Polarization and Cross Section of Protons Scattered by He^3 from 4 to 13 MeV*

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The polarization of protons elastically scattered by He^3 has been measured at six proton energies between 4 and 13 MeV and center-of-mass angles from 59 to 110°. Additional measurements were made at 133° from 7 to 11 MeV and at 124° at 10.7 MeV. The main feature of the data is the large polarization occurring near 120° for all energies. The maximum polarization measured was $+0.65\pm0.06$ at 10.7 MeV and 124°. The maximum polarization measured at 4 MeV was $+0.40\pm0.04$ at 110°. Above 8.8 MeV the polarization in the vicinity of 80° is negative and as large as -0.21 ± 0.03 at 12.8 MeV and 77°. The agreement with the 10-MeV measurements of Rosen and Brolley is good. New cross-section data between 4 and 10.8 MeV are also given.

I. INTRODUCTION

SEVERAL theoretical and experimental investigations have been made of proton-He^3 elastic scattering in the energy range from 1 to 20 MeV. Before any experimental cross section data were available, Swan[1] calculated the differential cross section by assuming a central potential and by applying the resonating group method of Wheeler. The calculations disagreed qualitatively with the actual cross section as was shown by the subsequent measurements of Sweetman[2] and Lovberg.[3] Using a refinement of Swan's method, Bransden and co-workers[4] were able to obtain qualitative agreement with the experimental data[2,3,5–8] in the energy range from 1 to 19.4 MeV.

Phase-shift analyses of the cross-section measurements by Famularo *et al.*[7] in the energy range from 1 to 3.5 MeV have been made by Lowen[9] and by Frank and Gammel[10] taking into account *s* and *p* waves. Spin-orbit splitting was neglected in both analyses. Moreover, Lowen was able to fit the data using only the single *s*-wave and the single *p*-wave phase shift which results if spin-spin forces are also neglected. Frank and Gammel assumed a spin-dependent potential and used the Born approximation to obtain a relation between the singlet and triplet phase shifts with the same orbital angular momentum. This reduced the number of independent phase shifts from four to two. Using these two parameters they arrived at a unique set of phase shifts.

Recently Tombrello *et al.*[11] and Clegg *et al.*[12] have extended Lowen's analysis to higher energies. A fairly good fit was obtained for proton energies up to 11.5 MeV.

Both the resonating group calculations and the phase-shift analyses tacitly assumed that the scattered protons would be unpolarized. Rosen and Brolley[13] made the first measurement of the polarization. They measured a single angular distribution of the polarization at 10 MeV and found that at some angles the polarization was as large as 50%. Consequently future analyses must include spin-orbit forces if they are to be realistic. Hochberg *et al.*[14] have shown that the resonating group method, when applied to *n*-T scattering, is mathematically tractable with a spin-orbit term in the potential. Hopefully the more extensive data on polarization and cross sections that is now available, will stimulate a new resonating group analysis of the *p*-He^3 interaction including spin-orbit effects. It would be especially interesting to see if such a calculation would explain the small polarization ($<15\%$) observed in *p*-D and *n*-D scattering[5,15,16] and the large polarization observed in *p*-He^3 and *p*-T scattering.[17]

II. APPARATUS

Only a few details of the apparatus will be given here since it has been described previously.[18] The polarization

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of the scattered protons was measured by the conventional double scattering method.[19] Both targets were high-pressure gas cells. Protons scattered symmetrically to the right and to the left by the second target were counted in two detector telescopes, each containing a proportional counter and a scintillation counter in coincidence. Both the first and second scattering angles were variable. Scattering from He^4 at approximately 45° was used as the polarization analyzer.

III. EXPERIMENTAL PROCEDURE

Generally He^3 was used as the first target. However, for p-He^3 measurements at low energies or large scattering angles it was advantageous to scatter from He^4 first so as to have a higher energy in the p-α scattering and therefore a greater polarization. Target pressures in the first target of 8–20 atm were used. The second target pressure was about 6 atm for all measurements. The maximum He^3 target thickness was 180 keV.

In order to eliminate the relative counter efficiency of the two detector telescopes from the ratio of the intensities, the ratio was measured with the first scattering angle to the left and with the first scattering to the right of the incident beam. The geometric mean of the two ratios is independent of the relative counter efficiency.

