Polarization of 9-Mev Protons Elastically Scattered from Magnesium

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The polarization as a function of angle has been measured for protons elastically scattered from a 1-Mev thick magnesium target with a mean energy of 9.1 Mev. The resulting polarization distribution is compared to a differential cross-section measurement with the same target.

INTRODUCTION

THE complete analysis of the elastic scattering of protons from nuclei is in general a very complicated problem. There may be contributions to the scattering from the various direct interactions and from compound nucleus formation. For intermediate energy protons the most significant contribution to the elastic scattering comes from the action of the target nucleus as a whole upon the incident particle. This action occurs during the first or independent particle stage of the nuclear reaction in which the incident particle is influenced by the target nucleus, but is still considered to be distinct from the nucleus. The scattering in the independent particle stage can be described fairly successfully in terms of the optical model in which a complex potential is used to account for the scattering and absorption of the incident beam. Many experimenters[1] have shown that the angular distribution of the elastic scattering of protons from nuclei has variations characteristic of optical diffraction patterns.

The elastic proton scattering cross-section data were fitted to a square well optical model potential by LeLevier and Saxon[2] but it was found that better fits to the experimental data could be obtained by using a rounded-off potential well.[3] Similar fits to elastic neutron scattering data have been made by Bjorklund, Fernbach, and Sherman.[4] Calculations of the elastic proton cross sections have also been made by Glassgold et al.[5] using the central optical model potential of Saxon. In some cases it was possible to choose a set of parameters which gave a very good fit to the cross-section data while in other cases this was not possible. Even where good fits were obtained, an ambiguity existed in that the set of parameters needed for a fit was not unique.

Suggestions for producing polarized nucleons were made by Schwinger.[6] The first successful proton polarization experiment was carried out by Heusinkveld and Freier.[7] Since then polarization has been found in several high-energy proton-nucleus scattering experiments.[8] These experiments seemed to indicate that the polarization became very small at low energies. Fermi[9] suggested that the polarization observed in high-energy proton-nucleus scattering could be related to the spin-orbit coupling assumed in the nuclear shell model. Subsequently Gammel and Thaler[10] showed that the proton-proton scattering and polarization data in the energy range 0–310 Mev require the inclusion of a spin-orbit term in the phenomenological potential. The effects of the spin-orbit potential on nucleon-nucleus scattering have been investigated by Erickson and Cheston[11] and Sternheimer,[12] and it was found that the inclusion of this potential made possible a better fit to the experimental data in some cases, for example, by filling in the valleys in the scattering angular distributions. Bjorklund and Fernbach[13] have also used a potential which includes a spin-orbit term to describe a series of elastic neutron scattering experiments. The importance of the spin-orbit term in describing low-energy scattering processes led to a search for polarization in elastically scattered protons and large polarizations have been found by Brockman and Blanpied[14] at 17 Mev, by Rosen and Brolley[15] at 10 Mev, and by

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[2] R. E. LeLevier and D. S. Saxon, Phys. Rev. **87**, 40 (1952).

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[15] L. Rosen and J. E. Brolley, Jr., *Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1958* (United Nations, Geneva, 1958), paper UN-668.

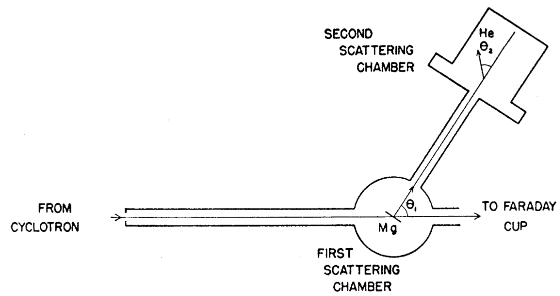

FIG. 1. Schematic view of polarization apparatus.

Warner and Alford[16] at 6 and 7 Mev. The purpose of the present experiment was to measure the polarization of protons elastically scattered from magnesium at 9 Mev in order to specify the parameters of the optical model potential for this process and for comparison with the 10-Mev data.[15] Such a comparison for the elastic scattering showed marked variations with energy and is referred to later in this paper.

