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Polarization of Protons from the $B^{10}(He^3,p)C^{12*}$(4.43-MeV) Reaction†⁑

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Proton polarizations were measured for the $B^{10}(He^3,p)C^{12*}$(4.43-MeV) reaction at He^3 energies of 2.5 and 2.8 MeV. These measurements were made for twelve angles from 0 to 135° at 2.5 MeV and for six angles from 15 to 75° at 2.8 MeV. The measurements at 2.5 MeV show that the polarization reaches a minimum of -0.36 ± 0.07 at $\theta_{\text{lab}}=15°$, where the sign of the polarization follows the Basel convention. At larger angles the polarization fluctuates and generally decreases. It could not be determined whether the polarization changes sign or is zero at the back angles. The angular dependences of the polarizations at 2.8 MeV are similar to those obtained at 2.5 MeV, indicating a weak energy dependence in the energy range used. The weak energy dependence is consistent with an interpretation of the reaction in terms of a direct reaction mechanism or a compound-nucleus process in which only a few, very broad levels are involved. The polarizations were analyzed by scattering the protons from a plastic scintillator, using the known properties of the polarization of protons scattered by carbon. With the plastic scintillator, it was possible to reduce the backgrounds in the side detectors. This was done by identifying the scattered protons as coincidences between the second scatterer and pulses of the proper energy in the side detectors. Geometrical uncertainties obtained by machine calculations are included in the statistical uncertainties.

I. INTRODUCTION

ANGULAR distribution and excitation measurements do not always lead to conclusive evidence as to whether a nuclear reaction can be interpreted in terms of direct interaction or compound-nucleus mechanisms. Thus, supplementary information, such as polarization of the reaction products, may be helpful in reaching a consistent conclusion. Although the products of any nuclear reaction will be polarized under suitable conditions,[1–3] the energy dependence of the polarization will differ depending on whether the mechanism of the reaction is direct or via compound-nucleus formation.

The $B^{10}(He^3,p)C^{12*}$(4.43-MeV) reaction has been interpreted by various workers[4–6] in terms of both direct and compound-nucleus reaction mechanisms. It was the purpose of this investigation to measure the proton polarization at He^3 energies of 2.5 and 2.8 MeV in the hope of shedding further light on this problem. This work represents the first known proton polarization measurements made from He^3-induced reactions.

Reaction cross sections and Q values for this reaction have been studied by various groups.[6–10] Almqvist *et al.*[6] investigated the proton spectra and differential cross sections at 90° for a He^3 energy of 2 MeV. Table I shows these results along with the corresponding energies, spins, parities, and isotopic spins of the first five levels in the final C^{12} nucleus.[8,11] The primary gamma-ray emitting levels are those at 4.43 and 15.10 MeV. Excitation curves to the ground state and the first excited state of C^{12} were measured from 0.5 to 5 MeV by Schiffer *et al.*[4] These measurements showed

TABLE I. Q values, differential cross sections, spins, and parities from the $B^{10}(He^3,p)C^{12}$ reaction.

			C^{12} final state			
	Q(MeV)	$d\sigma/d\Omega(90°)^a$ (mb/sr)	Energy (MeV)	Spin	Parity	T
P_0	19.7	0.05	0	0	+	0
P_1	15.3	0.57	4.43	2	+	0
P_2	12.1	0.02	7.65	0	+	0
P_3	10.1	0.11	9.60	3	−	0
P_4	8.9	0.02	10.76	1	−	0

[a] The total differential cross section to all proton levels at 90° center-of-mass angle is 2 mb/sr (Ref. 6).

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† Research supported in part by the U. S. Atomic Energy Commission.

⁑ Preliminary results of this work were reported by D. G. Simons and R. W. Detenbeck, Bull. Am. Phys. Soc. **8**, 486 (1963).

‡ Based on a thesis submitted to the Department of Physics and Astronomy, The University of Maryland, in partial fulfillment of the requirements for a Ph.D. degree.

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possible resonances at 2.0, 3.7, 4.1, and 4.6 MeV. Angular distributions were obtained at these resonances, but none were reported off resonance. These angular distributions show very little structure, especially for the first-excited-state group. The weak (Table I) ground-state proton group shows a strong asymmetrical peak at about 90° in the center-of-mass system which correlates to the possible broad resonance at 3.7 MeV. This distribution may be interpreted by the overlap of opposite parity states in the compound nucleus or by a direct interaction.[4] Since the angular distribution does not exhibit any strong forward peaking, a compound-nucleus formation leading to this weak group is favored.

Holmgren and Wolicki[5] investigated the proton-gamma angular correlations for the first-excited-state proton group in which they tried to determine whether there was any symmetry of the γ-ray distribution about the direction of nuclear recoil momentum (deuteron capture). The results appeared to indicate that there was no clear axis of symmetry, and hence, it was not possible to identify the dominant reaction mechanism.

Indirectly, Levinson and Banerjee[12] give strong support to the direct interaction interpretation of this reaction. In the numerical analysis of the $C^{12}(p,p')C^{12*}$ (4.43-MeV) reaction using a distorted-wave-Born-approximation approach, they were able to show that a direct interaction model may be used for proton energies ranging from 14 to 185 MeV. Since the two reactions have the same compound state (N^{13*}), it is reasonable that a direct interaction model would also be applicable for the analysis of the $B^{10}(He^3,p)C^{12*}$(4.43-MeV) reaction.