A background measurement was made for each polarization measurement by evacuating the second cell, except when He^3 was the second target, in which case the background measurements were made by blocking the entrance to the second cell with a 0.5-mm sheet of Ta. It was necessary to leave the He^3 in the cell since there was the possibility that the (n,p) reaction ($Q=+0.764$ MeV) in He^3 might contribute to the background. The background varied between less than 1% and 39% of the total number of counts under the observed peak in the pulse-height spectrum.

Tests showed that only a negligibly small fraction of the background came from accidental coincidences. Furthermore, background runs with 0.5-mm Ta between the second target and the entrance to the detector telescopes gave the same measured background as the other methods mentioned above. Apparently the background arose almost completely from neutrons producing charged particles in the telescopes.

High purity He^3 was obtained[20] for the experiment at a pressure of from 1 to 2 atm. A "balloon pump"[21] was used to prepare the high-pressure targets. Contamination of the He^3 was checked by observing the energy spectrum of singly scattered protons at 45 and at 130° with an incident proton energy of 6.8 MeV. The only contaminants observed were elements several times as heavy as He^3; probably nitrogen and oxygen. They resulted in a scattered proton intensity $\leqslant 1.5\%$ of the intensity from He^3. No protons scattered from the metal walls and foils of the gas cells were observed in these tests.

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TABLE I. Polarization of protons elastically scattered by He^3. The symbols E_p, $\theta_{c.m.}$, $P(He^4)$, $\%B$, and $P(He^3)$ are, respectively, the laboratory proton bombarding energy, the center-of-mass scattering angle, the polarization in the scattering from He^4, the percentage background and the polarization in scattering from He^3. Positive polarization is in the direction of $\mathbf{k}_{inc}\times\mathbf{k}_{scatt}$.

E_p(MeV)	$\theta_{c.m.}$	$P(He^4)$	$\%B$	$P(He^3)$
4.05	60.1	−0.411	0.7	+0.147±0.024
	77.7	−0.411	2.5	+0.261±0.021
	94.5	−0.413	3.7	+0.359±0.024
	109.9	−0.411	10.4	+0.399±0.039
5.52	59.1	−0.245	0.3	−0.003±0.028
	77.7	−0.464	1.3	+0.122±0.021
	94.5	−0.465	4.0	+0.355±0.023
	109.9	−0.469	7.6	+0.468±0.029
6.83	59.1	−0.404	2.7	−0.029±0.017
	77.0	−0.311	4.0	+0.019±0.022
	94.5	−0.461	3.1	+0.310±0.025
	109.9	−0.461	4.3	+0.493±0.028
	132.7	−0.461	9.7	+0.309±0.024
8.83	59.1	−0.478	3.6	−0.042±0.018
	77.0	−0.452	6.9	−0.078±0.017
	94.0	−0.373	18.5	+0.041±0.040
	109.9	−0.428	16.4	+0.469±0.037
	132.7	−0.428	30.6	+0.354±0.041
10.74	59.1	−0.468	2.2	−0.128±0.021
	77.0	−0.480	6.4	−0.124±0.019
	94.0	−0.460	5.7	−0.083±0.024
	109.5	−0.369	10.2	+0.443±0.034
	123.7	−0.231	13.7	+0.648±0.063
	132.7	−0.397	38.6	+0.332±0.062
12.79	59.1	−0.444	3.8	−0.120±0.018
	77.0	−0.465	15.7	−0.214±0.033
	94.0	−0.480	10.2	−0.172±0.027
	109.5	−0.457	26.5	+0.315±0.044

IV. EXPERIMENTAL RESULTS AND UNCERTAINTIES

1. Polarization Measurements

The results of the polarization measurements are tabulated in Table I and shown graphically in Fig. 1. The uncertainty of the proton energy is ±0.07 MeV. It arises from uncertainties in the target gas pressures, the thickness of the metal foil windows and the stopping cross sections.

The uncertainty given for the polarization includes contributions from four different sources: (1) statistics, (2) uncertainty in the analyzing power in p-α scattering, (3) finite slit dimensions, and (4) uncertainty in the background. The last three sources of error will be discussed in the following.

The analyzing power in p-α scattering at 45° was taken from Brown *et al.*[18] While it was necessary to interpolate their results with respect to energy, this did not substantially increase the uncertainty. An uncertainty in the p-α polarization of ±0.015 was assumed for all of the measurements.

