tions, and uncertainty in the efficiency correction due to an uncertainty in determining the bias energy. The absolute errors consist of the uncertainties in the efficiency determination and uncertainties in the absorption and multiple-scattering corrections. For each element the above errors were estimated and then combined under the assumption that they were statistically independent.

An additional uncertainty which affects both of the above categories is the contribution from inelastically scattered neutrons. The fact that 12.1- and 10.8-Mev bias measurements yield the same cross sections within statistics indicates that there is no appreciable contribution from inelastic neutrons.

V. CONCLUSIONS

With the exception of lead, the experimental data do not show the deep minima at back angles predicted by optical models without spin-orbit coupling.[2] The predictions of Bjorklund and Fernbach[9] employing a spin-orbit term are shown plotted in Figs. 6 and 7 (solid curve). Comparison with the experimental points shows that there is quantitative as well as qualitative agreement. The theoretical predictions also fit the existing scattering data for angles less than 90°.[9]

ACKNOWLEDGMENTS

The authors are indebted to S. Fernbach and F. Bjorklund for many discussions concerning their optical model, to M. Mansigh and J. Hudson for programming and running the Monte Carlo calculations, and to J. M. Peterson for continued encouragement during the course of the experiment.

[9] F. E. Bjorklund and S. Fernbach, University of California Radiation Laboratory Report UCRL-4932 (unpublished).

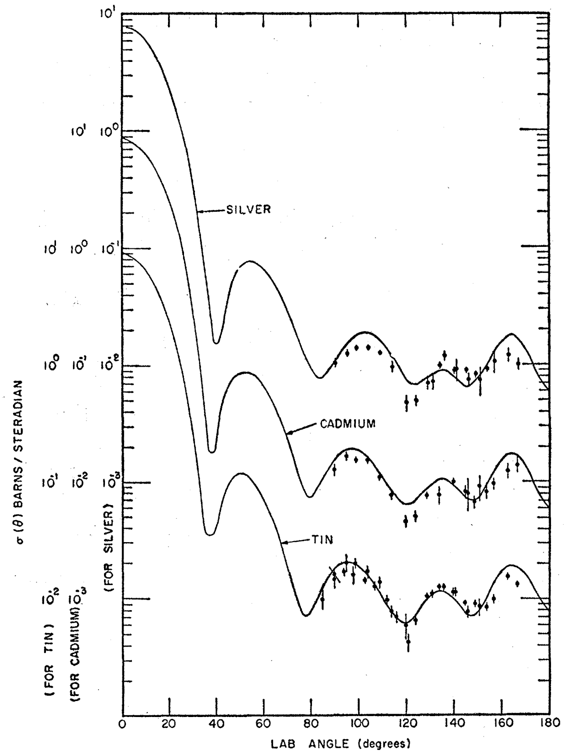

FIG. 7. Measured angular distributions for Ag, Cd, and Sn. The solid curves are the predictions of Bjorklund and Fernbach employing a spin-orbit coupling term.

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Proton Polarization Measurements near 18 Mev*

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Polarization of protons in proton-helium scattering may be calculated from phase shifts obtained from differential cross section measurements. Calculations of this type were performed for energies up to 18 Mev. On the basis of these results, an instrument was built with which proton polarizations could be measured for protons with energies from 5 Mev to 18 Mev and beyond. A second polarization analyzer was built utilizing the discovery of polarization in the scattering of protons by carbon around 17 Mev. Results are given for polarization measurements on H, D, Be, C, and Al near 18 Mev. Angular distributions for polarization in both elastic and inelastic (4.4-Mev excitation) scattering by carbon are also reported.