EXPERIMENTAL PROCEDURE

The polarization measurements were made by means of a double scattering experiment, in which 9.6-Mev protons were elastically scattered first from magnesium and then from helium. Helium was chosen for the second scattering because the magnitude of the polarization is large over a wide range of angles and the polarization as a function of energy and angle has been accurately calculated.[14] The asymmetry after double scattering is given by

$$\epsilon=\bar{P}_1\bar{P}_2\cos\phi, \tag{1}$$

where ϕ is the angle between the two scattering planes, $\bar{P}_1$ and $\bar{P}_2$ are the average polarizations produced in an unpolarized beam at the first and second scatterings, respectively, and

$$\epsilon=(N_{LL}-N_{LR})/(N_{LL}+N_{LR})$$

or

$$(N_{RR}-N_{RL})/(N_{RR}+N_{RL}), \tag{2}$$

depending on whether the first scattering is to the left or right. N_{LR} is a beam scattered to the left in the first scattering and to the right in the second scattering, etc. According to the sign convention used here, the normal to the scattering plane is in the direction $\mathbf{k}_{\rm inc}\times\mathbf{k}_{\rm sc}$ where $\mathbf{k}_{\rm inc}$ and $\mathbf{k}_{\rm sc}$ are the wave vectors for the incident and scattered beams, respectively. Thus the polarization is positive if it is in the direction of the normal to the scattering plane (i.e., for a process with a positive polarization, spin up protons will be scattered preferentially to the left).

A diagram of the apparatus used in this experiment is shown in Fig. 1. The proton beam was accelerated as H^+ ions in the University of Birmingham 60-in. cyclotron. The beam was magnetically analyzed and focused into a $\frac{1}{2}$-inch diameter circle on the magnesium target at the center of the first scattering chamber. The direction of the incident beam at the first target was defined to $\pm1.5°$ by a series of lead collimators. In order to achieve optimum energy resolution for the elastically scattered protons, the first target was adjusted for each angle of scattering so that the target normal bisected the angle of scattering. The first target was made of 99.5% pure natural magnesium foils, adjusted so as always to present an effective target thickness of 1.00±0.08 Mev to the incident beam. The energy of the incident proton beam was determined to be 9.62±0.06 Mev by measuring the range of elastically scattered protons in emulsions.

The beam of protons scattered from the magnesium target passed through ports placed at 10° intervals in the wall of the first scattering chamber into the second scattering chamber which contained helium at 11 atmospheres pressure. The protons entered this chamber

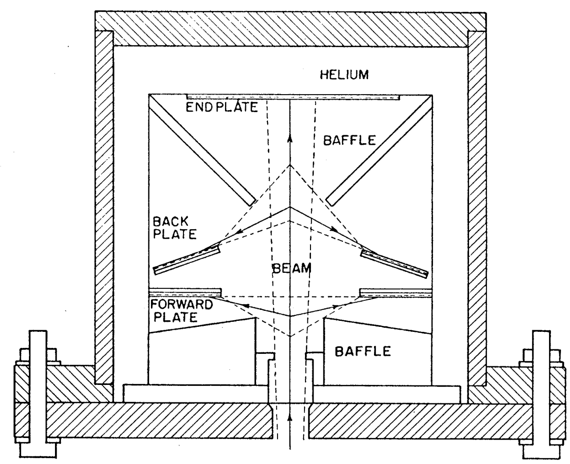

FIG. 2. Diagram of second scattering chamber, the polarimeter, showing positions of the photographic emulsions.

through a series of collimators which defined the direction of the scattered beam to $\pm2.7°$. The doubly scattered protons were detected in 100-micron thick Ilford *C*2 emulsions placed in the second scattering chamber as shown in Fig. 2. The angular resolution for the polarization data is determined by the collimators for the first and second scatterings so that the over-all resolution is about $\pm3°$. This resolution has been kept small so that a consistent treatment of both the polarization and differential cross-section data could be made. By having the helium scattering follow the magnesium scattering the rather large solid angle for the second scattering does not affect the resolution quoted for the polarization results.

