Polarization Measurements in p-α Elastic Scattering*†

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The polarization of protons elastically scattered from alpha particles was observed by measuring the asymmetry obtained by doubly scattering protons in helium. Protons from the Brookhaven National Laboratory Van de Graaff generator entered a helium-filled double-scattering chamber through a 50-microinch nickel window. The first scattering was at either 104° 29′ (c.m.) or 73° 38′ (c.m.) and the second scattering was to left and right at 73° 38′ (c.m.). The doubly scattered protons were detected by 50-μ Ilford C-2 plates. The polarization product, P_aP_b, was calculated from the left-right ratio (R) using the formula $R=(1+P_aP_b)/(1-P_aP_b)$, where P_a and P_b are the polarizations at the first and second scatterings, respectively. Three interdependent measurements, in which P_aP_b was equal to P_1P_2, P_1P_3, or P_2P_3, yielded values for P_1[3.580 Mev, 104° 29′ (c.m.)], P_2[2.020 Mev, 73° 38′ (c.m.)], and P_3[1.375 Mev, 73° 38′ (c.m.)]. The calculated polarizations are in the direction of the normal $\mathbf{n}$ ($\mathbf{n}=\mathbf{k}_0\times\mathbf{k}/|\mathbf{k}_0\times\mathbf{k}|$) to the scattering plane. The following results were obtained:

Polarization measured	Experimental value (%)	Calculated value (%)
P_1	54±2	+59±13
P_2	85±3	+80± 4
P_3	62±2	+59±16

INTRODUCTION

THE polarization of spin $\frac{1}{2}$ particles resulting from nuclear reactions may be defined in terms of the number (N_{up}) of protons with their spins parallel to the normal $\mathbf{n}$ ($\mathbf{n}=\mathbf{k}_0\times\mathbf{k}/|\mathbf{k}_0\times\mathbf{k}|$, where $\mathbf{k}_0$ and $\mathbf{k}$ are the momenta of the incoming and outgoing particles, respectively) to the reaction plane, and the number (N_{down}) with their spins antiparallel to the normal. This is the same definition of positive polarization as used by Wolfenstein,[1] and is the negative of that used by Lepore.[2] The polarization is therefore always perpendicular to the plane of the reaction. The polarization may be calculated from the left-right asymmetry obtained by demanding that the spin $\frac{1}{2}$ particles undergo a second polarization-dependent reaction, which will be called the analyzing reaction. In order to understand this clearly, let us consider the double scattering of protons by helium. The ratio R of the number of protons scattered twice to the right (or left) to the number scattered once to the left and once to the right is:

$$R=\frac{1+P_1(E_1,\theta_1)P_2(E_2,\theta_2)}{1-P_1(E_1,\theta_1)P_2(E_2,\theta_2)},$$

where P_1 and P_2 are the polarizations which would result from an unpolarized beam scattering at energies and angles E_1, θ_1, and E_2, θ_2, respectively.

Numerical values of the polarization in proton-alpha elastic scattering as a function of energy and angle can be calculated from the angular distributions when a spin-orbit force is assumed to be present in the nuclear forces. The experimental verification of the existance of polarization effects shows that a spin-orbit force is a necessary part of the nuclear forces. The usual method of calculating the polarization is to perform a phase shift analysis of the angular distribution data and then to use the resultant phase shifts in the calculation of the polarization. The formulas for the polarization P in terms of the phase shifts and the energy and angle of scattering are given below for p-α elastic scattering.[1]

$$P=P\sigma/\sigma,$$

$$P\sigma=2\sin\theta\sin(\delta_1^+-\delta_1^-)[(\alpha/2s^2)\sin(\delta_1^++\delta_1^-+\sigma_1+\alpha\ln s^2)-\sin\delta_0\sin(\delta_1^++\delta_1^-+\sigma_1-\delta_0)-3\cos\theta\sin\delta_1^+\sin\delta_1^-],$$

$$\sigma=(\alpha/2s^2)^2+\sin^2\delta_0+\cos^2\theta[4\sin\delta_1^+\sin\delta_1^-\times\cos(\delta_1^+-\delta_1^-)+4\sin^2\delta_1^++\sin^2\delta_1^-]-2(\alpha/2s^2)\sin\delta_0\cos(\alpha\ln s^2+\delta_0)-2(\alpha/2s^2)\times\cos\theta[2\sin\delta_1^+\cos(\alpha\ln s^2+\sigma_1+\delta_1^+)+\sin\delta_1^-\cos(\alpha\ln s^2+\sigma_1+\delta_1^-)]+2\sin\delta_0\sin\theta\times[2\sin\delta_1^+\cos(\delta_0-\sigma_1-\delta_1^+)+\sin\delta_1^-\times\cos(\delta_0-\sigma_1-\delta_1^-)]+\sin^2\theta\sin^2(\delta_1^+-\delta_1^-),$$

where θ=scattering angle, δ_0=s-wave phase shift, δ_1^+=p-wave phase shift for $j=\frac{3}{2}$, δ_1^-=p-wave phase shift for $j=\frac{1}{2}$, $s=\sin(\theta/2)$, $\alpha=(ze^2\mu)/(k\hbar^2)$, $\sigma_1=2\tan^{-1}\alpha$, and σ is proportional to the differential cross section.