This reaction is simultaneously qualified and unqualified for proton polarization measurements. Its high Q values for the first two proton groups make it virtually impossible for any target contaminants to give proton backgrounds which may interfere with data analysis. The only sources of protons in this energy range are from (He^3,p) reactions with $H^2(Q=18.35$ MeV), $Li^6(Q=16.8$ MeV), and $N^{14}(Q=15.2$ MeV).[11] It would be difficult to contaminate the boron target with the first two of these. Although nitrogen is a possible contaminant, the cross section to the ground state of O^{16} in the $N^{14}(He^3,p)O^{16}$ reaction is lower than the $B^{10}(He^3,p)C^{12*}$ cross section by a factor of one hundred.[13] In addition, the high Q value makes it possible to use a carbon polarimeter with a thick carbon scatterer for analyzing the proton polarizations. On the other hand, the low cross sections for this reaction make polarization measurements on all but the first excited proton group which has the highest cross section (Table I) virtually impossible.

II. EXPERIMENTAL PROCEDURE AND APPARATUS

A. Polarization Measurements

The proton polarizations were measured by double scattering techniques[14,15] in which the left-right asymmetry arising from the second scattering measures the polarization normal to the reaction plane. The experimental arrangement for measuring polarizations by double scattering is shown in Fig. 1. The particles whose polarization is to be analyzed are emitted from the target (by scattering or nuclear reaction) at the angle Θ_1 with respect to the incoming beam direction. In order to determine their polarization they are scattered again by the second scatterer (analyzer) through a fixed angle (Θ_2) into two detectors, D_L and D_R. The polarization is then determined by the asymmetry in particles detected by the two detectors and is given by

$$P_1P_2=(N_L-N_R)/(N_L+N_R)\,, \tag{1}$$

where P_1 is the unknown polarization, P_2 is the polarization which would have been obtained by the elastic scattering of unpolarized particles from the analyzer, and N_L and N_R are the total number of counts obtained in the two detectors. It is necessary, therefore, to have an independent measurement or calculation for the value of P_2.

The counting rate in a double-scattering experiment depends on the product of two cross sections, that due to the target reaction and that due to the analyzer scattering. This product of small numbers produces a low counting rate. Thus large solid angles and thick targets or scatterers must be used unless the cross sections are exceptionally large. The values chosen are, of course, limited by the energy and angular resolutions required for the particular reaction studied. The thickness of the second scatterer and the size of the detector solid angles are further limited by the requirement that the polarization of the analyzer [P_2 in Eq. (1)] be large and fairly constant (or at least well known) over the range of interest. Proton analyzers (usually carbon or helium) make use of the spin-orbit interaction in the

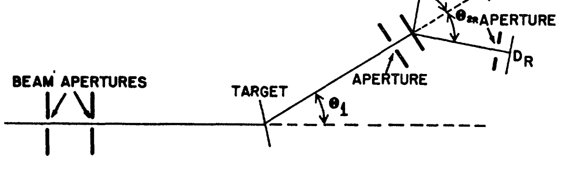

FIG. 1. Schematic diagram of experimental arrangement for the measurement of proton polarizations by double scattering.

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[12] C. A. Levinson and M. K. Banerjee, Ann. Phys. (N. Y.) 3, 67 (1958).

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proton elastic scattering which produces large, smoothly varying proton polarizations in this energy region. Compound-nucleus resonances in the elastic scattering are undesirable because the polarization is expected to vary quite rapidly with energy near such a resonance,[16] and may even go through zero.[1–3] Thus for maximum efficiency the proton-analyzer system should have no resonances over the entire energy range used. Carbon was chosen as the second scatterer for this measurement. Since there are no resonances in the p-C^{12} system in the energy range from 10.5 to 20 MeV,[11,17] it was possible to use a thick second scatterer and still be assured of a large average polarization in the analyzer system.

Although carbon has a disadvantage compared to the often used helium in that the polarization of elastically scattered protons is lower in the energy range of interest,[18–20] its use allows measurements to be made with better energy resolution. This resolution was necessary for the identification of the proton groups from this reaction. Furthermore, the polarization of elastically scattered protons by carbon has been widely studied,[14,18,20] and is found to be large over a wide energy range. Brockman[18] and Boschitz[19] report polarizations of -0.45 to -0.55 (Basel convention) at a lab angle of 45° in the energy range from 15 to 19 MeV. Carbon has been used extensively as the analyzer for other polarization measurements[21,22] where the angle of second scatter was 45°. This scattering angle was also used here.

The carbon analyzer used here was contained in a plastic scintillator 140 mg/cm^2 thick. The use of the scintillator allowed an additional role for the second scatterer. The passage of a proton through this scatterer could be determined by the scintillation pulses in the scatterer. Thus, detector pulses which were in coincidence with pulses from the plastic scintillator-scatterer were defined as charged particles which were scattered as required for a double-scattering measurement. All other detector pulses were rejected. The effectiveness of this rejection system was tested with absorbers, thick enough to stop all protons in front of the detectors.