Three independent checks were made for any possible instrumental asymmetry. First, the polarimeter and plate holder were machined with high precision so that the photographic emulsions were held symmetrical to the axis of the polarimeter to within ±0.005 in. Then

[16] R. E. Warner and W. P. Alford, Phys. Rev. **114**, 1338 (1959).

the sets of collimators were aligned optically at each scattering angle so that the axes of the two scattering chambers intersected at the center of the target. A second check for instrumental asymmetry was made in the first scattering chamber by burning a beam spot on a paper target at intervals throughout the experiment. The alignment of the beam in the second scattering chamber was determined by means of an emulsion at the end of the chamber. The position of the beam on this emulsion was measured with a microphotometer and found to be centered in the chamber to within ± 0.015 in. A third check for instrumental asymmetry was made by analyzing the two sets of plates in the polarimeter. The forward set of plates detected protons scattered from helium in the region of 75° and the backward set of plates detected protons scattered from helium in the region of 125°. The helium polarization has opposite sign for these two scattering angles, so that

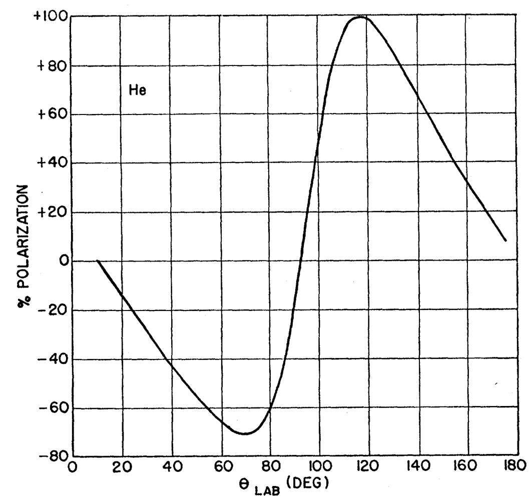

FIG. 3. Helium polarization distribution, P_2 (θ_2), for protons elastically scattered from magnesium at $\theta_1=80°$ and scattered from the helium with 7.00 Mev.

the backward set of plates could be used to verify the validity of the polarization results obtained from the forward plates.

The polarization results were calculated from Eq. (1) where the value of $\bar{P}_2$ had to be determined for each scattering angle θ_1. The value of $\bar{P}_2$ was obtained by a numerical integration of the equation

$$\bar{P}_2=\int P_2(\theta_2)\sigma_2(\theta_2)d\Omega_2\bigg/\int\sigma_2(\theta_2)d\Omega_2, \qquad (3)$$

where P_2 (θ_2) was taken from the helium polarization calculations of Brockman.[14] The polarization distribution, P_2 (θ_2), used for the $\theta_1=80°$ scattering is shown in Fig. 3. In Eq. (3) $\sigma_2(\theta_2)$ is the cross section and $d\Omega_2$ the solid angle for the second scattering. In a given area of the plates a range of scattering angles θ_2 was recorded with differing efficiencies which depended upon

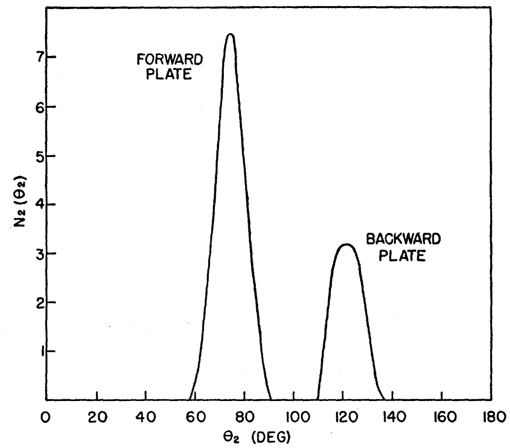

FIG. 4. Angular distribution $N_2(\theta_2)$ recorded in the emulsion for the second scattering by He of protons initially scattered elastically from Mg. $N_2(\theta_2)$ is proportional to $\sigma_2(\theta_2)d\Omega_2$.

the geometry. The angles θ_2 could be obtained from the track orientation and hence the number of protons $N_2(\theta_2)$, corresponding to different θ_2's, obtained for the area of plate used. The distributions for one set of forward and one set of backward plates are shown in Fig. 4. It is seen that these peaks correspond well with the maxima in the He polarization curve of Fig. 3.

The projected lengths of tracks in the emulsions were measured with a Cooke, Troughton, & Simms microscope. A typical spectrum is shown in Fig. 5. For the optical measurements a special jig was constructed so that the plates would be held exactly as they were held during the experiment. Corresponding areas of each pair of plates were scanned in order to determine the scattering asymmetry.