I. INTRODUCTION

WHILE polarization of protons by nuclear scattering at energies in excess of 100 Mev has received a great deal of attention during the past several years,[1] there has been relatively little interest in the possibility of obtaining polarizations at lower energies. It was, in fact, thought that such polarization should not exist; the high-energy polarization appeared to decrease with energy in such a way that it could be expected to vanish around bombarding energies of 50 Mev.[2] Recent

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[1] A comprehensive bibliography of pre-1956 polarization papers may be found in L. Wolfenstein's review article, *Annual Reviews of Nuclear Science* (Annual Reviews, Inc., Stanford, 1956), Vol. 6, p. 43.
[2] J. Marshall (private communication, 1955).

optical model calculations around 17 Mev,[3,4] however, show that the inclusion of a reasonable spin-orbit interaction not only helps a great deal in fitting scattering cross sections but also predicts the presence of remarkably large proton polarizations. The experiments described in this paper show, for the few particular cases that were measured, that polarization is present in quite large magnitudes in both elastic and inelastic scattering at a bombarding energy of 18 Mev.

II. EXPERIMENTAL PROCEDURE AND APPARATUS

A. General Procedure

Measurement of polarization is accomplished by double scattering experiments in which the first scattering is said to polarize and the second to analyze the polarization of the scattered protons. For either scattering, the polarization P, which is a function of the angle and energy of scattering, is defined as the expectation value per unit cross section for the spin to be normal to the plane of scattering. It may then be shown that in a double scattering experiment in which the two scatterings are coplanar, a left-right asymmetry in the second scattering will be observed which is related to the polarizations of the two scattering events by the equation $A=P_1P_2$. The subscripts on the P's refer, respectively, to the first and second events.

There are two possible schemes that can be adopted in making polarization measurements. In the first, a polarized beam is prepared by scattering from a known polarizer, then scattered from a target of the material under investigation, and then the asymmetry is measured. The second method consists of scattering first from the unknown and analyzing with a target of known polarization. Both of these schemes were employed in the work described in this paper; however most of the work was done following the second method because of its experimental convenience in the case of proton-helium scattering, the main analyzing reaction used.

Before proceeding with a description of the polarization analyzers, we refer the reader to Fig. 1 which shows schematically the general plan of the experiment. Both of the polarization analyzers, or polarimeters, constructed for these experiments are shown in this illustration. They were not used simultaneously, but rather the one or the other was used depending on the purpose of the experiment. The helium polarimeter was the one principally employed in these measurements while the second instrument, based on polarization in elastic scattering of protons by carbon, served to give valuable check measurements. Figure 1 shows the arrangement of either of the instruments with respect to the first scattering chamber. This 12-inch diameter chamber is equipped with ports spaced every 15° around its circumference. The polarimeters were plugged into these ports in order to observe the scattering. A pair of O rings in grooves spaced $1\frac{5}{16}$ inches apart on the necks of the polarimeters provided the vacuum seal for the scattering chamber and also provided a first order alignment of the instruments with the target.

The target plane was not placed perpendicular to the incident beam as shown in the illustration but was turned so that its normal bisected the scattering angle. This arrangement has the advantage, in thick targets such as those used, that all scattered particles pass through the same thickness of target regardless of the depth in the target at which the scattering occurs. This minimizes the energy spread imparted to the beam of scattered particles by energy loss through the target. Targets in this experiment were always used in the transmission position, i.e., scattered particles emerge from the opposite side of the target to that which they enter, even for scattering angles as large as 120°, because of the great energy spread that is introduced when the reflection position is used.

The target holder was mounted on a platform in the scattering chamber in such a way that the target could be moved back and forth in the direction parallel to the incident beam. This allowed the target to be located so that the spot where the incident beam struck the target was centered on the axis of the polarimeter. It will be seen later that this centering operation must be carefully performed since failure of the first scattering to lie on the polarimeter axis constitutes an instrumental asymmetry that can lead to false polarization measurements. It was necessary to realign the system each time the polarimeter was moved. The procedure was as follows. First, a polyethylene foil was mounted in the target holder and bombarded with protons for about two hours. At the end of this time a radiation darkening appeared on the target where the beam had gone through. The center of this spot was marked. Next a pointed mandril was attached to the polarimeter in such a fashion that its axis was that of the instrument