The choice of a second scattering angle of 45° lab angle (90° c.m.) was an unfortunate one since proton-proton scattering resulted in spurious effects. In this special case, when a proton was scattered into one detector by the hydrogen contained in the scintillator plastic, the recoil proton entered the other detector. Thus, there resulted simultaneous double coincidences (triple coincidence) between the center scintillator and each of the side detectors. Each of these protons had half the energy of the incident proton. A measurement on the multichannel analyzer used (Nuclear Data ND 130) showed that when parallel inputs are used for analysis of two signals the pulse heights are added if they arrive at the same time. This effectively doubled the gain for pulses of equal height, and it was not possible to separate proton-proton events from proton-C^{12} events by pulse height alone. Further electronic preselection was required.

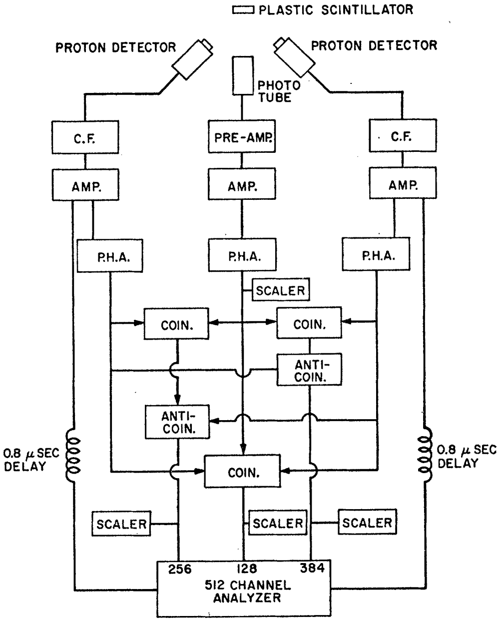

FIG. 2. Block diagram of detection and recording system.

The block diagram of the detection and recording system is shown in Fig. 2. As shown in the diagram the proton spectra of each of the detectors was stored in a different quadrant of the 512-channel analyzer. These detector signals were routed to the proper quadrant of the analyzer by the coincidence signal between the detector and the plastic scintillator-scatterer. The triple coincidences from proton recoils were used as routing signals to a third quadrant of the analyzer where the pulses of the two side detectors were summed (by the analyzer) and stored. To make certain that the detector pulses were not accidentally routed into either of the other two quadrants (since both double-coincidence circuits were also triggered at the same time), each double coincidence was placed in anticoincidence with the opposite side detector and thereby rejected.

B. Scattering Chamber and Polarimeter

The scattering chamber and polarimeter used are shown in Fig. 3. The scattering chamber had flat sides at each of the angular ports into which the polarimeter,

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[16] G. C. Phillips and P. D. Miller, Phys. Rev. **115**, 1268 (1957).

[17] Y. Nagahara, J. Phys. Soc. Japan **16**, 133 (1961).

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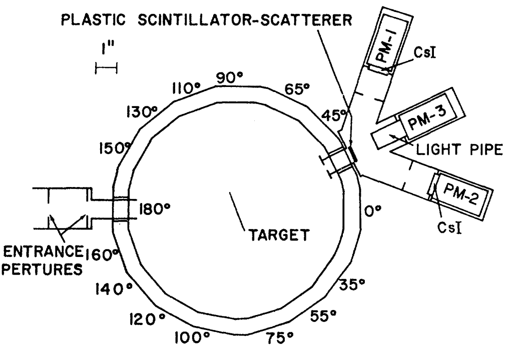

FIG. 3. Scattering chamber and polarimeter.

beam entrance port, and any accessories could be slip fit. In order to keep the solid angle to the second scatterer (5×10^{-3} sr) large, the ports could not be placed closer than 20° on center. However, the scattering chamber was constructed so that the beam could be brought into any port and the particles to be investigated could be brought out of any port. Then with an asymmetrical selection of angles, angular measurements could be made in 5° increments starting at 0°. Figure 3 shows the angles selected. The polarimeter and input-beam port were mounted on the scattering chamber by slipfitting their holders through the $\frac{3}{4}$-in.-thick walls of the scattering chamber. This method gave a firm bearing surface by which the polarimeter could be accurately and reproducibly pointed to the center of the scattering chamber (±0.3°). These were held firmly in place with large retainer nuts mounted on the inside of the chamber while the vacuum seal was made by an O-ring seal on the outside wall of the chamber. It was found that the gamma-ray background in the side detectors could be reduced by placing lead shielding inside the chamber directly between the detectors and the target. The construction of the polarimeter is shown in more detail in Fig. 4. The photomultiplier was optically coupled to the scintillator-scatterer by a light pipe which allowed the protons to scatter into the side detectors without interference. The suitability of this system was checked with monoenergetic protons from the $\mathrm{He}^3(d,p)\mathrm{He}^4$ reaction. The spectrum obtained from the scintillator-scatterer is shown in Fig. 5. The very broad peak obtained indicates that, while the resolution was poor as expected, the system was sufficiently sensitive to be used as a gross counter to detect all of the protons which passed through the plastic. A 1-mil aluminized Mylar sheet was inserted between the target and the second scatterer to cut out any light which may have leaked to the bare phototube.