The method of calculating the polarization from the angular distribution by means of the phase shifts inherently yields a large uncertainty in the polarization. The phase shifts are fitted to the angular distribution in such a way as to minimize their errors with respect to the angular distribution data. Since the dependence

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[1] L. Wolfenstein, Phys. Rev. **75**, 1664 (1949).
[2] J. V. Lepore, Phys. Rev. **78**, 137 (1950).

of the polarization on the phase shifts is different from that of the angular distribution, namely all terms are proportional to a trigonometric function of the difference between the $p_{\frac{3}{2}}$ and $p_{\frac{1}{2}}$ phase shifts, the polarization is more sensitive than the angular distribution to uncertainties in the phase shifts.

In order to ascertain the magnitude of the uncertainties in the polarizations resulting from uncertainties in the phase shifts, $P\pm dP$ was calculated from the phase shifts and uncertainties as given by Critchfield and Dodder.[3] The calculation of dP was done using the statistical error formula.[4] This formula states that the error ΔF in a function $F(x_i)$, $i=1$ to n, in terms of the Δx_i, is given by

$$\Delta F(x_i)=\left[\sum_{i=1}^{n}\left(\frac{\partial F}{\partial x_i}\Delta x_i\right)^2\right]^{\frac{1}{2}}.$$

This method of calculation of dP assumes the phase shifts to be independent variables and does not take into consideration the interdependency of the phase shifts. Therefore the calculated values of dP are likely to be larger than the actual uncertainties in the polarization P due to uncertainties in the phase shifts.

The phase shift analysis of the angular distribution of protons elastically scattered from alpha particles yields two independent sets of phase shifts which fit the data equally well. These two sets of phase shifts correspond to a real and an inverted doublet in Li^5.

Since the calculated polarization, as a function of energy and angle, is quite different for the two sets of phase shifts, Heusinkveld and Freier[5] performed a double scattering experiment in which the energies and angles were chosen so that the final ratio would be about 2 for an inverted doublet and about 1/20 for a real doublet. Their results proved conclusively that the better set of phase shifts is that corresponding to an inverted doublet, so that the $p_{\frac{3}{2}}$ level in Li^5 is at a lower energy than the $p_{\frac{1}{2}}$ level.

Another measurement of the polarization in p-α elastic scattering by double scattering protons in helium was performed by Juveland and Jentschke.[6] They chose energies and angles for the two scatterings in order to check the prediction of the calculated polarizations that the sign of the polarization changes in the vicinity of about 4 Mev for certain angles. Their results were in agreement with the polarizations calculated from the angular distribution data.

In the experiment of Heusinkveld and Freier,[5] the statistics were very poor and the acceptance criteria for the energies and angles were very large.

Juveland and Jentschke[6] measured the polarization product P_1P_2, where P_1 and P_2 were the polarizations at the first and second scatterings, respectively, with the energy and angle of the first scattering such that, according to the calculated values of the polarization, P_1 should be negative. In analyzing their results, they used the calculated value of P_2 without taking into consideration the uncertainties in $P_{2(\text{calc})}$ due to uncertainties in the phase shifts.

TABLE I. Results of the double-scattering experiment of Scott and Segel.[a]

Measurement	R(observed)	P_aP_b(observed)	P_aP_b(calculated)
P_1P_2	2.19±0.09	0.37±0.05	0.48±0.11
P_1P_3	1.94±0.09	0.32±0.05	0.35±0.09
P_1P_4	1.57±0.08	0.22±0.05	0.18±0.05

[a] See reference 7.

It is to be noted that the validity of these experiments is not being questioned. They were designed to detect gross effects and therefore did not yield a quantitative check on the calculated values of the p-α polarization.

The double-scattering experiment of Scott and Segel,[7] which was the forerunner of the experiment reported here, measured the three polarization products: P_1P_2, P_1P_3, and P_1P_4, where P_1 was the polarization at $E_1=2.865$ Mev and $\theta_1=76°$ [90° (c.m.)] and P_2, P_3, and P_4 were the polarizations at $E_2=1.640$ Mev and $\theta_2=61°$ [73° (c.m.)], $\theta_3=86°$ [110° (c.m.)], and $\theta_4=111°$ [124.5° (c.m.)], respectively. The results, which are shown in Table I, agree with the polarizations calculated from the phase shifts, within the limits of error of the experimental and calculated results.

These more accurate results cannot be analyzed in terms of the individual polarizations since the polarizations were not measured individually but only as inseparable parts of a product. They therefore indicated a need for a careful measurement of individual polarizations in p-α elastic scattering. Unfortunately, in most double-scattering experiments, the result is the product of two polarizations, not an individual polarization.