The background tracks consisted mostly of proton recoils in the emulsion produced by neutrons. This background was measured by duplicate sets of plates which recorded only the neutron flux. It was found that with the criteria used in counting tracks there was no background contribution to the elastic group in the

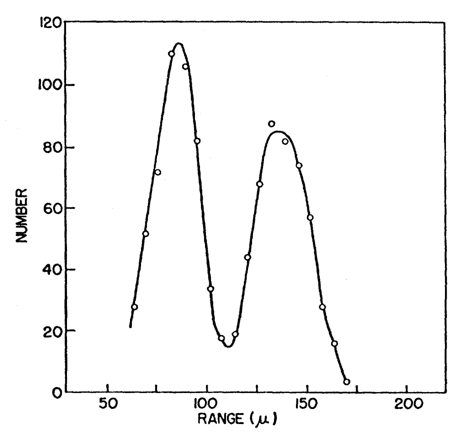

FIG. 5. Range spectrum of protons elastically scattered from magnesium at $\theta_1=60°$.

TABLE I. Polarization of 9.1-Mev protons elastically scattered from magnesium (forward plates).

$\theta_{c.m.}$	$P(\theta)$
20.8	-0.071 ± 0.057
31.2	-0.073 ± 0.050
41.5	$+0.024\pm0.051$
51.8	$+0.265\pm0.061$
62.0	$+0.385\pm0.060$
72.2	$+0.353\pm0.060$
82.4	-0.105 ± 0.057
92.4	-0.057 ± 0.063
102.4	-0.327 ± 0.069
112.3	-0.094 ± 0.072
122.1	$+0.384\pm0.072$
131.8	$+0.190\pm0.071$
141.5	-0.012 ± 0.087

forward plates, but there was a background of short tracks present in the backward plates. This background became serious at large scattering angles.

The energy resolution of the doubly scattered protons was about 500 kev (full peak width at one-half maximum). With this resolution it was possible to separate the group of elastically scattered protons from the group of protons scattered from the first excited state in Mg^{24} at 1.37 Mev. In most cases there was negligible inelastic contamination of the elastic group. As a natural magnesium target was used in this experiment there was a small amount of inelastic scattering from the 0.58-Mev level in Mg^{25}, but at these proton energies the intensity is extremely small and hence the results are for pure elastic scattering.

RESULTS

The polarization results are given in Table I. The geometry of the helium scattering chamber is such that the track density on the plates depends critically on the centering of the beam within this chamber. It was calculated that the uncertainty in the beam position would produce a maximum error of ±0.056 in the asymmetry. This error has been added in quadrature to the statistical error. The uncertainty in the beam position was obtained from the optical alignment and microphotometer measurements. The measurements with the backward plates confirmed that this was a maximum error. The polarization data presented in Table I has been obtained from the forward set of plates in the helium scattering chamber. Data was obtained from the backward set of plates for $\theta_1=20°$, 30°, and 40° and the polarization results at these angles are given in Table II. These polarization values are in good agreement with those calculated from the forward plates. Since the sign of P_2 is opposite for the forward and backward scatterings, this agreement rules out any large and consistent instrumental asymmetry and confirms the beam alignment which was measured directly in the plate at the end of the chamber. It was not possible to obtain reliable measurements from the backward plates for $\theta_1>40°$ because of a high background of short tracks produced by neutron-proton recoils in the emulsions.

TABLE II. Polarization of 9.1-Mev protons elastically scattered from magnesium (backward plates).

$\theta_{c.m.}$	$P(\theta)$
20.8	0.000 ± 0.047
31.2	-0.166 ± 0.047
41.5	$+0.010\pm0.052$

In order to determine the relation between the polarization and differential cross-section distributions,