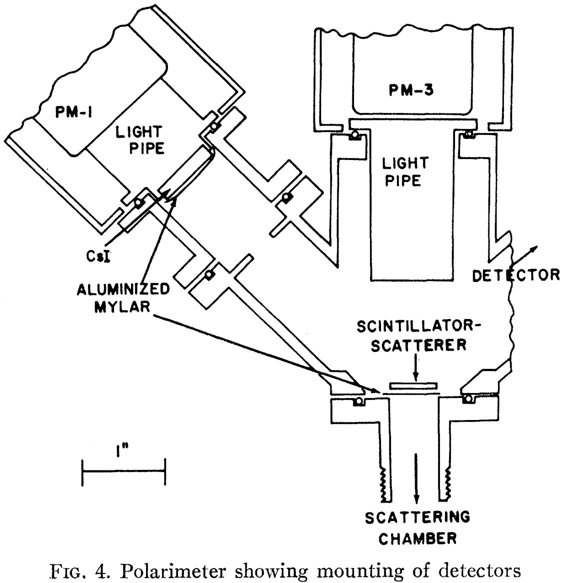

FIG. 4. Polarimeter showing mounting of detectors and scintillator-scatterer.

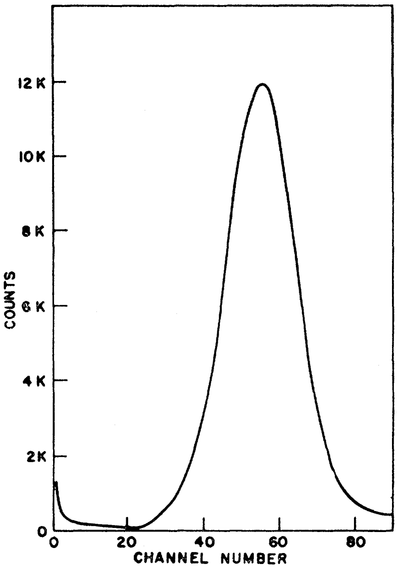

FIG. 5. Direct proton spectrum from $\mathrm{He}^3(d,p)\mathrm{He}^4$ reaction obtained with plastic scintillator-scatterer and bare photomultiplier.

The polarimeter was constructed so that it was also possible to interchange the side detectors with the straight-through phototube. This feature allowed a valuable measurement of the detector's resolution and the target thickness. It also proved to be very worthwhile and, at times, necessary for a check of the coincidence system. Since the counting rate after double scattering was so low, it was not easy to determine whether the counting or coincidence system was operating correctly. By interchanging the positions of the CsI detector and the bare phototube, it was possible to test the coincidence circuit and calibrate the detection system. In this arrangement the particle detector was exposed to the protons passing directly through the scintillator-scatterer. Since the plastic scintillator will give a light pulse for every proton passing through it (transmitted as well as scattered), a coincidence pulse should have been obtained for all of the directly viewed protons. Thus, the coincidence rate was much higher here than in the double-scattered arrangement. By checking the straight-through spectra with the coincidence on and off, an estimate was made of the coincidence efficiency, which was always found to be better than 80%. Losses were due to light-collection and dead-time inefficiencies in the phototube viewing the second scatterer, and were the same for left and right scattering.

C. Detectors

Attempts to use thin (6-MeV protons) solid-state detectors showed the advantages of using total E detectors for all of the proton groups. Cesium iodide detectors just thick enough to stop 22-MeV protons were used for the side detectors. These detectors were placed in the vacuum and coupled to RCA 6342 photomultipliers with $1\frac{1}{2}$-in.-long Lucite light pipes. This arrangenent is shown in Fig. 4. Since the cesium iodide detector was also sensitive to gamma radiation from the target, lead shielding was placed inside the scattering chamber between the target and the detectors (Fig. 3) when they were used in the second scatter position. Figure 6 shows the direct spectrum from the $B^{10}(He^3,p)C^{12}$ reaction obtained with a 0.100-in.-thick CsI detector. The ground state and first three excited-state groups are easily identifiable. The extra proton group as seen in the figure is from the $B^{11}(He^3,p)C^{13}$ reaction.[11] Although the energy spread in each of the proton groups was greater after the second scatter, the energy difference between groups was sufficient so that the first excited-state and ground-state groups could be separated. A typical spectrum obtained in the side position is shown in Fig. 7.

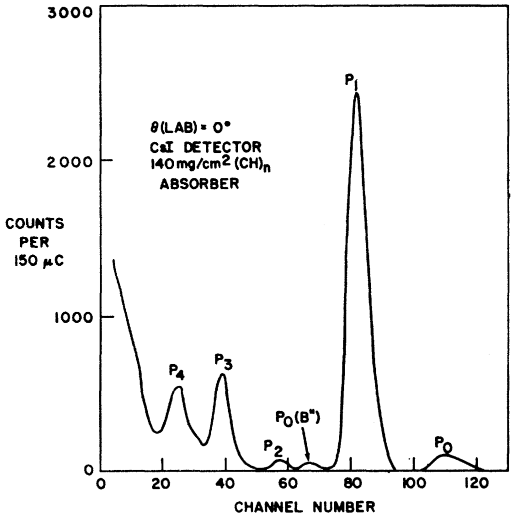

FIG. 6. Direct proton spectrum obtained from $B^{10}(He^3,p)C^{12}$ reaction with CsI detector.