Individual polarizations in p-α elastic scattering can be measured by means of three interdependent measurements in which the polarization product P_aP_b is equal to P_1P_2, P_2P_3, or P_1P_3. P_a and P_b are the polarizations at the first and second scatterings respectively and P_1, P_2, and P_3 are the polarizations of protons scattered at energies E_1, E_2, and E_3 through angles in the laboratory system of θ_1, θ_2, and θ_3, respectively. The present experiment was designed to make these three interdependent measurements.

The results of these measurements can be analyzed in terms of three equations in three unknowns. The explicit solution of the equations may be seen by considering the values of the ratio R obtained from the first, second, and third measurements, which are $R_{1,2}$, $R_{2,3}$, and $R_{1,3}$, respectively. The polarization products

[3] C. L. Critchfield and D. C. Dodder, Phys. Rev. **76**, 602 (1949).
[4] H. Margenau and G. M. Murphy, *The Mathematics of Physics and Chemistry* (D. Van Nostrand Company, Inc., Princeton, New Jersey, 1947), second edition, p. 498.
[5] M. Heusinkveld and G. Freier, Phys. Rev. **85**, 80 (1952).
[6] A. C. Juveland and W. K. Jentschke, Z. Physik **144**, 521 (1956).
[7] M. J. Scott and R. E. Segel, Bull. Am. Phys. Soc. Ser. II, **30**, 16 (1955).

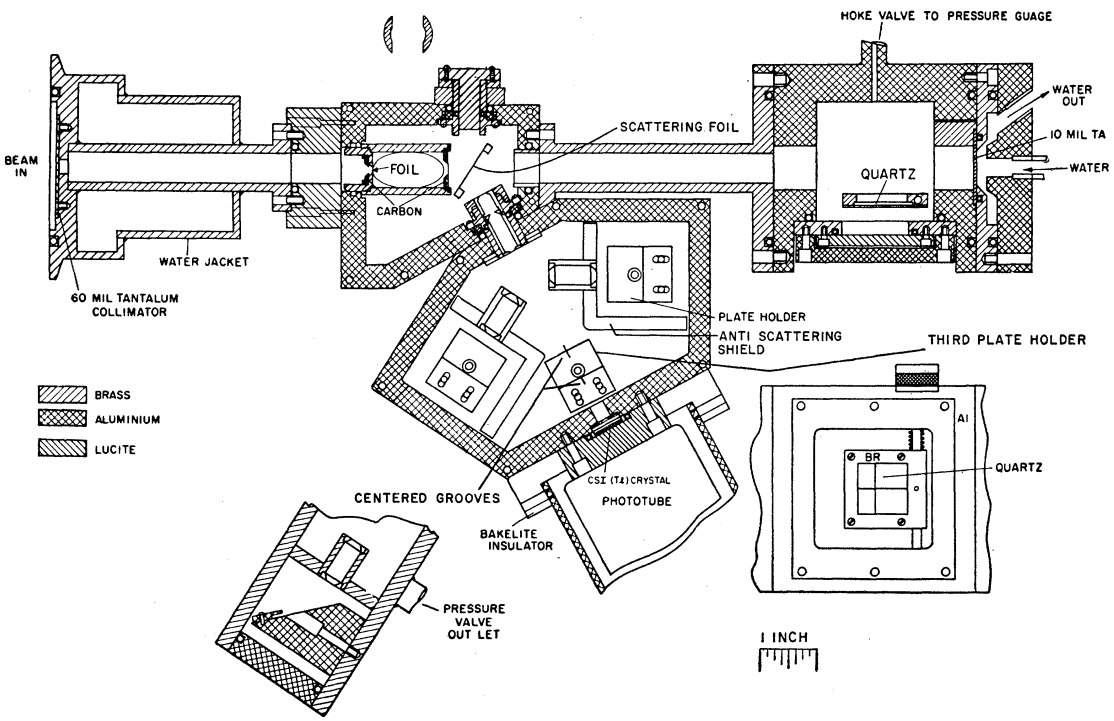

FIG. 1. Target chambers with scattering foil and third plate holder in position.

P_aP_b resulting from these ratios are called $N_{1,2}$, $N_{2,3}$, and $N_{1,3}$, respectively. The polarizations may then be written down directly:

$$P_1=(N_{1,2}N_{1,3}/N_{2,3})^{\frac{1}{2}},$$
$$P_2=(N_{1,2}N_{2,3}/N_{1,3})^{\frac{1}{2}},$$
$$P_3=(N_{1,3}N_{2,3}/N_{1,2})^{\frac{1}{2}}.$$

Two of the energies (3.58 Mev and 2.02 Mev) at which the polarization is measured were chosen to be energies at which the cross section and angular distribution had been previously measured[8] in the hope that combining the data from the two experiments might yield better values of the phase shifts.

It is to be noted that the measurements given here, because of their improved accuracy over other polarization measurements, should be of use when helium is used as an analyzer for protons of unknown polarization.

