Direction of Polarization Produced by Quasi-Elastic Scattering of 315-Mev Protons*

HUGH BRADNER AND WILLIAM ISBELL
Radiation Laboratory, University of California, Berkeley, California
(Received June 21, 1957)

Protons scattered quasi-elastically with energy 315 Mev at 13° from a beryllium target in the Berkeley synchrocyclotron were brought out of the machine, slowed by absorbers, and scattered in helium at 765 psi absolute pressure. Scattering events at angles of $90°\pm22.5°$ were detected in nuclear emulsions. Observed asymmetries in left *versus* right scattering of protons with energies below 14 Mev were used, in conjunction with phase shifts from p-He scattering data, to compute the direction of spin polarization. We find spin up from left scattering, in agreement with the predictions of spin-orbit coupling theory and with the findings of other experimenters.

INTRODUCTION

THIS is the final report on an experiment[1,2] to determine the spin direction in the polarization experimentally observed[3] from small-angle quasi-elastic scattering of high-energy protons. The results presented here are a confirmation, with somewhat improved statistics and background, of work by Marshall and Marshall[4] and by Brinkworth and Rose,[5] who did very similar experiments. These experiments indicate a direction of polarization in agreement with theoretical predictions based on spin-orbit coupling.[6]

PRINCIPLE

When a beam of low-energy protons with polarization P is scattered from a material such as helium with known polarizing properties, it can be shown that the scattered beam will have an asymmetric angular distribution,

$$\sigma_i(\theta_i\phi_iE_i,P)=g_i(\theta_iE_i)[1+PP_i(\theta_iE_i)\cos\phi_i], \quad (1)$$

where $P_i(\theta_iE_i)$ is the polarization that would be present if an unpolarized proton beam of energy E_i were scattered at a center-of-mass angle θ_i in helium, while ϕ_i is the angle between the plane of scattering in helium and the plane of original scattering which produced the polarization P.[7]

The function $P_i(\theta_iE_i)$ can be calculated for energies up to about 15 Mev from phase shifts for proton-helium elastic scattering.[7] The polarization of a higher energy beam can be determined by passing the protons through a degrader before scattering them in helium, since Wolfenstein has shown that reducing the proton energy in this way produces negligible depolarization.[8]

METHOD

In this experiment a $73\pm8\%$ polarized beam of 315 ± 5 Mev protons was obtained by scattering protons from a 1-in.-thick beryllium target in the circulating beam of the 184-in. synchrocyclotron.[9] The beam, scattered outward—, i.e., "left"—was collimated to a 1-in. diameter and passed through a copper and iron absorber before entering the helium-filled scattering chamber. The energy-degraded protons entering the helium had an essentially flat energy distribution between zero and the upper measured energy of 14 Mev.

The chamber was surrounded by 4-in. lead shielding. Backscattering was reduced by making the chamber as long as was practical for handling.

The 200-micron $C2$ nuclear emulsion plates were placed in the chamber as shown in Fig. 1 with their

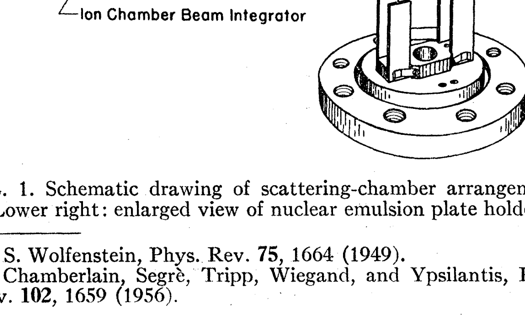

FIG. 1. Schematic drawing of scattering-chamber arrangement. Lower right: enlarged view of nuclear emulsion plate holder.

* This work was performed under the auspices of the U. S. Atomic Energy Commission.
[1] H. Bradner and E. Iloff in Physics Division Quarterly Report, UCRL-2691, 1954 (unpublished), p. 23.
[2] H. Bradner and W. Isbell, University of California Radiation Laboratory Report UCRL-3656, June, 1957 (unpublished).
[3] Oxley, Cartwright, Rouvina, Baskir, Klein, Ring, and Skillman, Phys. Rev. **91**, 419 (1953); Chamberlain, Segrè, Tripp, Wiegand, and Ypsilantis, Phys. Rev. **93**, 1430 (1954); Marshall, Nedzel, and Marshall, Phys. Rev. **93**, 927 (1954).
[4] L. Marshall and J. Marshall, Phys. Rev. **98**, 1398 (1955).
[5] M. J. Brinkworth and B. Rose, Nuovo cimento **3**, 195 (1956).
[6] Joseph V. Lepore, Phys. Rev. **79**, 137 (1950); E. Fermi, Nuovo cimento **11**, 407 (1954); Snow, Sternheimer, and Yang, Phys. Rev. **94**, 1073 (1954); W. Heckrotte and J. V. Lepore, Phys. Rev. **95**, 1109 (1954).
[7] See, for example, Joseph V. Lepore, Phys. Rev. **79**, 137 (1950).
[8] S. Wolfenstein, Phys. Rev. **75**, 1664 (1949).
[9] Chamberlain, Segrè, Tripp, Wiegand, and Ypsilantis, Phys. Rev. **102**, 1659 (1956).