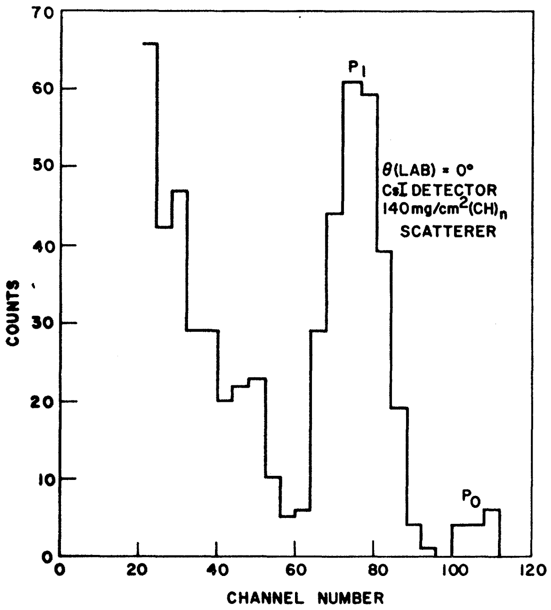

FIG. 7. Coincidence proton spectrum obtained from $B^{10}(He^3,p)C^{12}$ reaction after scattering protons through 45° with plastic scintillator.

D. Targets

Targets were prepared by evaporating enriched B^{10} (96.5% B^{10}) onto a backing of half-mil tantalum foil. This backing is sufficient to stop the incoming beam of He^3 but thin enough to allow transmission of the emitted protons at all forward angles ($\approx$2-MeV thick for 20-MeV protons). Target thicknesses of 200 to 300 $\mu g/cm^2$ (0.25 to 0.50-MeV He^3 energy at 2.5 MeV) were used for the polarization measurements. The thicknesses were crudely checked by weighing, and finally measured by the yields from both the $B^{10}(He^3,p)C^{12*}$ reaction[6] and from the $B^{10}(d,p)B^{11}$ reaction.[23] However, the polarization measurements did not depend critically on the target thickness.

Even with these relatively thick targets the counting rate in the side detectors was less than $\frac{1}{3}$ count/min. Since target heating limited the beam current, long runs could not be made with currents greater than 0.8 μA. To obtain an increase in beam current it was necessary to use a rotating target in the manner shown in Fig. 8. The target was rotated at a rate of 100 rpm in a plane perpendicular to the reaction plane. The use of the rotating target made it possible to increase the beam current to 5 μA without overheating the target. This increase raised the counting rate to $\approx 1\frac{1}{2}$ counts/min. Even so, a polarization measurement at a single angle took at least 6 h to accumulate enough counts for statistical reliability.

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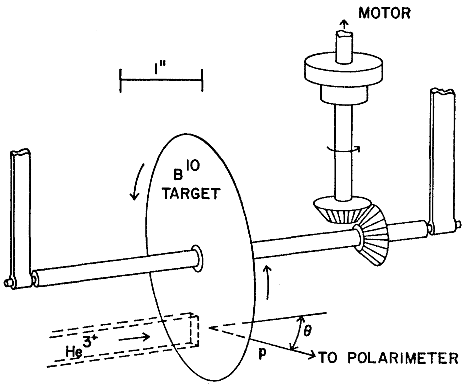

FIG. 8. Schematic of rotating target.

III. MEASUREMENTS

The left-right asymmetry obtained for the polarization measurement by double scattering was made using two side detectors simultaneously. There are obvious advantages in normalizing measurements made with two detectors aside from the time which is saved by this type of measurement. In spite of using two detectors to measure right and left scattering simultaneously, there are asymmetries which are inherent in the geometry of the polarimeter or the reaction being studied. Some of these asymmetries were eliminated by rotating the entire polarimeter about its axis by 180°; i.e., exchanging the positions of the left and right detectors with respect to the direction of second scattering but not with respect to their geometrical position in the polarimeter itself. This procedure eliminated effects which might have indicated a false asymmetry such as those which may be due to differences in the solid angles subtended by the two detectors or to a nonuniform second scatterer.

There are also effects not eliminated by polarimeter rotation. These result from nonisotropic angular distributions of the reaction products, poor beam alignment or nonuniform detector backgrounds. A nonisotropic angular distribution can lead to a nonuniform "illumination" of the second scatterer by protons which, in turn, can result in a higher counting rate for one of the detector positions. This asymmetrical illumination is independent of the polarimeter orientation. Calculations of the slope which would produce a given asymmetry were carried out using numerical methods. These calculations show that a logarithmic derivative of the cross section of $(1/\sigma)d\sigma/d\theta=0.05/\text{deg}$ is needed to give an asymmetry of 0.005 for the geometry chosen for this experiment. This slope is large compared to that of the actual angular distribution $[(1/\sigma)d\sigma/d\theta=0.005/\text{deg}]$.

A similar calculation was made on the effects of beam misalignment. This effect also has the feature that it can result in the nonuniform illumination of the second scatterer. Using a displacement of half beam width ($\frac{3}{32}$ in.) at a reaction angle of 0° (the polarimeter position at which the greatest effect is expected) an asymmetry of 7×10^{-5} was calculated. This correction is negligible. Beam alignment procedures centered the beam on the target to $\frac{1}{16}$ in.