EXPERIMENTAL PROCEDURE

In the first measurement a fairly high bombarding energy was used and the polarization at the first scattering was P_1(3.58 Mev). The polarization at the second scattering was then P_2(2.02 Mev), since energy was lost both by giving energy to the helium nucleus in the first scattering and in the helium gas between the two scatterings.

[8] Freier, Lampi, Sleator, and Williams, Phys. Rev. **75**, 1345 (1949).

The bombarding energy for the second measurement was then chosen to that the energy at the first scattering was the same as that at the second scattering in the first measurement and the polarization was again P_2(2.02 Mev). The polarization at the second scattering in the second measurement was then P_3(1.375 Mev).

The bombarding energy for the third measurement was the same as that for the first measurement so that the polarization at the first scattering was again P_1(3.58 Mev). A foil was then placed between the first and second scatterings in order to degrade the proton energy so that the energy at the second scattering in the third measurement would be the same as that at the second scattering in the second measurement and the polarization would be P_3(1.375 Mev).

Wolfenstein[1] has shown that charged particles of these energies do not lose their polarization in passing through matter and therefore the foil between the first and second scatterings lowers the proton energy without affecting the polarization.

A diagram of the experimental arrangement is shown in Fig. 1. The four main components are a first-scattering chamber, a second-scattering chamber, a line-up chamber, and a phototube. The second chamber may be placed either in the position shown, with its axis at an angle of 61° from the direction of the incoming beam, or on the opposite side of the first chamber, with its axis at an angle of 90° from the direction of the incoming beam.

The P_2P_3 run was taken with the second chamber in

the 61° position, and the P_1P_2 and P_1P_3 runs were taken with the second chamber in the 90° position. In both positions, the second chamber may be rotated through 180° about its own axis.

Wallace and Tiernan gauges were used to measure absolute pressure in units of millimeters of mercury. The ranges of the gauges on the first and second chambers were 400 to 800 mm, and 0 to 400 mm, respectively.

The first scattering chamber was sometimes modified by the addition of a scattering foil cemented to a U-shaped holder (Fig. 1). This was done when it was desirable to scatter protons of a well-defined energy into the second chamber.

A third plate-holder was sometimes placed in the second chamber directly in front of the phototube collimator (Fig. 1). It was equipped with positioning-pins to insure reproducibility of position and was grooved as shown to aid in marking the center of the chamber on the nuclear emulsions. It was used to detect the singly scattered protons.

The piece of quartz in the line-up chamber could be rotated to a position which was at an angle of 45° from the position shown so that the cross-hairs indicated the center axis of the first chamber. By means of horizontal and vertical screws in the support of the chamber, it was possible to change the position of the chamber until the cross-hairs were in the center of the spot formed on the quartz by the beam. It was necessary to cover the Lucite lid while a run was in progress in order to prevent scattered light from reaching the emulsions.

The phototube was used to detect singly scattered protons. A thin CsI(Tl) crystal was optically coupled to a Lucite light pipe which was then coupled to a DuMont 6292 phototube. Vaseline was used as the coupling material. The CsI(Tl) crystal was covered by a 40-microinch aluminum foil to protect it from the light generated in the helium gas by the proton beam. The output of the phototube was fed into a Radiation Instrument Development Laboratory hundred-channel pulse-height analyzer through a linear amplifier.

The water jacket in back of the 60-mil tantalum collimator and the water-cooled backstop were necessitated by the large beam currents which were used.

In order to increase the yield in this experiment, the 50-microinch nickel entrance foil (grade *B*, obtained from the Chromium Corporation of America) was cooled with a jet of cooled helium. If a foil is not cooled, the maximum current which can be used without breaking the foil is about two microamperes. When a foil is cooled, as was done in this experiment, the maximum becomes about 20 microamperes. The apparatus is easy to construct once the basic design is known. The construction of the cooling system and the procedure followed in cementing the foil to the entrance collimator is described elsewhere.[9]

[9] M. J. Scott and R. Lindgren, Rev. Sci. Instr. **28**, 1090 (1957).

When it was desirable to have different gases in the first and second chambers, a foil was cemented over the central defining aperture of the interchamber collimator. The cementing procedure was the same as that for the entrance foil for the first chamber.

The entrance collimator was held in position by the pressure of the gas inside the first scattering chamber. The interchamber collimator was mechanically positioned by a screw-on cap since there usually was no pressure differential between the first and second scattering chambers to position the interchamber collimator reproducibly.

The antiscattering shields (Fig. 1) in the second target chamber were hard-soldered to the bottom lid of the chamber and the final collimators were press fit into the shields. Positioning-pins in the lid assured reproducibility of alignment of the final collimators relative to the interchamber collimator. It was not necessary to position the plate holders precisely since the final collimators defined the proton beam which was incident on the nuclear emulsions.

The plate holders were designed so that the protons would enter the emulsion at an average angle of 45° in order to yield a maximum track length projection when the emulsion was placed on the horizontal stage of a microscope, without significantly increasing the emulsion area to be scanned.

It is obvious that in this experiment, in spite of taking all reasonable precautions in the construction of the apparatus, one could never be certain that all spurious asymmetries had been eliminated and only polarization effects remained. It is therefore desirable to measure directly the asymmetries not due to polarization.