A discussion of the corrections to the experimental data arising from finite slit dimensions has been given

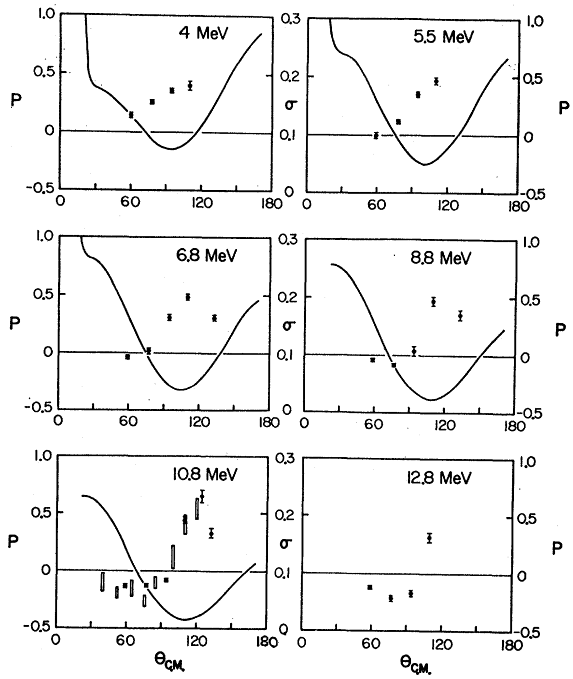

FIG. 1. Polarization and cross section of protons elastically scattered by He^3. The present polarization data are represented by dots. The open rectangles are the measurements of Rosen and Brolley at 10 MeV (Ref. 13). The solid lines are smooth curves drawn through the present cross-section measurements (Table II). The cross-section scale is in the center-of-mass system and is given in units of barns per steradian.

by Brown *et al.*[18] Using their general method the upper bound for the geometrical corrections to the measured left-right intensity ratio was found to be approximately 1% of the ratio. Since in the present experiment no corrections were applied, an uncertainty of ±1% of the ratio was added.

The uncertainty in the background measurements is difficult to evaluate accurately but it is important since the background was large in some cases. The background is produced almost entirely by neutrons which presumably originate mainly at the defining slits for the beam from the accelerator and at the beam stop. If the same neutron flux was produced during a foreground and a background run, the background subtraction would undoubtedly be very accurate. In practice the background is subject to fluctuations. To assure reliable results several foreground and background measurements were made for each point to check the internal consistency of the data. The background fluctuations were found to be essentially random. Roughly speaking, a 10% background resulted in an uncertainty of ±0.01 in the polarization and proportionally more or less for higher or lower background. The percentage background for each polarization measurement is tabulated in Table I.

The final uncertainty given in Table I is the square root of the sum of the squares of the four uncertainties listed above.

An additional uncertainty can arise from misalignment. The greatest uncertainty of this type arises from a 0.2° uncertainty in the angle between the detector telescopes. This contributes a maximum uncertainty of 0.1% of the left-right intensity ratio.

2. Cross Section Measurements

Differential cross section measurements were made for 16 angles at each of five bombarding energies between 4.00 and 10.77 MeV. The results are listed in Table II and shown as solid lines in Fig. 1. An excitation curve at a center-of-mass angle of 170.6° was taken from 4.0 to 10.8 MeV. These results are shown in Fig. 2 together with the results of Tombrello[11] at lower energies.

The measurements were carried out with a scattering

TABLE II. Center-of-mass cross sections for protons elastically scattered by He^3. The tabulated energies are in the laboratory coordinate system. The cross sections are in millibarns.

