important because it shows that no large unknown asymmetries appear in the present apparatus.

It is important to note that this reaction corresponds to $l=0$ neutron capture, for which case polarization of the emitted protons can only be due to spin-dependent forces in the distorting potentials. Although very recent theoretical work[17,19,30] does show the possibility of large polarizations arising from this source, the polarizations expected at forward angles assuming reasonable distortion parameters for the present reaction turn out to be small[18] as is found experimentally.

C^{13}

The ground state of C^{13} is obtained by $p_{\frac{1}{2}}$ neutron capture. The polarization of the proton group corresponding to this transition has been measured for several deuteron energies.[8–10,12] In all previous experiments, the measured polarizations have clustered near a value of -0.17 for center-of-mass scattering angles between 15.5° and 30° and for deuteron energies ranging from 4–12 Mev. (See Allas and Shull[12] for a summary of these measurements.) The polarization of -0.32 ± 0.05 reported here is considerably larger than would be expected in comparison with previous data, although our value has been obtained for a laboratory observation angle which is the smallest used to date. This suggests the possibility that the polarization of this proton group rises sharply at small scattering angles before vanishing at 0°.

Mg^{25} (3.40 Mev)

The polarization of the proton group corresponding to this state was measured in order to compare with the results of Martin *et al.*[20] obtained by $(d,p\gamma)$ angular correlation measurements at a deuteron energy of 15 Mev and a proton emission angle of 15°. Table IV shows a comparison of the significant quantities which can be extracted from both experiments. It will be noted that though the results do not coincide, they all agree within the experimental errors quoted. The parameter λ is a measure of the amount of distortion present in the interaction, and it must lie between the limits $0\leq\lambda\leq1$, where $\lambda=1$ corresponds to the plane-wave Butler theory. λ was obtained by Martin *et al.* directly from their measured correlation parameters, and in the present work from the measured polarization using Eq. (5). Table IV shows that both experiments indicate that distortion effects are present. A correlation experiment can give the argument of the complex ratio $B_{1,-1}/B_{1,1}$ as well as the magnitude of the ratio, except that it cannot distinguish between this magnitude and its reciprocal. The present measurement gives the magnitude of the ratio uniquely using Eq. (5), and Table IV shows that the magnitude quoted by Martin *et al.* in their Table I is apparently the correct one. Similarly, the correlation experiment

TABLE III. Summary of measurements of the polarization of protons produced in the $C^{12}(d,p)C^{13*}$ (3.09 Mev) reaction.

E_d (Mev)	$\theta_{c.m.}$	Polarization	Reference
7.8	16.8°	0.00 ± 0.03	8
7.8	50°	$+0.04\pm0.04$	8
11.9	15.5°	$+0.06\pm0.05$	9
11.9	37.0°	-0.11 ± 0.14	9
10.8	14.1°	$+0.03\pm0.04$	Present work

[29] Tables I and II include the corrected product P_1P_2 for every reaction. Thus if a better value of P_1 in the α-p scattering becomes available, a new value of P_2 for the polarimeter can be calculated in Table I, and all of the results of Table II modified accordingly.
[30] W. Tobocman and W. R. Gibbs, Bull. Am. Phys. Soc. **6**, 295 (1961).

TABLE IV. Comparison of the results of the present experiment obtained for the polarization of the protons produced in the $Mg^{24}(d,p)Mg^{25*}$ (3.40 Mev) reaction with the $(d,p\gamma)$ angular correlation measurements of reference 20 for the same reaction. Remarks on the significance of this comparison in view of differences in experimental conditions and theoretical uncertainties are given in the text.

Reference	E_d (Mev)	Proton emission angle	λ	$\lvert B_{1,-1}/B_{1,1}\rvert$	P
Martin *et al.*	15	15°	0.82 ± 0.11	1.91 ± 0.74	Predicted magnitude 0.096 ± 0.026
Present work	10.8	12.5°	$0.95_{-0.12}^{+0.04}$	$1.36_{-0.31}^{+0.50}$	Measured -0.050 ± 0.042

predicts the *magnitude* of the polarization expected but not the sign. Combining this magnitude prediction with the results of the present measurement suggests that the actual polarization is negative.