Pure Coulomb scattering is known to be polarization-insensitive at the energies and angles used here.[1] When a heavy gas is substituted for the helium in the second scattering chamber, most of the asymmetries due to nonpolarization effects are therefore measured. Furthermore, the strong angular dependence of Coulomb scattering would enhance the effect of asymmetries caused by errors in angle. A heavy gas is one in which the charge on the nucleus is sufficiently large so that the Coulomb scattering predominates at the proton energies used. Xenon ($Z=34$) was used in the present experiment.

Normalization to the xenon asymmetries would be sufficient if the geometrical asymmetries were only due to errors in the measurement of distances and dimensions in the second scattering chamber, i.e., length of the final collimators, size of the defining apertures, their distance from the center of the second scattering volume, etc. However, asymmetries can also be introduced by errors in the definition of angles. If the final collimators are at different angles relative to the beam entering the second chamber, the ratio (R) could well be affected since the angular distributions of protons scattered by helium and xenon are not spherically

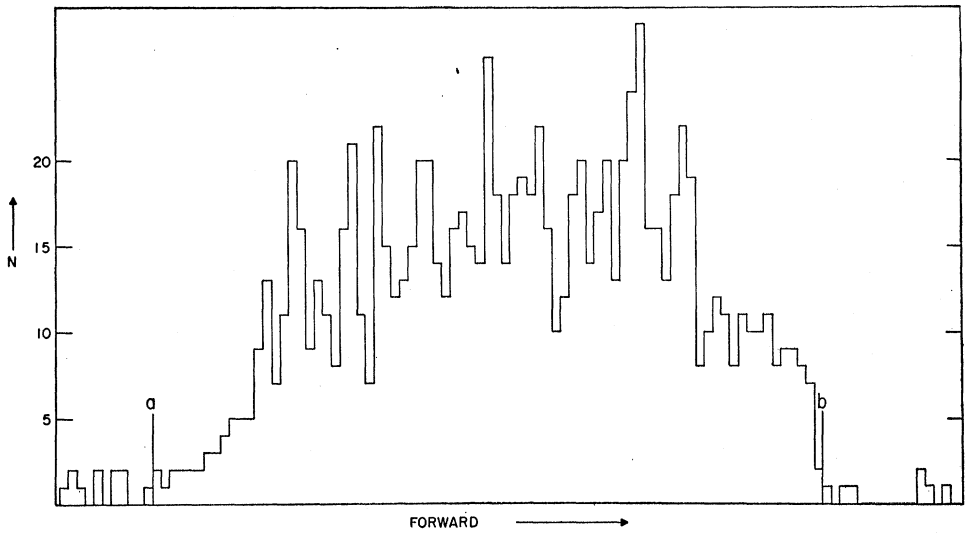

FIG. 2. The number of tracks (N) per swath *vs* position on the detection plate. Data from a P_1P_2 plate were used. The protons detected at b were scattered through smaller angles than those detected at a. The area located between a and b was considered to be the significant area of the plate. On the basis of all other tracks the background was estimated to be 0.63 ± 0.13 tracks per swath and subtracted from the number of tracks in each swath in the significant area. Each swath was approximately 0.08 mm wide and 12 mm long so that the distance on the figure between a and b corresponds to 6.4 mm.

symmetric. Furthermore, the two angular distributions are somewhat different, which means that different asymmetries could be introduced in the two cases.

A large part of the error due to improper angular definition can be eliminated by repeating all runs with the second scattering chamber rotated through 180° about its own axis. The angular error should then be cancelled in averaging the results of the "up" and "over" runs, and the helium to xenon ratio should be the same in the two positions. The xenon ratio should average to unity unless either an asymmetry has been introduced by the variation in the p-α cross section over the angular definition of the interchamber collimator, or the interchamber collimator system is misaligned with respect to the first chamber.

In this experiment, there was no measurable chamber asymmetry and the ratio measured with the second chamber in the "up" position was within statistics of that measured in the "over" position. However, the average of the xenon runs was 0.965 ± 0.012, indicating a slight asymmetry due to effects in the first chamber or in the interchamber collimator.

Since the effect on the xenon ratio could differ from the effect on the helium ratio, because of the different angular distribution over the angular definition of the final collimators, calculations were done of the expected ratios for the cases of helium and xenon in the second chamber. The helium calculation was done for the P_1P_2, P_1P_3, and P_2P_3 measurements and the xenon calculation was done for the two cases of the second chamber on the 90° and 61° sides of the first scattering chamber.

The results of these calculations do not show any significant difference between the xenon ratios and the helium ratios. The calculated ratios are all within one percent of unity so that the experimental xenon ratio was probably due to an interchamber asymmetry and not to the variation in p-α cross section over the angular definition of the interchamber collimator.