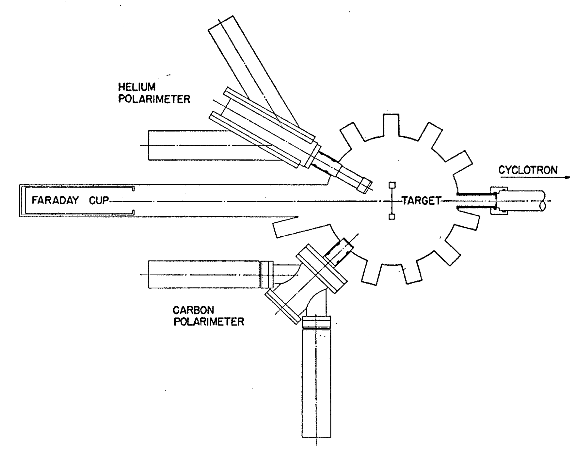

FIG. 1. Scattering chamber showing how the polarimeters are located with respect to first target.

[3] Culler, Fernbach, and Sherman, Phys. Rev. **101**, 1047 (1956).
[4] F. Bjorklund (private communication).

(both polarimeters could be so equipped). Then the target was adjusted by moving it parallel to the incident beam until the mandril pointed directly at the marked center of the beam spot. Once such an intersection of beam and target plane is located, it is in principle not necessary to repeat the burning in procedure (provided the beam spot lies on the axis of rotation of the target) each time the polarimeter is moved, since there is sufficient play in the position of the polarimeter in the scattering chamber port that the polarimeter can be lined up on the spot rather than the spot on the polarimeter. However, it was felt desirable to repeat the burning in each time the angle was changed, though not on occasions when the polarimeter was rotated 180° about its axis, because of the sensitivity of the apparatus to misalignment. In general, the "center of mass" of the beam spot could be made to lie within $\frac{1}{32}$ inch of the polarimeter axis. The consequences of misalignments of this order will be discussed later.

In cases where a gas target was used, a high-pressure gas cell was mounted in the center of the chamber. Then, following normal gas scattering procedure, the target was defined by a pair of collimators along the axis of the polarimeter. In the case of the helium instrument the two collimators are shown in the drawing of that apparatus (Fig. 3). The carbon apparatus was never used for gas scattering but could be adapted for it by the addition of a forward slit.

As shown in Fig. 1, the Faraday cup was set a good way back from the scattering center to reduce background radiation. In the experiments, most of the empty space in and around the apparatus was filled with shielding—mainly lead.

B. The Helium Polarimeter

The use of nucleon-helium elastic scattering as a polarization analyzer was first suggested by Schwinger.[5] The first application was by Heusinkveld and Freier[6] to determine the energy dependence of proton-helium polarization itself, and thus to answer certain questions concerning the scattering phase shifts and the ordening of energy levels in Li^5. Subsequent similar experiments also have been performed at energies of 10 Mev and below.[7,8] These experiments substantiate the predictions for the polarization obtained from cross-section measurements.

The proton-helium interaction is sufficiently simple that with the wealth of scattering experiments at various energies, it is possible to find the energy dependence of the nuclear phase shifts without recourse to any model for the interaction. Once phase shifts are known, the polarization may be calculated. This

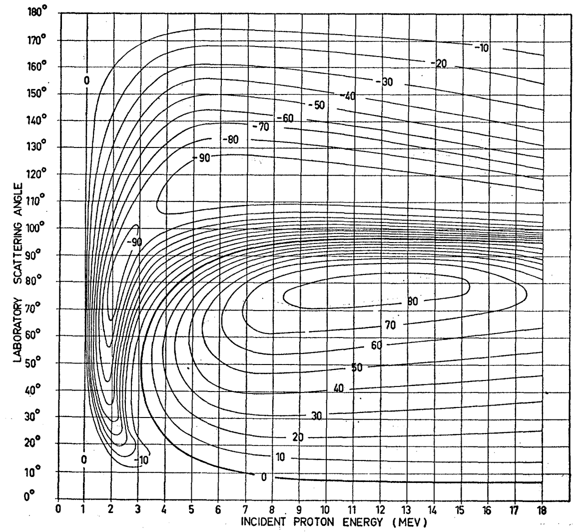

FIG. 2. Contour plot of percent polarization in proton-helium scattering as a function of incident proton energy and laboratory scattering angle.