A. Procedure and Data Handling

Before each polarization measurement each detector was checked out in the straight-through position. This checkout allowed for final gain changes and detector calibration. Polarization measurements were then conducted as described in the previous sections. After the spectra in the side detectors were obtained, the number of scattered first-excited-state protons was determined by simply adding the number of counts under the proper spectral peak. By placing absorbers in front of the detectors it was determined that all of the pulses in this energy range were the results of scattered protons. The polarization was determined using Eq. (1). The estimation of errors in these measurements is discussed below.

B. Calibration

Ideally the polarimeter should be calibrated by a processes in which the calibration is independent of previous polarization measurements from other reactions. Brockman[18] shows that this type of calibration can be carried out by elastic double scattering of protons by two carbon targets. By proper energy choice with absorbers in front of one or both of the targets, the square of the polarization of the scatterer can be determined with three measurements. This measurement results in the magnitude but not the sign of the analyzing power. Unfortunately, a proton source of sufficient energy ($\approx$15 MeV) was unavailable, and it was not possible to calibrate the polarimeter by this procedure.

The next best procedure was a combination of measured polarizations of protons scattered from carbon and machine calculations to determine the average value of the cosine of the angle between the reaction plane and the scattering plane for the particular geometry chosen. These calculations were then checked by a comparison of measurements made on the $\text{He}^3(d,p)\text{He}^4$ reaction with other, independent measurements of the same reaction.[22,24] This reaction is ideal for this use since its high Q value (18.3-MeV) results in protons in the energy range of interest. The target used was made by H. Fann and adapted for the scattering chamber described above. Special apertures were inserted to limit the observed reaction region to one similar to that of the solid B^{10} target. This geometry is shown in Fig. 9. The target chamber was cylindrical with a diameter of 1 in. and a height of $\frac{5}{8}$ in. It was filled with He^3 to a pressure of 15 psi. The measurement procedure was as follows: First, asymmetries were determined at the low-

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[24] H. L. Fann, R. W. Detenbeck, and H. Taketani, University of Maryland, Department of Physics and Astronomy Technical Report 348 (unpublished).

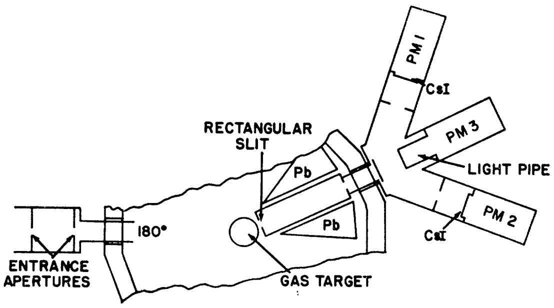

FIG. 9. Schematic of scattering chamber and polarimeter with slit system for use with gas target.

energy resonance ($E_d=430$ keV).[25] This resonance is due to a single, compound-nucleus level for which it has been well established that $l=0$. The resultant polarization is therefore zero.[3] This measurement was used as a good indication of the alignment of the polarimeter and its inherent asymmetries. Asymmetry measurements made at lab angles of 60 and 90° were found to be -0.015 ± 0.011 and -0.010 ± 0.017, respectively. Thus, within the errors indicated, the asymmetry of an unpolarized beam was measured as zero. Measurements were then made at a deuteron energy of 2.7 MeV (at the center of the gas target) at lab angles of 60 and 70°. An additional measurement was made at 60° in which the energy of the proton was reduced to the lowest proton energy obtained from the $B^{10}(He^3,p)C^{12*}$ reaction at 135°. This energy was measured to be 11.6 MeV after leaving the second scatterer. The calibration results are shown in Table II.

TABLE II. Calibration asymmetries and polarizations from the $He^3(d,p)He^4$ reaction.

θ_{lab} (deg)	E_d (MeV)	ϵ	P		Measured by
60	0.430	-0.015 ± 0.011			
60	2.7	$+0.07\ \pm0.015$	$-0.15\ \pm0.03$	[a]	
60	2.7	$+0.067\pm0.018$	$-0.13\ \pm0.04$[b]		
70	2.7	$+0.108\pm0.020$	$-0.22\ \pm0.04$		
70	2.7	$+0.11\ \pm0.01$	$-0.21\ \pm0.04$		Fann (Ref. 24)
60	3.0		-0.346 ± 0.039		Brown, Haeberli (Ref. 22)

[a] Assumed analyzing power $=-0.50$.
[b] Proton energy reduced to 11.6 MeV by absorber.

These results compare favorably with measurements made by Fann[24] in which he used the same gas target but measured the asymmetries using a helium polarimeter and emulsion detectors. These measurements are consistent with the analyzing power of the polarimeter to be taken as -0.50 ± 0.05. This is very close to the value given for the polarization for protons scattered from carbon by Brockman,[18] Phillips,[16] and Boschitz.[19] Calculations were made of the average value of the cosine of the angle between the two scattering planes for this carbon polarimeter. This average value was found to be 0.995 at 90°.

C. Errors

The final errrors in measurements originate from three independent areas. These are counting statistics, inherent asymmetries which cannot be eliminated by flipping the polarimeter, and undesirable scattering effects from the second scatterer.

The choice of carbon as an analyzer leads to possible difficulties in this particular experiment since the final state of the reaction is also C^{12}. Protons from the following processes were indistinguishable in this experiment:

(a) $B^{10}(He^3,p)C^{12*}$(4.43 MeV)
followed by $C^{12}(p,p)C^{12}$(G.S.)

and

(b) $B^{10}(He^3,p)C^{12}$(G.S.)
followed by $C^{12}(p,p')C^{12*}$(4.43 MeV).