It must be emphasized, however, that the two experiments being compared were performed at slightly different angles (12.5° and 15° lab) and considerably different bombarding energies (10.8 and 15 Mev). Since the matrix elements B_{lm} are angle dependent and can vary rapidly, the apparent agreement in Table IV may not be significant. Furthermore, the theoretical basis of this comparison assumes no spin-orbit coupling in the distorting potentials, which now seems to be a doubtful approximation.

Since the 3.40-Mev level of Mg^{25} has a $p_{\frac{3}{2}}$ character, the expected polarization according to the Huby *et al.* formulation is given by Eq. (1) as $P=\frac{1}{6}\langle m\rangle$, where $\langle m\rangle$ is the mean value of the component of orbital angular momentum along the quantization axis defined by Eq. (2). According to the "rule" for the sign of the polarization proposed by various authors[7] ($P=\pm$ for $j=l\pm\frac{1}{2}$), positive values of $\langle m\rangle$ are expected. Positive values result from the assumption that the distortion of the incoming deuteron wave is greater than the distortion of the outgoing proton wave. The present measurement for $Mg^{24}(d,p)Mg^{25*}$ (3.40 Mev) represents another example, in addition to the $B^{10}(d,p)B^{11}$ and $Ca^{40}(d,p)Ca^{41}$ ground-state reactions,[11,13] which suggests that $\langle m\rangle$ is negative. Hence, exceptions to the above expectation that $\langle m\rangle$ is positive now appear to have been found over the range of atomic weights from 11 to 41.[31]

Ca^{41*} (1.95 Mev) and Ca^{41*} (3.95 Mev)

The experimental ratio of $-0.07_{-0.28}^{+0.18}$ obtained for the polarizations of the proton groups corresponding to these two states seems to lie clearly outside the limits of experimental error from the result of -0.5[32] expected from Eq. (3). Several possible explanations for this discrepancy may be proposed. From an experimental standpoint, since the result obtained for the 1.95-Mev level is so nearly zero, it is clear that the ratio is very sensitive to experimental errors in this particular measurement. However, any reasonable systematic error, such as an unknown inherent asymmetry in the apparatus, could not simultaneously give agreement for the ratio here in question and the other measurements already discussed. Further, as pointed out in Sec. II.C, it does not appear that the contribution of nearby levels would appreciably affect the polarization measurements for the proton groups in question. Finally, it is possible that the 3.95-Mev state does not have $p_{\frac{1}{2}}$ character, although this seems rather unlikely.[21,33]

From the theoretical standpoint, several explanations for the discrepancy can be proposed. Probably the most likely possibility is the failure of the theory to take into account spin-orbit coupling in the distorted waves, as has already been discussed earlier. Another possibility arises from the fact that $\langle m\rangle$ depends slowly upon the reaction Q normally, but if the single angle chosen in the present experiment happens to be in a region where the polarization is varying rapidly with angle, this Q dependence might give a considerably different ratio at the particular angle employed. In any event the theoretical uncertainties appear to be comparable to the experimental uncertainties, so that further work in both areas would appear to be useful.

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[31] It is interesting to note from Table II and Eq. (1) that the quantity $\langle m\rangle$ is positive for the 3.95-Mev state of Ca^{41*} (and possibly positive for the 1.95-Mev state) in agreement with the polarization sign "rule" just mentioned. However, the polarization found in references 11 and 13 for the proton group corresponding to the ground state of the same nucleus indicates a negative value for $\langle m\rangle$.

[32] It should be mentioned that the theoretical polarization ratio does not depend upon the reduced widths of the nuclear levels involved provided only one j value can participate for each level (as in the present case where Ca^{40} has zero spin). This can be seen from Eq. (1) where the reduced widths cancel out in this case.

[33] H. E. Mitler, Nuclear Phys. 23, 200 (1961).