	4.00 MeV	5.51 MeV	6.82 MeV	8.82 MeV	10.77 MeV
$\theta_{c.m.}$	$\sigma_{c.m.}$	$\sigma_{c.m.}$	$\sigma_{c.m.}$	$\sigma_{c.m.}$	$\sigma_{c.m.}$
18.63	478 ±24	311 ±20	307 ±13	260 ±12	221 ±18
22.60	249 ±14	252.9± 9.6	266.8± 7.5	255.2± 8.9	231.1± 5.3
26.57	187.3± 4.1	242.0± 7.3	264.9± 6.9	256.7± 6.9	226.6± 6.1
30.50	176.6± 3.9	243.4± 6.8	263.3± 6.8	252.8± 5.6	224.5± 6.3
34.42	172.8± 3.8	236.2± 6.1	253.6± 6.8	247.0± 5.4	224.6± 6.1
38.32	168.9± 4.4	231.3± 6.0	245.5± 6.4	237.4± 5.7	210.9± 5.9
42.20	164.0± 4.3	225.0± 5.9	236.8± 6.2	226.6± 5.4	200.4± 5.6
58.92	130.0± 2.9	162.7± 3.6	168.4± 3.7	158.6± 3.8	144.7± 4.0
77.05	90.3± 2.1	95.1± 2.2	92.8± 2.0	83.8± 1.9	74.1± 1.9
94.03	71.3± 1.6	55.9± 1.3	46.5± 1.0	37.8± 0.9	31.8± 0.8
109.72	84.6± 1.9	54.8± 1.2	37.3± 0.8	22.8± 1.0	15.4± 0.4
124.02	122.2± 2.7	83.6± 1.8	57.6± 1.3	34.8± 0.8	22.2± 0.5
132.80	151.6± 3.3	110.4± 2.4	81.8± 1.8	51.8± 1.2	34.7± 0.8
144.98	194.8± 4.3	156.7± 3.4	121.8± 2.7	83.8± 2.0	60.8± 1.3
156.18	238.5± 5.2	196.1± 4.3	160.2± 3.5	115.8± 2.8	87.9± 1.9
170.63	270.4± 5.7	233.9± 5.2	191.6± 4.2	145.1± 3.2	113.0± 2.5

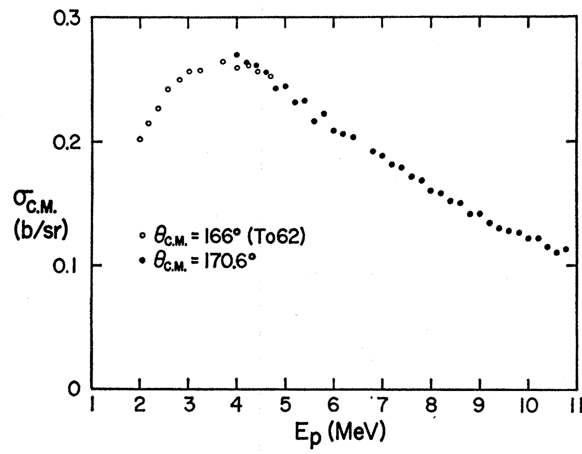

FIG. 2. Cross section of protons elastically scattered by He^3. The open circles are measurements by Tombrello *et al.* (Ref. 11) for a center-of-mass scattering angle of 166°. The present data (dots) are for a center-of-mass angle of 170.6°.

chamber[22] which had a beam entrance foil either of carbon ($\sim$1 mg/cm^2) or aluminum ($\sim$0.6 mg/cm^2). The analyzing slits were circular apertures of 2.5-mm diameter; the extreme angular spread was about $\pm 2°$. A silicon surface barrier detector was used.

Most of the data was taken with a He^3 pressure of about 0.1 atm, although for some measurements at foreward angles a pressure of 0.02 atm was used.

Several corrections were applied to the data. A correction of about 2% was applied to the target pressure because of the presence of air contamination in the target gas. Except at the most foreward angles, the protons scattered by air and by He^3 were well resolved in the pulse-height spectrum. At these angles, a correction to the yield for the unresolved contamination peak was made by extrapolating the intensity observed at larger angles, assuming that the angular dependence is that of Rutherford scattering.

Geometrical corrections were made to compensate for the extended size of the detector slits[23] and for the finite extent of the incident proton beam,[24] taking into account the spreading of the beam by scattering in the foil. The correction is energy dependent because of multiple scattering in the foil. The average correction was about 1%. In addition the 4-MeV data had to be corrected by 0.2% for beam not collected in the Faraday cup because of multiple scattering in the foil that sealed off the chamber.

The over-all estimated uncertainty of the cross section (compounded of both systematic and random uncertainties) is given in Table II for each measurement. The uncertainty is less than $\pm 3\%$ in most cases. The statistical uncertainty (usually less than 1%) is also included. The proton energy is uncertain by about ± 15 keV. The uncertainty in angle is less than 0.2°.