This effect though small should be included in the error calculation. The asymmetries given by Eq. (1) are not quite correct but must be rewritten as

$$\epsilon=\frac{(N_L+n_L)-(N_R+n_R)}{(N_L+n_L)+(N_R+n_R)}, \tag{2}$$

where N_L and N_R are counts due to the first-excited-state reaction and n_L and n_R are counts in the first-excited-state energy range due to the inelastic scattering of the ground-state group from C^{12}. Let

$\epsilon_1=$ actual asymmetry from first-excited-state proton group $=(N_L-N_R)/(N_L+N_R)$;

$\epsilon_2=$ actual asymmetry of ground-state proton group $=(n_L-n_R)/(n_L+n_R)$.

But $(n_L+n_R)/(N_L+N_R)=1/50$ since the ground-state yield is less than the first excited state yield by a factor[6] of 10, and the p-C^{12} inelastic scattering cross section at the ground-state energy is less than the elastic scattering cross section at the first-excited-state energy by a factor[26] of 5. Thus, expanding and keeping the first two terms, Eq. (2) becomes

$$\epsilon=0.98\ \epsilon_1+0.02\ \epsilon_2\,.$$

Since ϵ_2 cannot be measured easily, the maximum error in ϵ was obtained by taking the polarization of the ground-state proton group to be 1.00, or $\epsilon_2=0.5$.

IV. RESULTS AND CONCLUSIONS

Proton polarizations were measured for the $B^{10}(He^3,p)C^{12}$ reaction at He^3 energies of 2.5 and 2.8 MeV. These measurements were made on the first-excited-state proton group since the cross sections leading to all of the other states of C^{12} were too low to make a polarization measurement practical. The energies of 2.5 and

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2.8 MeV were chosen since the excitation curves for this reaction[4] do not show any resonances in this energy range. At 2.5 MeV, measurements were carried out for twelve angles from 0 to 135° while those at 2.8 MeV were made at six angles from 15 to 75°. The results obtained are given in Table III and are also shown in Figs. 10 and 11. The sign of the polarization follows that of the Basel convention and is positive for $\mathbf{k}_{\text{in}}\times\mathbf{k}_{\text{out}}>0$. The errors given in the table accumulate errors from counting statistics, analyzing power of the polarimeter, inelastic scattering effects from the ground-state proton group, beam alignment, and geometry effects due to the slope of the angular distribution. Those in the figures show errors due to counting statistics only. The increase in error over those due to counting statistics is only of the order of ±0.01 and is therefore small with respect to the counting errors obtained in these measurements.

TABLE III. Polarization of protons from $B^{10}(He^3,p)C^{12*}$(4.43-MeV) reaction.

$E(He^3)$ (MeV)	Θ_L (deg)	$\Theta_{c.m.}$ (deg)	P_1[a]	σ[b]
2.5	0	0	0.00	0.09
	10	10.58	−0.30	0.09
	15	15.78	−0.36	0.07
	25	26.28	−0.12	0.09
	35	36.74	−0.22	0.08
	45	47.14	−0.29	0.08
	60	62.62	+0.01	0.07
	75	77.93	−0.16	0.07
	90	93.03	+0.06	0.07
	105	107.93	+0.16	0.08
	120	122.62	−0.16	0.08
	135	137.14	−0.04	0.08
2.8	15	15.82	−0.14	0.09
	25	26.35	−0.35	0.09
	35	36.83	−0.20	0.07
	45	47.25	−0.16	0.07
	55	57.61	−0.32	0.08
	75	78.08	−0.07	0.09

[a] P_1 is measured by a double scattering from C^{12}, taking the analyzing power as −0.5, where $\mathbf{k}_i\times\mathbf{k}_0$ is positive.

[b] Accumulated errors from: counting statistics, analyzing power of the polarimeter, inelastic scattering effects from the ground-state proton group, variations in the second-scattering thickness, beam alignment, and geometry effects due to slope of angular distribution.

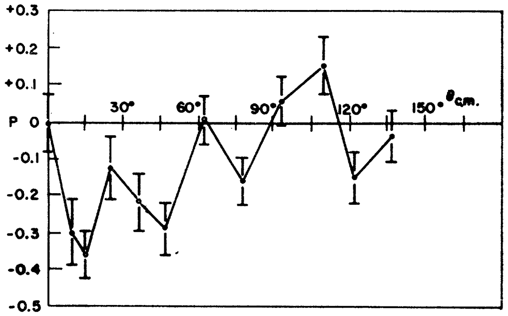

FIG. 10. Angular dependence of polarization of protons from the $B^{10}(He^3,p)C^{12*}$ (4.43-MeV) reaction at $E(He^3)=2.5$ MeV. Errors shown are counting errors only. Analyzing power of polarimeter was taken as −0.50, where $\mathbf{k}_i\times\mathbf{k}_0$ is defined as positive.

