Polarization in the $H^2(d,p)H^3$ Reaction*

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The polarization of the protons in the $H^2(d,p)H^3$ reaction has been measured at a deuteron energy of 0.64 Mev in the laboratory system, and a proton angle 45° in the center-of-mass system. The deuterium gas target was approximately 70 kev thick. Scattering in helium gas was used to measure the polarization. Corrections for geometrical asymmetries were determined by comparing the scattering in helium with scattering in xenon gas. Measurements made at three different proton energies yield an average value of $-(17\pm7)\%$ for the polarization. The negative sign signifies a direction opposite the vector $[\mathbf{V}_d\times\mathbf{V}_p]$, where $\mathbf{V}_d$ and $\mathbf{V}_p$ are the deuteron and proton velocities, respectively.

INTRODUCTION

THE angular distributions in the important reactions:

$$H^2(d,n)He^3,\quad Q=3.25 \text{ Mev}$$
$$H^2(d,p)H^3,\quad Q=4.04 \text{ Mev}$$

have been analyzed by Konopinski and Teller and others[1] in terms of a large amount of spin-orbit coupling. More recently the angular distributions have been treated according to stripping theory.[2]

The presence of spin-orbit coupling in the reaction leads to polarization of the reaction products. Several experimenters[3–9] have now measured this polarization as summarized in Table I, which also includes the results of the present work. The agreement among the various measurements is generally good. As yet, the range of deuteron energies covered is not great and the measurements have been made by using a thick or semithick D_2O ice target.

The present investigation was undertaken with a thin target to provide a measurement of the proton polarization, which has not been so extensively studied as the neutron polarization. Scattering of the protons in helium provided the polarization analysis. [In the course of the investigation the proton energy was varied (by means of absorbing foils) and a rough confirmation was obtained of the predicted trend in the polarization of the p-α scattering.]

EXPERIMENTAL PROCEDURE

A diagram of the apparatus is shown in Fig. 1. The deuteron beam of energy 0.90 Mev entered the gas target chamber through a nickel window 0.05×10^{-3} in. thick. Beam currents of approximately 1.5 μa were used. The chamber was filled to one atmosphere of deuterium, producing a target about 70 kev thick and a deuteron energy approximately 0.64 Mev at the center of the target. The protons emerged at an angle of 39° (45°, c.m.) through a thin aluminum window which could be varied in thickness to change the energy of the protons. Wolfenstein[10] has shown that polarized charged particles should not become depolarized in passing through matter. The 45° angle was chosen because the polarization in this energy region is expected to vary approximately according to the formula:

$$P\sim\frac{\sin\theta\cos\theta}{(d\sigma/d\omega)},$$

where $d\sigma/d\omega$ represents the differential cross section for an unpolarized beam.[10]

The protons entered the helium scattering chamber through a 1.0×10^{-3}-in. aluminum foil. The helium chamber was lined with carbon in order to eliminate

TABLE I. Polarization measurements in the $H^2(d,n)He^3$ and $H^2(d,p)H^3$ reactions. The direction of polarization is taken positive along the $(\mathbf{V}_d\times\mathbf{V}_n)$ axis, where $\mathbf{V}_d$ and $\mathbf{V}_n$ are the velocities of the deuteron and neutron (proton), respectively.

Reaction	Reference	E_d Mev	Target	θ_1(lab) deg	Analyzer	P_1 percent
(d,n)	3	0.61	Thick ice	45	Carbon	20[a]
(d,n)	4	0.60	Thick ice	45	Carbon	-11 ± 5[b]
(d,n)	5	0.60	Thick ice	50	Carbon	-10.8 ± 1.2
(d,n)	6	0.80	Thick ice	49	Helium	-17.5 ± 2.0
(d,n)	7	0.60–0.70	Thick ice	46	Carbon	-10.6 ± 1.0
(d,p)	8	0.30	Thick ice	120	Helium	$+30\pm6$
(d,p)	9	1.20	Thick ice	135	Helium	$+24\pm10$
(d,p)	This work	0.65	Thin gas	39	Helium	-17 ± 7

[a] Only $|P_1|$ measured.
[b] This is the result of Huber and Baumgartner[4] as computed by Meier, Scherrer, and Trumpy[5] using the carbon analysis of the latter authors.