In order to check the reliability of the measurements, proton-proton scattering data were taken at several angles for 3.037, 4.203, and 9.69 MeV, where the cross sections are well known.[25,26] The measurements agreed with the published values within the uncertainty assigned to our measurements. Another check on the data was obtained from cross sections found from He^3 recoils. Agreement with interpolated back-angle data was within 2%.

At laboratory angles less than 45°, data were taken on both the left and right side, to cancel the effect of slight asymmetry caused by a small deviation of the incident beam direction from the geometric axis of the chamber.

V. DISCUSSION OF RESULTS

Comparison of our cross-section data with those of Clegg *et al.*[12] shows agreement within the assigned errors. However, on the average, their cross sections are about 2% higher than ours. The difference between the present data and those of Brolley *et al.*[27] at 6.5 and 8.34 MeV is less than 4%, except for a few points where differences as large as 22% occur.

The principal feature of the polarization data is the large polarization observed in the vicinity of 120° at all energies. The maximum polarization occurs within the interval 115°$\pm$10° at energies of 6.83 through 10.74 MeV. At lower and higher energies the data are not complete enough to define the position of the maximum although it probably still is in the same region. The angle at which the polarization goes through zero moves toward smaller angles as the energy is decreased. It moves from approximately 100° at 12.8 MeV to about 60° at 5.5 MeV.

The maximum observed polarization decreases from 0.65 at 10.7 MeV to 0.40 at the lowest energy. The slow change of the polarization with energy is consistent with the absence of any resonance structure in the energy dependence of the cross section (Fig. 2). The angular distributions over this energy range (see Fig. 1) are characterized by a single minimum at approximately 105°. Thus, the polarization maximum occurs within about 10° of the cross-section minimum.

Measurements of the polarization by Rosen and Brolley[13] at 10 MeV are in good agreement with the present results at 10.8 MeV (see Fig. 1). The measurements at 14.5 MeV by Rosen and Leland[17] are close to the present results at 12.8 MeV.

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Ali *et al.*[28] have analyzed the differential cross-section data of Sweetman[2] and Lovberg[3] in terms of an optical-model with a square-well potential and a spin-orbit term. At 9.8 MeV the calculated polarization is in qualitative agreement with the present measurements, while at lower energies the agreement is poorer.

So far no phase-shift analysis of p-He^3 scattering has been carried out which takes into account polarization. In the recent analysis of the Rice group[12] it was pointed out that no spin dependence of the phase shifts is required in fitting the cross section up to about 8 MeV. The present results show that already at much lower energies the polarization is quite large and therefore an analysis neglecting spin dependence is unrealistic.

The present results suggest that the polarization is appreciable even below 4 MeV. At 4 MeV the present measurement at 78° gives a polarization of 0.26 ± 0.02. An extrapolation to lower energies suggests that at this angle the polarization is increasing with decreasing energy. If charge symmetry of nuclear forces holds and if Coulomb effects are not important, the p-He^3 polarization should be the same as the n-T polarization. Seagrave and co-workers[29] measured the polarization for n-T scattering at 1 MeV. The largest value they found was 0.10 ± 0.07 at 83°. Clearly it would be interesting to extend the present measurements below 4 MeV and to carry the n-T measurements to higher energies.

A phase-shift analysis of p-He^3 scattering should be carried out without *a priori* assumptions about spin-spin or spin-orbit forces. The difficulty is that a relatively large number of phase shifts must be determined. It would therefore be desirable to have additional experimental information beyond the cross section and the polarization of the scattered protons. If one excludes triple scattering experiments, the only other possibility is to measure the polarization of the recoiling He^3 nuclei. This in fact gives additional data which is independent of the proton polarization data. In practice this experiment could be carried out by bombarding a target of polarized He^3 with unpolarized protons and measuring the left-right asymmetry of the outgoing particles. It has recently been shown[30,31] that such an experiment is feasible.

Note added in proof. In reporting the present results it was assumed that the so-called polarization-asymmetry theorem holds. To test for a possible violation of the invariance principle (reciprocity) which underlies this theorem,[32] P and A were measured accurately at 10.0 MeV for a center-of-mass angle of 60.1°. The results were $P=-0.094\pm0.009$, $A=-0.106\pm0.009$. The results agree well with each other and with the value -0.10 obtained by interpolating the results given in this paper.

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