computation was first done by Wolfenstein[9] and by Critchfield and Dodder[10] for energies below 3.5 Mev, and has been extended by others for various energy and angle regions.[5,11] In order to extend these calculations above 10 Mev, the author has measured the proton-helium cross section at a number of energies between 11 and 18 Mev,[12] analyzed the results for phase shifts, and computed the polarizations. The design of the analyzing apparatus used in this experiment was based on these calculations. More recently, Thaler and Gammel have reanalyzed the scattering data for phase shifts and by including higher order phase shifts have obtained better fits to the scattering curves. The polarization results, however, were only slightly affected. In Fig. 2 contours of the polarization obtained in proton-helium scattering are plotted for incident proton energy and laboratory scattering angle. The phase shifts used above 12 Mev are based on information obtained from Thaler and Gammel.[13]

The convention adopted in Fig. 2 for the sign of the polarization is that of the original paper of Critchfield and Dodder.[10] It calls polarization positive if the direction of the polarization vector is that of $\mathbf{K}_{\text{scatt}} \times \mathbf{K}_{\text{inc}}$, these being, respectively, the scattered and incident wave vectors. All polarizations reported in this paper are based on this convention. While, as is well known, the sign of polarizations cannot be obtained by double scattering experiments alone, the sign of proton-helium polarization, and consequently of all polarizations obtained when using this interaction as an

[5] J. Schwinger, Phys. Rev. **69**, 681 (1946); Phys. Rev. **73**, 407 (1948).
[6] M. Heusinkveld and G. Freier, Phys. Rev. **85**, 80 (1952).
[7] A. C. Juveland and W. Jentschke, Z. Physik **144**, 521 (1956).
[8] L. Rosen and J. E. Brolley, Phys. Rev. **107**, 1454 (1957).
[9] L. Wolfenstein, Phys. Rev. **75**, 1664 (1949).
[10] C. L. Critchfield and D. C. Dodder, Phys. Rev. **76**, 602 (1949).
[11] L. Marshall and J. Marshall, Phys. Rev. **98**, 1398 (1956).
[12] K. W. Brockman, Phys. Rev. **102**, 391 (1956); **108**, 1000 (1957).
[13] R. M. Thaler and J. L. Gammel (private communication).

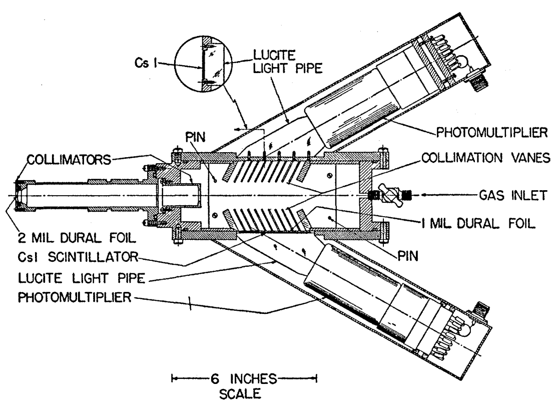

FIG. 3. The helium polarimeter. The upper half shows the mechanical connection of the light pipes to the covering plates. The lower half shows the position of the scintillators.

analyzer, is known because one knows the signs of all phase shifts from interference of nuclear and Coulomb scattering amplitudes.

The laboratory scattering angle of 65° was chosen for the construction of the helium analyzer. Looking at Fig. 2, one sees that at this angle a roughly constant polarization of around +70% extends from about 7 Mev through 18 Mev. At first glance it might be thought better to take advantage of the higher polarizations around 77° or around 115° where the polarization is almost −100%. However, there are two experimental reasons for choosing as small an angle as possible compatible with a reasonably large polarization. First, the cross section for scattering is greater, and second, the energy of the scattered particles is greater. This latter reason is of great importance because of difficulties that are encountered in detecting the small flux of doubly scattered particles in the presence of background radiations. It is much easier to identify more energetic particles.