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[1] E. J. Konopinski and E. Teller, Phys. Rev. **73**, 822 (1948); Y. Nakano, Phys. Rev. **76**, 981 (1949); Beiduk, Pruett, and Konopinski, Phys. Rev. **77**, 622 and 628 (1950).
[2] W. M. Fairbairn, Proc. Phys. Soc. (London) **A67**, 990 (1954); P. R. Chagnon and G. E. Owen, Phys. Rev. **101**, 1798 (1956).
[3] R. Ricamo, Nuovo cimento **10**, 1607 (1953).
[4] P. Huber and E. Baumgartner, Helv. Phys. Acta **26**, 545 (1953).
[5] Meier, Scherrer, and Trumpy, Helv. Phys. Acta **27**, 577 (1954).
[6] Levintov, Miller, and Shamshev, Doklady Akad. Nauk (S.S.S.R.) **103**, 803 (1955).
[7] McCormac, Steuer, Bond, and Hereford, Phys. Rev. **104**, 718 (1956).
[8] Bishop, Preston, Westhead, and Halban, Nature **170**, 113 (1952).
[9] B. Maglić (private communication).
[10] L. Wolfenstein, Phys. Rev. **75**, 1664 (1949).

neutron-induced charged particle background from aluminum. Helium pressures from 40 to 100 psi (gauge) were used. The mean scattering angle was 72° (90°, c.m.), with a total angular spread of about 60°. The protons were detected with thallium-activated sodium iodide crystals, about 10^{-2} in. thick and $\frac{1}{8}$ in. square. The crystals were cleaved and polished in a dry atmosphere and then quickly mounted in the chamber. They were backed with nickel foil 0.05×10^{-3} in. thick which stopped the recoil alpha particles from n-α scattering and also acted as a light reflector. The scintillations were viewed by 5819 photomultiplier tubes through glass light pipes. Great care was taken to avoid all hydrogenous material which would produce n-p recoils in the vicinity of the detectors. The pulses from the photomultipliers were amplified and each spectrum was displayed on a 10-channel analyzer.

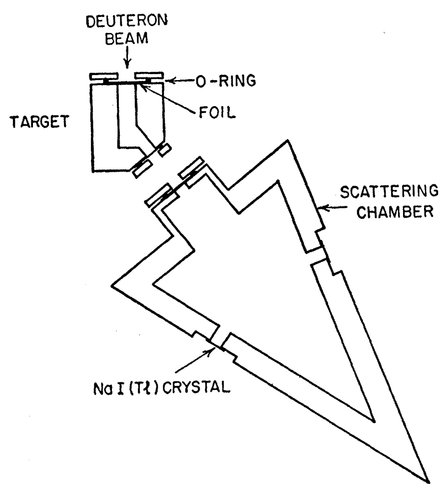

FIG. 1. Schematic diagram of the target and scattering chamber.

The procedure was to observe for equal periods with the chamber filled with helium and with the chamber evacuated. The runs were monitored with a stilbene scintillation detector which counted the d-D neutrons. Typical spectra obtained with the chamber filled with helium are shown in Fig. 2. The background in the forward counter was considerably higher since the background was due mainly to the d-D neutrons which have a strong component in the forward direction. The same spectra after subtraction of background are also shown in Fig. 2.

The small size of the scintillators combined with the care and speed with which they had to be handled precluded accurate matching of their areas. In order to measure directly this artificial asymmetry, as well as other unavoidable asymmetries, xenon was substituted for helium in the scattering chamber. The high Coulomb barrier of the xenon nucleus virtually insures pure Coulomb scattering, which is known to be insensitive to polarization at these energies.[10] With the scattering chamber filled with xenon, asymmetries from 0–20% were observed. However, when the chamber was inverted, this asymmetry was in the opposite direction and of the same magnitude, within the statistical fluctuations which were a few percent. Furthermore, the ratio of the asymmetry obtained with helium in the chamber to that obtained with xenon was the same in both positions, again within statistics. These results indicate that the asymmetries observed in the helium scattering, when normalized to the xenon data, were due to polarization and not to spurious geometric effects.