In view of the fact mentioned above that the strong angular dependence of Coulomb scattering would tend to enhance the effect of asymmetries due to angular inaccuracies, it was decided to use one-half of the asymmetries measured by the xenon runs as the correction factor for the helium runs. An error of 2% in the xenon measurement would result in an error of only about 0.5% in the measured value of the polarization.

A xenon run was taken for each set of helium runs in order to check that the target chamber could be taken apart and reassembled reproducibly. Since the results of the xenon runs did not show a statistically significant variation, it was decided to average them in order to obtain the correction factor for the helium runs to as great an accuracy as possible. The results for all the xenon runs are given in detail in Table II.

Tracks on the emulsions which were not due to protons that had been doubly scattered in helium were another possible source of spurious asymmetries. These tracks, which could have been caused by either protons or neutrons, could either increase or decrease the measured ratios.

The background due to neutrons was measured by reading the plates well beyond the significant area (Fig. 2) containing the tracks which were the result of protons reaching the plates through the final collimators. That this background was only due to neutrons and not to protons which had been scattered from the walls of the chamber was demonstrated by the virtual absence of background in the runs which were taken with a bombarding energy of 2.230 Mev.

The neutron background in the runs which were taken with a bombarding energy of 3.720 Mev was due to neutrons produced in the 60-mil tantalum collimator at the front of the target chamber. For the second set of runs this background was lessened by a factor of three by the insertion of a box of Borax between the collimator and the second scattering chamber.

The background due to neutrons was considerably worse for the P_1P_3 plates than for the P_1P_2 plates since the former runs were three times as long as the latter and the final track lengths on the former plates were considerably shorter than on the latter plates. The number of tracks which were mistakenly accepted was reduced somewhat by increasing the magnification of the microscope objective lens and by substituting objective lenses of the oil type for lenses of the dry type. Both of these changes helped in applying the criteria for acceptance more effectively.

The background due to protons which entered the second chamber through the interchamber collimator, but had not been scattered from helium, was measured using both the phototube and the third plate holder. A sample spectrum, taken with the target chamber set up for a P_1P_3 run is shown in Fig. 3, where the second chamber was always evacuated and the "He in" and "He out" refer to the first chamber. Runs of this type were also taken for the P_1P_2 and P_2P_3 measurements with the phototube and for all three measurements with a nuclear emulsion in the third plate holder. The conclusion which was drawn from these data is that the background due to protons is less than 0.1%.

The Brookhaven Van de Graaff beam tubes were so arranged that when the mass-one beam was magnetically directed into one tube (No. 1), the mass-two beam was directed into another tube (No. 2). Since there was an electrostatic analyzer in position on beam tube No. 2, this experiment was set up on beam tube No. 1. The energy of the machine could then be regulated by the mass-two beam which had passed through the electrostatic analyzer. This was done because the only other way of measuring the beam energy was with a generating voltmeter which does not take into account the voltages applied to the beam before it leaves the ion source. The electrostatic analyzer was calibrated by using the $Li^7(p,n)Be^7$ threshold at 1.8814 Mev.[10]

Bombarding energies of 3.720 Mev and 2.230 Mev were used. At the lower energy it was possible to regulate continuously on the mass-two beam. At the higher energy, however, the electrostatic analyzer tended to blow fuses so that it was necessary to restrict its use to periodic checks of the beam energy.

The protons were detected by Ilford C-2 50μ 1×3-in. emulsions on glass backings which were cut to 1×1-in. size before being placed in the chamber. They were developed in the standard manner and were then glued with Vinylite cement to 1×3-in. glass microscope slides and allowed to dry for several hours before they were scanned through the microscope. Bausch and Lomb moving-stage microscopes with 15× eyepiece lenses were used to scan the emulsions. Different objective lenses were used for different sets of plates.

In order to discriminate as much as possible against spurious tracks, several acceptance criteria were applied to the tracks. The track length had to lie within set limits, which were determined for each type of plate and the track had to start in the surface of the emulsion and enter in the correct direction in both the horizontal and vertical planes. The sufficiency of these criteria is demonstrated by the low density of tracks when the plates were scanned beyond the significant area (Fig. 2).

The energetics for the runs were calculated by using the usual elastic scattering formula and the range-energy curves which are given in the literature.[11] A curve of $-dE/dx$ *vs* E was used to calculate the energy lost in the helium. Since no such curve was available for nickel, it was necessary to use a curve of range *vs* energy for copper. Inasmuch as copper and nickel are adjacent in the periodic table and their densities are quite similar ($\rho_{Cu}=8.30$ to 8.95 g/cm^3 and $\rho_{Ni}=8.50$ to 8.90 g/cm^3),[12] this was considered to be a valid procedure.