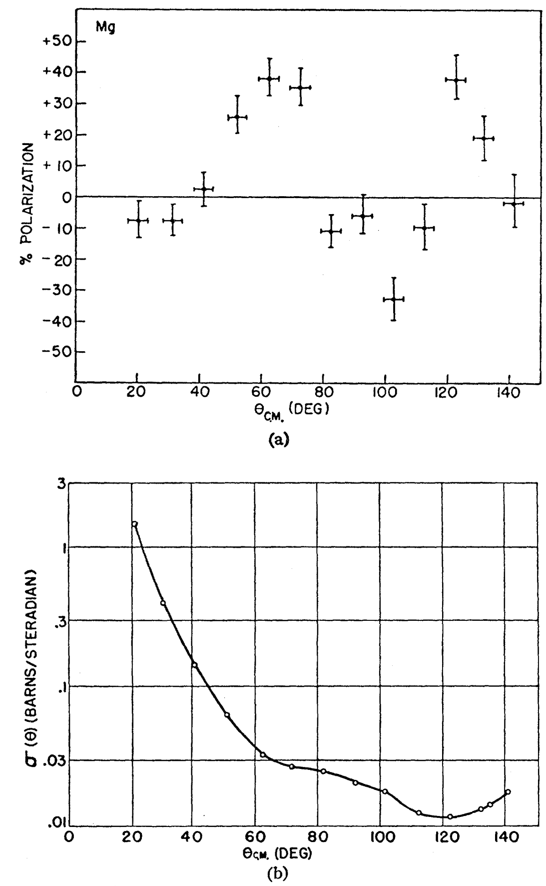

FIG. 6. Polarization and cross-section distributions for 9.1 ± 0.5 Mev protons elastically scattered from magnesium.

a cross-section measurement was made with the same 1-Mev thick magnesium target used for the polarization measurements. The cross-section measurements were made with a 12-in. diameter scattering chamber, using a 2-mm thick CsI(Tl) crystal and Dumont 6292 photomultiplier for detection. The estimated error in each differential cross section is $\pm4\%$ and the angular uncertainty is $\pm\frac{1}{2}°$. The details of this apparatus are described in an earlier paper.[17] The polarization distribution and cross-section curves are shown in Fig. 6.

[17] G. W. Greenlees, B. C. Haywood, L. G. Kuo, and M. Petravić, Proc. Phys. Soc. (London) **A70**, 331 (1957).

DISCUSSION

Results for the polarization of elastically scattered protons from magnesium have been obtained at 10 Mev by Rosen and Brolley.[15] The general shape of the present 9.1-Mev data (Fig. 6) and the 10-Mev data is similar; in the present results, however, the maxima occur at somewhat larger angles (60° rather than 50°) and in general larger positive polarizations are observed. Better angular definition was used in the present work but this is insufficient to explain the differences in the two sets of results. An estimate has been made of the polarization of the inelastic scattering to the first level of Mg^{24} (1.37 Mev); this is found in general to be smaller than, and sometimes of opposite sign to, the elastic polarization. This inelastic group was resolved from the elastic in the present experiments; contamination of the observed elastic scattering by inelastically scattered protons in the 10-Mev data could explain the differences in the two sets of results.

The angular distribution for elastic scattering given in Fig. 6 represents an average over the energy range 8.6–9.6 Mev. Earlier measurements[17] of this angular distribution using a thinner target (150 kev) showed marked variations with energy around 9 Mev, but an integration of these measurements is in agreement with the present results. The fact that marked energy variations occur in the elastic scattering of protons from magnesium makes it unlikely that good fits will be obtained using an optical model type of analysis. It is probable[18] that significant compound nucleus contributions are being observed which are not included in an optical model description. Effects due to compound elastic scattering are most marked at backward angles where the shape elastic and compound elastic contributions are of comparable magnitude. At forward angles, the compound elastic scattering will be negligible compared with the shape elastic contribution and thus it may be reasonable to discuss the present results, at forward angles, in terms of the optical model. Since the compound elastic scattering may be polarized, this is true of both the angular distribution and the polarization curves of Fig. 6.

Optical model calculations by Fernbach and Bjorkland[19] at 10 Mev and by Easlee[20] at 9.1 Mev have given a reasonable representation of the two sets of polarization data. Assuming the variation with energy between 9.1 and 10 Mev is real and not instrumental, it is too great to be explained with reasonable changes in either set of parameters. It is perhaps significant that both sets of experimental points show a small negative peak in the polarization at forward angles ($<40°$) whereas the optical model calculations show a monotonic increase of positive sign. More accurate experimental data and extended optical model computations are needed before any decisive conclusions can be drawn from this apparent discrepancy. A similar discrepancy has been observed in the polarization of elastic scattering from copper at 10 Mev where more extensive calculations[21] have shown that it is not possible to obtain a fit to the data at both forward and backward angles.

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[20] B. Easlee (private communication).

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