A plan view of the helium polarimeter is shown in Fig. 3. Partially polarized protons from the first target enter from the left through a collimation tube. At the entrance of the tube a 2-mil Dural foil seals the helium filling the polarimeter from the first scattering chamber. Protons pass down the tube through a second collimator into the second scattering region. The scattering by the helium gas is viewed by a pair of scintillation counters through a series of collimation vanes set at an angle of 65° with respect to the axis of the instrument. These vanes, which define the target thickness and detector solid angle according to usual gas-scattering practices, were spaced a quarter of an inch apart along the length of the chamber. They were fabricated of 25-mil brass sheet. Both left and right sets of vanes were held in slots machined in two brass plates, one above and one below the vanes, and the whole collimator assembly was located in the polarimeter chamber by a pair of pins. The vanes were one inch long and the opening between the vanes and the scintillators was one inch high. This extremely close geometry was used to increase as much as possible the solid angle in the second scattering. By using many vanes the target thickness was increased as much as possible consisted with the large solid angle. These increases, of course, maximize the counting rate.

Knowledge of the energy and angular variation of the proton-helium polarization and differential cross section made it possible to calculate the average polarization factor, P, for the instrument. P is calculated as a function of the mean proton energy in the second scattering region by folding the angular resolution of the vane system into the angular distributions and averaging over energy. It turns out that P is less than the values shown in Fig. 2 for 65° by a factor which remains close to 0.95 for the entire energy range between 7 Mev and 18 Mev.

In order to obtain reasonable counting rates (a few counts per minute) it was necessary to use helium pressures of the order of 7 atmospheres in the polarimeter. At this pressure the energy drop across the scattering region viewed by the vanes was between 0.25 and 0.5 Mev depending on the mean energy of protons at this point. This energy could be adjusted by placing foils in front of the entrance collimator of the polarimeter. One could thus run the second scattering at as low an energy as he might wish. It was found most convenient experimentally, however, to use no moderation foils and to run at the highest energy possible for a given scattering situation.

A second gas seal was made by stretching a one-mil Dural sheet between the box holding the vanes and the side plates carrying the counters. The foil was supported against the high gas pressure within the box by the side plates and by the scintillators and the Lucite light pipes which were screwed onto the side plates. The upper half of Fig. 3 (in which the section taken across the polarimeter is somewhat different than that in the lower half) and its inset show the mechanical connection of the light pipe to the side plates.

The scintillation crystals were thallium-activated cesium iodide 3 in.$\times 1\frac{1}{8}$ in.$\times$0.040 in. thick. The thickness corresponds to the range of 14-Mev protons, which is a little more energy than protons from the Princeton cyclotron could have after the two scattering events.

The Lucite light pipes were shaped so the photomultipliers could view the crystals at an angle of 30° from the polarimeter axis. Sweeping the photomultipliers back at this angle was necessary in order to be able to measure polarizations at scattering angles as low as 30° since both scatterings had to be in the same plane. The arrangement is not, however, ideal from the point of view of scintillation spectrometry because the light collection efficiency of the photo multipliers varied for different positions on the scintillator. This variation decreased the resolution of the counters which was already poor for the following reasons: (1) the energy spread imparted to the protons by passage through the target and other matter in their paths, (2) a variation of the energy of the second scattering due to energy loss in the helium target between the final and last vanes, and (3) the variation of the energy with scattering angle in the range of angles allowed by the vane system. The resulting resolution was such that one could distinctly separate elastic and inelastic scattering by carbon (4.4-Mev separation), but would begin to run into trouble with groups spaced much closer.

The Lucite light pipes had the disadvantage that the juxtaposition of the hydrocarbon and the scintillator made the counters sensitive to neutrons. In cases when targets giving high neutron yields were used, the background separation became difficult and in some cases impossible. A better design, with regard to this problem, would have been to use glass pipes.

In experiments involving measurement of an asymmetry, one must take great care to avoid or to be able to account for any asymmetry of instrumentation that may lead to false measurements. The most obvious of these is a left-right asymmetry in the geometry of the apparatus. The precision with which the polarimeters described here were built was such that it was most unlikely that any errors arose from this cause. Errors of this type were guarded against by the practice of turning the polarimeter over during each measurement, taking half the data in one orientation and half in the other. No systematic trend indicating such an asymmetry was found during the many measurements in which this procedure was followed.