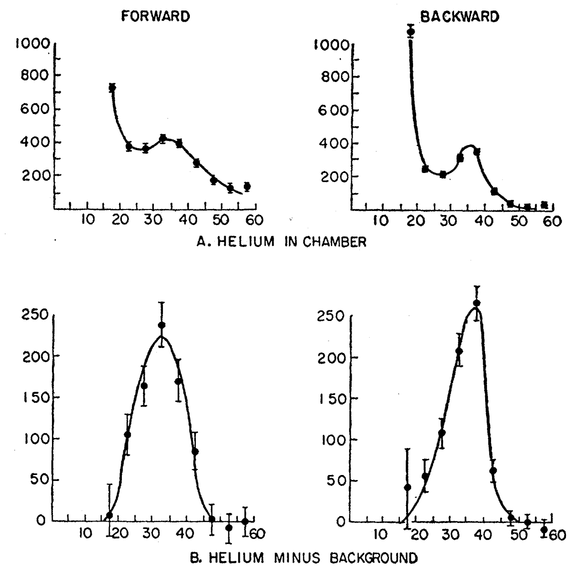

FIG. 2. Observed pulse-height spectra for one proton-helium scattering run. The abscissa represents the pulse height in volts and the ordinate the number of counts per five-volt channel.

Spectra from a xenon run are shown in Fig. 3. When one compares Fig. 3 with Fig. 2, it can be seen that the protons scattered from xenon enter the scintillating crystals with higher energy than those scattered from helium. This result is to be expected as the protons lose about 30% of their energy in scattering from helium at 90° (c.m.).

RESULTS

Eleven runs were made with helium, and an equal number with xenon. The crystals were changed three times and three different foil thicknesses were used between the two chambers. Each run lasted about 12 hours and consisted of about 12 cycles with gas in and gas out of the chamber. The statistical accuracy of the xenon data was considerably better than that of the helium data because (1) the scattering yield from xenon is higher, (2) the protons lose about 30% of their energy in the helium scattering at 90° (c.m.) and are therefore in a region of higher background, and (3) the wide angular acceptance introduces a spread in laboratory energy in the helium scattering. The statistical accuracy of the data is therefore limited almost entirely by the statistics in the helium data. A summary of the measure-

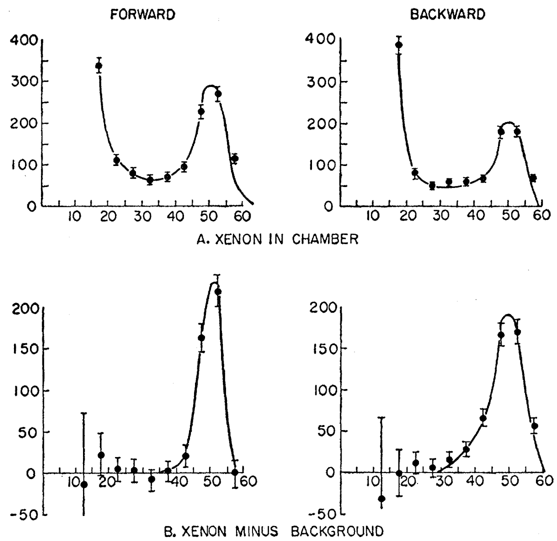

FIG. 3. Observed pulse-height spectra for one proton-xenon scattering run.

ments is given in Table II. In order to handle the data in an objective fashion, the yield for each run was obtained by adding up all channels above channel 2 (channel 3 is centered at 22.5 volts in Figs. 2 and 3). The result is not changed significantly when the less objective procedure is used of selecting only those channels which appear to contain the proton groups. The helium data have been corrected for the asymmetry obtained with xenon as scatterer, as explained above. The errors given in Table II include statistical uncertainties only. The uncertainty in the data using the 2.0×10^{-3} in. aluminum foil is large since the protons were in a region of high background because of their lower energy.