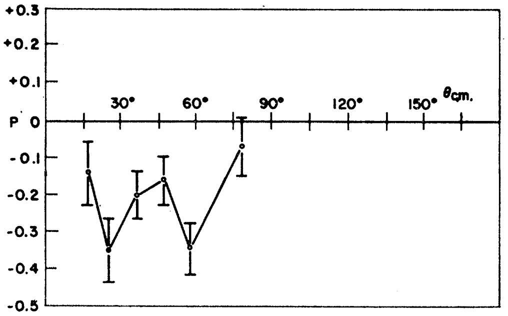

FIG. 11. Angular dependence of polarization of protons from the $B^{10}(He^3,p)C^{12*}$ (4.43-MeV) reaction at $E(He^3)=2.8$ MeV. Errors shown are counting errors only. Analyzing power of polarimeter was taken as −0.50, where $\mathbf{k}_i\times\mathbf{k}_0$ is defined as positive.

A comparison between the two sets of measurements shows a strong similarity in the polarization as a function of angle. This similarity indicates a weak energy dependence in the energy range used. The peak polarization at 2.8 MeV ($\theta_{\text{lab}}=25°$) is at a slightly larger angle than that at 2.5 MeV ($\theta_{\text{lab}}=15°$). It should be noted that the energy difference between the two measurements is of the order of the target thickness used (approximately 250 keV for a He^3 energy of 2.5 MeV). The large error flags make a more detailed angular analysis of the polarizations rather difficult.

The small cross section for this reaction to go to the ground state of C^{12} made it difficult to make polarization measurements on the corresponding proton group. It was possible, however, to obtain the average polarization over all of the angles measured. This average was found to be -0.21 ± 0.09 at the He^3 energy of 2.5 MeV and -0.16 ± 0.15 at 2.8 MeV. The corresponding averages for the first excited state group are -0.11 ± 0.02 at 2.5 MeV and -0.20 ± 0.03 at 2.8 MeV. The polarization at 90° ($E_{He^3}=2.8$ MeV) was measured to be -0.34 ± 0.19. More information is needed here, and it may be worthwhile to try to make more accurate measurements of the ground-state proton group at a single angle near 90°.

A. Reaction Mechanism

This experiment establishes conclusively that there is an appreciable polarization of the protons from the $B^{10}(He^3,p)C^{12*}$ reaction. Furthermore, this large polarization was measured with a target about 250 keV thick, and involves an average over a corresponding energy interval. We conclude that the polarization can be ascribed to one of two mechanisms: The interference of only a few, very broad levels in a compound-nucleus reaction, or a direct reaction.

If the polarization is due to a fluctuation in compound-nucleus formation,[27] then the characteristic width must be $\gtrsim 250$ keV, since the measurement involved an average over this interval. In fact, the similarities in the angular distributions of $P(\theta)$ at 2.5 and 2.8 MeV suggest that the characteristic width is $\gtrsim 500$ keV. Schiffer *et al.*[4] suggested that two widely separated resonances at 2.0 MeV ($\Gamma = 0.5$ MeV) and 3.7 MeV ($\Gamma = 0.7$ MeV) dominate the reaction in this energy region.

The smooth energy variations are, of course, consistent with a direct-reaction mechanism. Even spin-independent distorted-wave-Born-approximation theories predict the possibility of large polarizations for this particular direct reaction.[28] In (d,p) reactions it has been shown that spin-orbit terms in the distorting potentials are important,[29,30] and they would probably be required here as well.

The large size of the polarization contradicts the hypothesis that the reaction involves many overlapping levels in a statistical compound nucleus. The smooth energy variation rules out contributions to the polarization from levels with widths appreciably less than 250 keV.

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$N^{14}(He^3,n)F^{16}$ Reaction*

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Time-of-flight neutron spectra from the bombardment of a chromium nitride target by 3.5- and 6.2-MeV He^3 particles indicate five neutron groups corresponding to the ground state of F^{16} and to excited states at 0.20 ± 0.05, 0.436 ± 0.030, 0.736 ± 0.040, and 3.78 ± 0.06 MeV, with widths of 50 ± 30, <40, 40 ± 30, <15 and <40 keV, respectively. The ground state Q value is -0.963 ± 0.040 MeV, corresponding to a F^{16} atomic mass excess of 10.686 ± 0.040 MeV. The results are discussed in terms of the known information on the $T=1$ states in the $A=16$ isobaric triad.

INTRODUCTION

FLUORINE^{16} can be investigated by means of three reactions: $N^{14}(He^3,n)F^{16}$, $O^{16}(p,n)F^{16}$ and $O^{16}(He^3,t)F^{16}$. From charge-independence arguments and knowledge[1] of the excitation energy of the first $T=1$ state in O^{16}, one calculates Q values of approximately -1 MeV for the (He^3,n) reaction and approximately -16 MeV for the (p,n) and (He^3,t) reactions. The energy-level structure of F^{16} can be roughly predicted from the known information on the levels of N^{16} and on the $T=1$ states in O^{16}: There should be a cluster of four odd-parity states [in N^{16} these occur at 0, 0.120, 0.296, 0.396 MeV with $J^{\pi} = 2^-, 0^-, 3^-, 1^-$; in O^{16} at 12.79, 12.97, 13.10, 13.26 MeV with $J^{\pi} = 0^-, 2^-, 1^-, 3^-$] followed by a sizable energy gap devoid of levels [in N^{16}, 3 MeV; in O^{16}, not known]. F^{16} should be proton-unstable.

The difficulties in investigating F^{16} can be summarized as follows: (a) the close spacing of the first four states of F^{16} require both a well-defined incident-

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