One asymmetry which is unavoidable arises from the finite geometry of the instrument. This may be estimated, however; for the helium polarimeter, the asymmetry was $[0.095-0.023(\sigma''/\sigma)](\sigma'/\sigma)$ where σ, σ', and σ'' are the cross section and its first and second derivatives with respect to the scattering angle (in degrees). For the worst case in the measurements described here, this asymmetry turned out to be about 0.01, a value several times less than statistical and other uncertainties for all measurements.

The foregoing result is for a target perfectly aligned with respect to the axis of the polarimeter. If the beam spot on the target is displaced y inches from the polarimeter axis, an asymmetry of $0.426y$ will result. Thus, for the previously mentioned uncertainty of $\pm\frac{1}{32}$ inch in the centering process, an uncertainty of ± 0.013 occurs in asymmetry measurements. It was possible to check this calculation experimentally by displacing the target forward and backward along the line of the incident beam. In this check measurement the displacement y was 0.18 inch, giving a predicted change of asymmetry of 0.077. The averaged change of asymmetry for several measurements was 0.083 in very good agreement with the prediction.

There were also certain other asymmetries in the instrumentation. First, the scintillation counters could not be identical because of the impossibility of matching photomultipliers. Then, the electronic scaling equipment was different for the two sides. In experiments of this type, a great advantage is obtained by counting simultaneously the scattering to the right and to the left. Such a procedure frees one of the need of exact current integration and of worries about conditions that could change with time if the two sides were counted separately. It is also almost imperative, because of the slow counting rates, that one uses multichannel discriminators to record the data. The equipment available at Princeton were an Atomic Instruments 20-channel discriminator and a 100-channel analyzer built at Princeton. In principle, the differences in instrumentation should cause no difficulties. In practice, one must exercise greater care in matching the spectrum from the left counter with the spectrum from the right counter. The procedure of turning the polarimeter over and repeating the run was a great help here. It would certainly be much simpler if the two sides could be electronically identical.

Another asymmetry that should in principle make no difference is an asymmetry in background events recorded by the two counters. Such a situation can occur, for example, if background pulses are due to a neutron flux from a particular direction. Great care was taken to subtract away the background. After each run in which double scattering was recorded, a shutter thick enough to stop protons was closed over the entrance of the polarimeter. The run was then repeated and the background spectrum was recorded. The lengths of the regular and the background runs were matched by integrating the incident proton current on the primary target. Background runs were usually as long as the regular runs.

C. The Carbon Polarimeter

It was extremely fortunate that the first measurement attempted, elastic scattering by carbon at 45°, turned out to be polarized. A second polarimeter was built utilizing this polarization as an analyzer. The carbon polarimeter is shown in Fig. 4. Scattering by a polyetheline target foil was viewed from the left and right by scintillation counters. Sodium iodide scintillators were used. The counter apertures were circular with diameters of $\frac{7}{8}$ inch and were $4\frac{3}{4}$ inches from the center of the target. The procedure with the carbon polarimeter was the same as with the helium polarimeter. The same pulse-height analyzers were used to record the data.

The carbon polarimeter had two advantages over the helium instrument, but also three disadvantages. The advantages were: first, a much better energy resolution since almost all the causes leading to the poor resolution of the helium instrument are absent here; and second, the neutron background was much lower because these scintillators were mounted on glass rather than plastic. The disadvantages were: first, the counting rate with

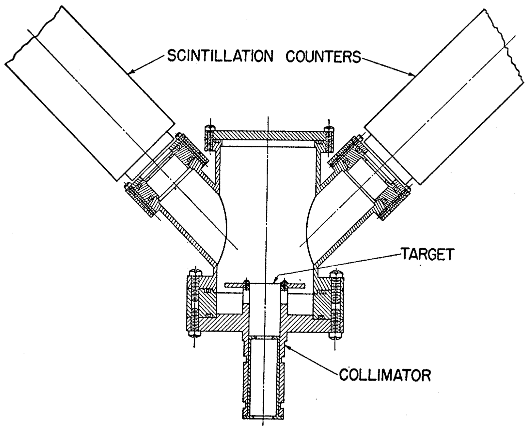

FIG. 4. The carbon polarimeter.

the carbon instrument was lower. Second, it was much more sensitive to errors in misalignment. In this case the asymmetry due to a displacement of y inches of the target spot from the polarimeter axis is $1.04y$; thus the misalignment error of $\pm\frac{1}{32}$ inch amounts to an asymmetry error of ± 0.032. The third disadvantage is that there are no predictions of the polarization in this case as there were for helium so that considerable effort must be given toward the calibration of the instrument.