The measured forward-backward ratio is related to the polarization by the well-known formula:

$$R=(1+P_1P_2)/(1-P_1P_2),$$

where R=forward-backward ratio (forward and backward being defined relative to the direction of the incident deuteron beam), P_1=polarization before scattering, and P_2=polarization efficiency of analyzer. The quantity P_1 can therefore be determined from

$$P_1=\frac{1}{P_2}\left(\frac{1-R}{1+R}\right).$$

P_2 was calculated as a function of energy for the p-α scattering, according to the formula of Wolfenstein,[10] using the phase shifts of Critchfield and Dodder.[11] The phase shifts corresponding to an inverted doublet in Li^5

[11] C. L. Critchfield and D. C. Dodder, Phys. Rev. **76**, 602 (1949). It should be noted that these authors, as well as those in reference 12, define the vector along which the polarization is measured antiparallel to the reference vector used in the present work.

TABLE II. Analysis of the data.

Foil thickness 10^{-3} in. Al	Number forward	Number backward	Ratio forward/backward	E_p Mev	P_2 %	P_1 %
1.0	1533	1412	1.09 ± 0.07	3.25	28	$-(15\pm11)$
1.5	810	700	1.16 ± 0.10	2.94	47	$-(16\pm9)$
2.0	729	530	1.38 ± 0.25	2.51	75	$-(21\pm14)$
Average						$-(17\pm7)$

were demonstrated to be the correct set by the double-scattering experiment of Heusinkveld and Freier.[12] The quantitative correctness of the polarization in p-α scattering as calculated from the phase shifts has been demonstrated by Juveland and Jentschke,[13] and by Scott and Segel.[14]

The agreement among the three values of P_1 at the different proton energies may be taken as further evidence for the correctness of the energy dependence of P_2 as computed from the phase shifts. The value of the polarization P_1 obtained by averaging the data in Table II is $-(17\pm7)\%$. Following the convention of previous authors, we measure the polarization with respect to the $[\mathbf{V}_d\times\mathbf{V}_p]$ axis, where $\mathbf{V}_d$ and $\mathbf{V}_p$ are the deuteron and proton velocities, respectively. The negative sign signifies that the polarization is antiparallel to this axis. The agreement in sign with the work of Bishop *et al.*[8] and Maglić[9] is easily demonstrated since these authors, working in the backward quadrant of the $H^2(d,p)H^3$ reaction, obtained just the opposite right-left asymmetry from the present result. The identity of the two incident deuterons in the center-of-mass system insures that the polarization must be antisymmetrical about 90° (c.m.). The agreement of the various neutron measurements with the proton result of Bishop *et al.*[8] is discussed by Meier *et al.*[5]

CONCLUSIONS

The observed polarization is in good agreement with other experiments, both as to magnitude and sign. The agreement within experimental error of the measurement of Bishop *et al.*[8] at 0.30 Mev, the present measurement at 0.64 Mev, and Maglić's[9] result at 1.20 Mev indicates that the polarization does not change rapidly with energy. This is emphasized by the fact that the polarization is not altered significantly when a thin target is used. This result is quite reasonable in view of the nonresonant character of the d-D reaction. There also appears to be fairly good agreement between the neutron and the proton polarization measurements, as expected from the general symmetry between the two reactions.

[12] M. Heusinkveld and G. Freier, Phys. Rev. **85**, 80 (1952).
[13] A. C. Juveland and W. Jentschke, Z. Physik **144**, 521 (1956).
[14] M. J. Scott and R. E. Segel, Phys. Rev. **100**, 1244(A) (1955). The uncertainties in the calculated p-α polarizations noted by these authors are small compared to the experimental errors in the present work.