The calculations showed that the interchamber foils

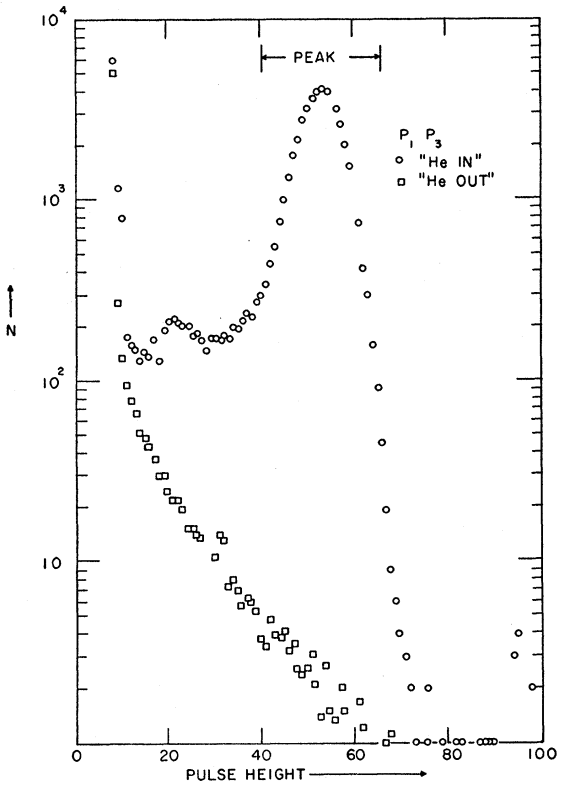

FIG. 3. Pulse-height spectra from a typical pair of runs taken with the CsI(Tl) crystal in order to measure the background due to protons entering the second chamber which had not been scattered from helium in the first chamber. The "He in" and "He out" refer to the first chamber. The second chamber was evacuated in both runs. The pulse height is given in arbitrary units, and the number of counts per channel for the two runs are given for the same amount of integrated beam current.

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

[11] Aron, Hoffman, and Williams, Atomic Energy Commission Report AECU-663 (1949) (unpublished).

[12] *Handbook of Chemistry and Physics* (Chemical Rubber Publishing Company, Cleveland, 1952), thirty-fourth edition, p. 183.

for the P_1P_3 measurement should be chosen so that the protons would lose 614 kev in the foils. Since the range-energy curves are not always accurate for foils, and the stated thickness is not reliable, it was decided to measure the equivalent thickness of the foils in kev at the energy desired.

The measurement of the foil thickness was done with the aid of a thin (20- or 50-microinch nickel) scattering foil (Fig. 1) and the CsI(Tl) crystal. Protons of a known energy were scattered from the foil through the interchamber collimator and the pulse-height spectra from the CsI(Tl) crystal were displayed on the hundred-channel analyzer. The analyzer was calibrated by scattering protons of three widely separated energies from the scattering foil with no interchamber foil in position.

The interchamber foils were then placed in the interchamber collimator, in the position occupied by the 50-microinch foils during the xenon runs, and the bombarding energy chosen so that the protons incident on the interchamber foils would have an energy of 2.099 Mev, which was the energy before the interchamber foil in the P_1P_3 run.

In the hope of finding a combination of foils whose total thickness would be as close to 614 kev as possible, several foils were sandwiched together. The foil thickness for the first set of runs was measured to be 601 ± 15 kev and the runs were therefore taken with a helium pressure of 800 mm. A remeasurement of the thickness showed that the true thickness was 576 ± 15 kev so that the second scattering took place at 1.400 Mev instead of 1.375 Mev. The foil thickness for the second set of runs was 635 ± 10 kev and a helium pressure of 657 mm was therefore used.

The energy uncertainties at the second scattering volumes were estimated to be

$$E_2(P_1P_2)=2.020\pm0.026,$$
$$E_3(P_2P_3)=1.375\pm0.012,$$
$$E_3(P_1P_3)=1.375\pm0.040.$$

The energy uncertainty at the first scattering volume was estimated to be ±10 kev for all three measurements.

The energies and cross sections are all monotonic in the regions of the energy uncertainties given above. Since the mean is therefore very close to the average, it was felt that these energy uncertainties did not affect the validity of the polarizations measured in the present experiment. For example, in the case in which there is the largest variation in the polarization, $E_3(P_1P_3)=1.375\pm0.040$ Mev, the calculated value of the polarization is $60\pm6\%$. The largest variation in the cross section is found at $E_2(P_1P_2)=2.020\pm0.026$ Mev where the cross section is 0.19 ± 0.08 barn.

RESULTS

The measurements were taken in four sets of runs. For the first two sets of runs, the second scattering chamber was on the 61° side of the first scattering chamber and the bombarding energy was $E_B=2.230$ Mev (i.e., P_2P_3 was measured). For the second two sets of runs, the second scattering chamber was on the 90° side of the first scattering chamber and the bombarding energy was 3.720 Mev (i.e., P_1P_2 and P_1P_3 were measured).

The procedure in each of the sets of runs was to take a xenon measurement in each position (up and over) immediately before or after each helium measurement, i.e., without removing the second chamber from the first chamber. The bombarding energy for a xenon run was the same as that for the corresponding helium run. Therefore the sequence in the 61° runs was: P_2P_3 up, xenon up, P_2P_3 over, xenon over. In the 90° runs, only one xenon measurement was taken in each position, even though two helium measurements were taken, since the xenon measurement was independent of the energy at the second scattering. Therefore the sequence in the 90° runs was P_1P_2 up, P_1P_3 up, xenon up, P_1P_2 over, P_1P_3 over, xenon over.