Despite these numerous disadvantages, the check measurements made with the carbon polarimeter proved to be of great value.

III. RESULTS

The experiments that were preformed divide themselves into (1) those designed primarily to test the apparatus and (2) those to obtain new information on scattering polarizations.

The primary concern for testing the apparatus is to calibrate the polarimeters, that is, to find the appropriate polarization factors P. This is presumably known for the helium polarimeter from the calculation based on the scattering phase shifts. Nevertheless, it is of great value to verify those results. It was possible to calibrate both polarimeters without any reference to the helium calculations. The procedure is as follows. A double scattering experiment is performed in which scattering at 45° by carbon is analyzed with the carbon polarimeter. An asymmetry $A_1 = P_1 P_2$ is found, where P_1 is the polarization in the first scattering and P_2 is that in the second. P_1 will not, in general, be equal to P_2 because the energy of the first scattering is different than that of the second. If, however, the ratio $B = P_2/P_1$ can be found, the original equation will have the solution $P_1^2 = A_1/B$. Finding the ratio requires two more measurements. The set up used for these additional measurements had a carbon first target and analyzed polarization with the helium polarimeter. In the first measurement, the energy of the proton beam is reduced until it has the value with which protons were incident on the second carbon target in the experiment just described. An asymmetry $A_2 = P_2 P_{\mathrm{He}}$ is observed. P_2 is the same as before and P_{He} is the polarization of the helium polarimeter at the particular energy at which the second scattering occurs. Then the proton beam is returned to its original energy but enough absorber is inserted between the first and second scatterers to cause the second scattering, in helium, to occur at the same energy as in the preceding experiment; the asymmetry is $A_3 = P_1 P_{\mathrm{He}}$. Now it is seen that $B = P_2/P_1 = A_2/A_3$ and $P_1^2 = A_1 A_3/A_2$. The reader will be aware of the fact that the helium polarimeter was not necessary and that the entire procedure could have been carried through with carbon alone.

The calibration procedure gave $P = 0.42$ for carbon at 17.7 Mev, and a value of 0.73 for the helium polarimeter at 14.5 Mev. The calculated value for helium was 0.65. The agreement is fair when one considers statistical errors and also the large uncertainty that can enter measurements because of uncertainties in centering the carbon polarimeter.

It was further desired to check the shape of the calculated helium polarization curves, in particular to check the prediction of a polarization of nearly -100% at 115°. This measurement was easily done by reversing the vane block in the helium polarimeter (115° is the supplement of 65°) and observing the scattering from carbon at 45°. According to the previous calibration for carbon, the polarization turned out to be a little greater than 100% and to have the correct sign. With this information, the gross shape of the polarization curve was determined to be correct. Later, some runs with the helium polarimeter were made with a first target of helium gas. These measurements were made at 30° and 45°. An analysis of all these results

TABLE I. Polarizations observed in scattering from several targets at 17.7 Mev. Results are for elastic scattering except the last row which is inelastic scattering leading to 4.4-Mev excitation of C^{12}.

θ_{lab} target	30°	45°	60°	75°	90°	105°	120°
H	−0.012±0.020						
D	−0.09 ±0.07						
Be		0.154±0.034					
C	0.200±0.052	0.450±0.020	0.298±0.045	−0.362±0.046	−0.056±0.040	0.218±0.039	−0.145±0.052
Al	0.098±0.018						
$C_{(\mathrm{in})}$	0.055±0.050	0.184±0.043	0.240±0.032	−0.018±0.053	−0.272±0.065		

showed that the carbon-carbon experiment was probably in slight error and the helium polarizations were substantially correct as calculated. The best value for the polarization of protons scattered by carbon is 0.45 ± 0.02.