Blin-Stoyle[15] has calculated a theoretical maximum polarization of 7% at 300 kev bombarding energy using the matrix elements of Beiduk, Pruett, and Konopinski[1] and assuming that only the tensor force contributes to the spin-orbit coupling. However, he shows that by a plausible alteration of the parameters of Beiduk *et al.*[1] one can remain within the experimental error on the angular distribution data and yet greatly increase the polarization. Cini,[16] using the same assumption, has calculated a maximum polarization of 9% at a bombarding energy of 500 kev and an angle of 51° (c.m.). Although the measured polarizations are in all cases higher than these theoretically predicted maxima, the crudeness of the theory renders the significance of these discrepancies doubtful.

[15] R. J. Blin-Stoyle, Proc. Phys. Soc. (London) **A65**, 949 (1952).
[16] M. Cini, Nuovo cimento **8**, 1007 (1951).

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Neutron-Proton Scattering at 90 Mev*

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An investigation of 90-Mev neutrons scattered by protons has been conducted with a cloud chamber filled with hydrogen or with a mixture of methane and hydrogen in a magnetic field of 22 000 gauss. The neutron energy spectrum has a full width at half-maximum of about 30 Mev. The neutron scattering angles range from 8° to 180° in the center-of-mass system. The differential scattering cross section is found to have a symmetry about 90° in the center-of-mass system.

1. INTRODUCTION

NEUTRON–proton scattering experiments at 90 Mev have been performed in the past few years by a number of observers, both with counters and with cloud chambers. The small neutron angles have been of particular interest because of their bearing on nuclear force theory. It is necessary to use entirely different experimental procedures for forward- and backward-scattered neutrons when counters are employed, and therefore it was felt that any questions about proper normalization could be checked by a thorough cloud-chamber experiment, where the corrections are few and of an entirely different nature. This experiment differed from that by Brueckner *et al.*[1] in the use of a higher magnetic field and a larger number of tracks at extreme angles, so as to increase the accuracy.

A summary of work of all types of experiments is given in the recent paper by Stahl and Ramsey.[1]

2. RESULTS AND CONCLUSIONS

The experiment here reported extended over a period of 3 years. Three runs were made. Altogether, 5019 actual tracks were carefully measured. Table I shows the operating conditions for the three runs.

The analysis of the first run (1951) was devoted to neutron angles lying between 8° and 40°, and between 140° and 180°, in the center-of-mass (c.m.) system. A total of 1738 actual tracks was measured and the angular distribution of the differential *n-p* scattering cross section obtained in this run is shown in Table II.

The data of the first run in the 140°–180° region were normalized to those of the third run in the same region. This same normalizing factor was used for the small-angle region.

The neutron energy spectra, obtained from forward proton tracks (neutron angles from 140° to 180° in the

TABLE I. Operating conditions for the three runs.

	Chamber gas	Chamber pressure (cm Hg)	Chamber temperature (°C)	Cycle of operation (min)
First run (1951)	98.1% hydrogen 1.9% water vapor	89.7	19.5	~1
Second run (1952)	56.5% methane 41.5% hydrogen 2.0% water vapor	84.1	19.5	~1
Third run (1953)	98.0% hydrogen 2.0% water vapor	89.3	19.3	~2

* This work was done under the auspices of the U. S. Atomic Energy Commission.
† Now at Middlebury College, Middlebury, Vermont.
[1] Hadley, Kelly, Leith, Segrè, Wiegand, and York, Phys. Rev. **75**, 351 (1949); Brueckner, Hartsough, Hayward, and Powell, Phys. Rev. **75**, 555 (1949); Robert H. Fox, University of California Radiation Laboratory Report UCRL-867, August, 1950 (unpublished); R. Wallace, Phys. Rev. **81**, 495 (1951); O. Chamberlain and S. W. Easley, Phys. Rev. **94**, 208 (1954); W. M. Powell, Phys. Rev. **94**, 786 (1954); Selove, Strauch, and Titus, Phys. Rev. **92**, 724 (1953); R. H. Stahl and N. F. Ramsey, Phys. Rev. **96**, 1310 (1954).