The data resulting from these runs are summarized in Table II, where the average ratio for the two sets of runs ($\bar{R}$) is given in addition to the value of P_aP_b averaged over the up and over positions of the second target chamber and corrected for one-half of the measured xenon asymmetry ($\bar{R}_{\mathrm{Xe}}=0.965\pm0.012$). The values of R for the first set of P_1P_3 measurements have been corrected for the error in foil measurement which resulted in the second scattering taking place at 1.400 Mev instead of 1.375 Mev. The calculated values of P_3 were used since it was felt that they were sufficiently accurate for this small correction. The result was a 4% correction on the polarization product.

No data are shown for the first set of 90° xenon runs

TABLE II. Summary of results, where the first value of R for a given measurement refers to the first run, $\bar{R}$ is the average over the two runs, and $\langle P_aP_b\rangle_{\mathrm{Av}}$ is the average over the two positions (up and over) of the second target chamber, after the xenon correction has been applied to $\bar{R}$.

Measurement	R	$\bar{R}$	$\langle P_aP_b\rangle_{\mathrm{Av}}$
P_2P_3 up	3.10 ±0.18	2.96 ±0.12	0.512±0.011
	2.82 ±0.16		
over	3.34 ±0.21	3.13 ±0.13	
	2.92 ±0.18		
Xe up	0.965±0.028	0.978±0.020	
	0.990±0.027		
over	0.953±0.028	0.946±0.019	
	0.938±0.024		
P_1P_2 up	2.51 ±0.15	2.64 ±0.15	0.460±0.015
	2.77 ±0.22		
over	2.67 ±0.21	2.67 ±0.13	
	2.66 ±0.19		
P_1P_3 up	1.99 ±0.15	1.81 ±0.10	0.325±0.010
	1.63 ±0.14		
over	2.02 ±0.18	2.07 ±0.13	
	2.12 ±0.18		
Xe up	...	0.936±0.027	
	0.936±0.027		
over	...	1.009±0.032	
	1.009±0.032		

because the runs were taken with too much xenon in the second chamber so that the plates were so difficult to read that the resultant data was unreliable. In view of the consistent results of the other runs, it was not felt to be necessary to repeat this run.

Although the plates were scanned by three different scanners, the same person always read both plates in a set (i.e., those resulting from a single run). Since there was no background on the P_2P_3 plates, they were very easy to scan so that when one set of plates was read by both of the scanners who worked on the P_2P_3 plates, the results were identical. In the case of the plates taken at the higher bombarding energy, however, a significant neutron background was present. Considerable care was therefore taken to assure that the final ratios would be independent of the scanner. In particular, microscope objectives of magnifications as high as 60× were used. Since these objectives were of the oil type, they had a shorter depth of focus so that the criterion that a track must start in the surface of the emulsion in order to be accepted could be applied more stringently.

Using the values of the polarization products shown in Table II, corresponding values of the polarization may be calculated. The results are:

$$P_1=54.4\pm1.4\%,$$
$$P_2=84.7\pm2.1\%,$$
$$P_3=62.2\pm1.6\%,$$

where the errors are statistical and the positive roots of the squares of the polarization have been taken in order to agree with the definition of positive polarization given above.

In order to allow for the small uncertainties in geometry and energy mentioned above, it was decided to attach somewhat larger errors to the measured values of the polarizations and to quote the values to only two places. The final results and errors are given in Table III. The values of the calculated $P\pm dP$ are included for comparison.

DISCUSSION OF RESULTS

The measured values of the polarization are in agreement with the calculated values within the estimated uncertainties of both. The estimated uncertainty in the experimental value of P_2 is larger than either of the other two experimental uncertainties because $\Delta P_i = P_i\Delta P'$, where $\Delta P'$ is the same for all three polarizations.

TABLE III. Final values of the polarization, with the corresponding estimated errors.

Polarization measured	Experimental value (%)	Calculated value (%)
P_1[3.580 Mev, 104° 29′ (c.m.)]	54±2	59±13
P_2[2.020 Mev, 73° 38′ (c.m.)]	85±5	80±4
P_3[1.375 Mev, 73° 38′ (c.m.)]	62±2	59±16

The polarization in p-α elastic scattering was measured to greater accuracy than that to which it can be calculated from the phase shifts. Therefore more accurate values of the phase shifts would be necessary for further comparison of the experimental polarizations with the calculated polarizations.

The results indicate that the calculated values of dP are too large for P_1 and P_3, but about right for P_2. This is probably due to the method which was used to estimate the dP, which did not take into account the possibility of interdependent variations of the phase shifts within their estimated uncertainties.

On the basis of the above data, it is felt that when helium is used as a polarization analyzer for protons, the calculated values of the p-α polarization may be used in the energy region of 1.4 Mev to 4 Mev with an uncertainty of ±0.05.

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