Such measurements as these cannot give the sign of the polarization. As previously noted, this is known only from phase shift analyses of proton-helium scattering data. It was therefore of interest to prove the prediction that at 65° the polarization maintained the same sign from 7 Mev up to 16 Mev. The check was made by scattering first by carbon and analyzing with the helium polarimeter. The energy of the helium scattering was adjusted by inserting moderating foils between the carbon target and the polarimeter entrance. The experiment showed that the helium polarization did indeed maintain the same sign.

The results of the experiments are given in Table I. Polarizations are listed for several targets and laboratory scattering angles. Solid (foil) targets were 1 Mev thick and gas targets a few hundred kev thick. The mean energy of bombardment, i.e., incident energy minus half the energy lost in the target, was 17.7 Mev for all cases. All results are for elastic scattering except the last row which is for inelastic scattering leading to excitation of the 4.4-Mev level in carbon.

Table II contains some results on the variation of the polarization of carbon at 45° with the energy of bombardment.

The experiments on p-p scattering were done both by hydrocarbon-carbon subtraction methods using foil targets, and by scattering by hydrogen gas. If polarization exists it should have an angular distribution proportional to $\sin 4\theta$, where θ is the laboratory scattering angle. While the angle 22.5° is best for measurements, the angle 30° which was available on the scattering chamber was suitable. The measurements can hardly be said to do more than to indicate an upper limit on the magnitude of the polarization. Zero polarization is expected from theory.[14]

Deuterium measurements were made using a gas target. The large uncertainties in the measurement stemmed from a large neutron background.

In the beryllium experiment, the neutron background rendered the helium polarimeter useless. The measurement was made with the carbon polarimeter.

The carbon experiments were done mainly with graphite targets. Lack of neutron background and the wide separation of levels made it possible to measure the angular distribution of polarization in both the elastic and 4.4-Mev inelastic scattering. The oscillatory character of the elastic polarization angular distribution is what one would expect to obtain by including a spin-orbit term in optical model calculations. It seems likely that the distorting influence of such a potential should also lead to a similar polarization pattern in the inelastic scattering such as is seen here.[15]

[14] J. L. Gammel and R. M. Thaler, Phys. Rev. **107**, 291 (1957).

TABLE II. Polarization in elastic scattering by carbon at 45° as a function of energy.

Energy (Mev)	15.9	16.7	17.7	18.1
Polarization	0.550 ± 0.028	0.535 ± 0.032	0.450 ± 0.020	0.425 ± 0.026

The region where the carbon polarization is positive and where proton-helium polarization is positive is what may be called the first slope of the cross section. By this is meant the region of angles smaller than the angle of the first diffraction minimum. It may be noted that the measurements on beryllium and aluminum were also on the first slopes of their cross section and that these measurements also gave positive polarization. This common behavior is what one would expect if polarization arizes from a spin-orbit interaction of a type common to all nuclei. Furthermore, since we already know the sign of this interaction for helium, we know the sign of this common spin-orbit interaction.

It is probably correct to draw the following conclusions by induction. (1) There is a nucleon-nucleus spin-orbit interaction of a type common to all nuclei. In optical model calculations, this interaction would be expressed by adding a term $\langle \mathbf{L}\cdot\mathbf{S}\rangle V(r)$ to the interaction Hamiltonian. (2) The sign of $V(r)$ is such as to be attractive for states in which $j=l+\frac{1}{2}$. This is the sign required for the proton-helium polarization. It is also the sign required by the j-j coupling shell model; hence these experiments agree with the expectations of that theory.

The shape and strength of the potential $V(r)$ can probably be found by optical model calculations in which simultaneous fits are made to both scattering and polarization angular distribution. The angular distribution of the polarization in carbon elastic scattering should allow one to distinguish for this case whether the spin-orbit potential has the shape of the non-spin-dependent potential well or if it is the Thomas type as is more commonly expected.

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[15] C. Levinson (private communication).