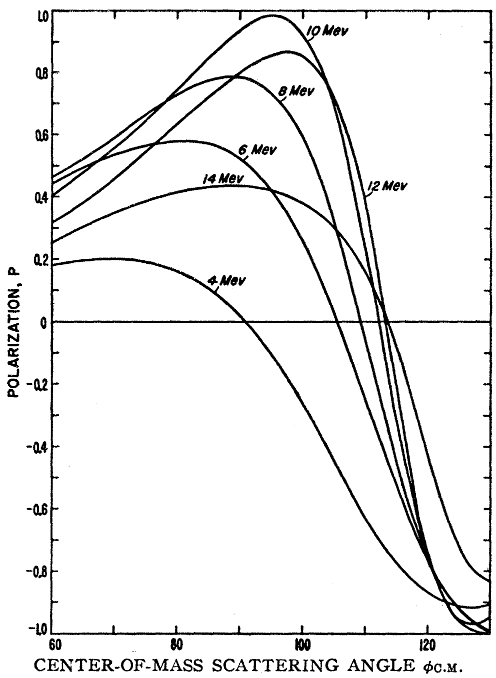

FIG. 2. Graph of computed values for polarization P that would be produced when protons of incident energy E (lab) are scattered at center-of-mass angles ϕ in helium. Values were computed from phase-shift analyses of proton-helium scattering experiments up to 9.48 Mev, and by extrapolation of the phase shifts up to 14 Mev.

faces horizontal so that the range and direction of the scattered protons could be accurately determined.

Three exposures were made. The first run was made with the polarized beam and with the chamber filled with helium at 765 psi. The second run was similar except that an unpolarized proton beam was used to provide a check on systematic errors in the system. The third run was like the second, but with the helium chamber evacuated to determine background.

Each plate was scanned twice. Range and horizontal and azimuthal scattering angles were measured for tracks entering the emulsion at $90°\pm22.5°$ to the beam direction. Only tracks with ranges corresponding to incident-proton energies of 3.5 to 14.0 Mev were considered.

All together, 296 tracks in the polarized plates and 309 tracks in the unpolarized plates were recorded. These include 13% background, computed from data obtained from the third run. The angular distribution of the background tracks was calculated and was correlated with the polarized tracks by noting the tracks in the polarized plates that passed the range and angle criteria but were traveling in the backward direction. These tracks provided a basis of comparison with similar tracks in the background plates.

ANALYSIS

In the interest of brevity, we follow the nomenclature and analysis method of Marshall and Marshall.[4] Their equations are in agreement with a more formal treatment of the maximum-likelihood method applied by Solmitz to this particular experiment.[10]

It is obvious from our Eq. (1) that the probability of having found an event with characteristics $(\theta_i\phi_iE_i)$ is proportional to σ_i; hence the probability of finding the events $(\theta_1\phi_1E_1)$, $(\theta_2\phi_2E_2)$, $\cdots$ $(\theta_n\phi_nE_n)$ is proportional to the product of the corresponsing σ_i's. Calling the true value of the polarization P^*, and expanding $\ln\sigma$ in a Taylor's series about this value, we find that the experimental values of P lie in a reasonably narrow Gaussian distribution about P^* if the term in $(P-P^*)$ is zero and the terms beyond $(P-P^*)^3$ are small. Following this reasoning we obtain the Marshalls' condition (4),

$$\sum_{\text{Right}}\left(\frac{P_i\cos\phi_i}{1+PP_i\cos\phi_i}\right)_{P=P^*}=\sum_{\text{Left}}\left(\frac{P_i\cos\phi_i}{1-PP_i\cos\phi_i}\right)_{P=P^*}. \quad (2)$$

The expected polarization $P_i(\theta_iE_i)$ was computed in terms of phase shifts for proton-helium scattering, following the treatment by Lepore.[6] With proper treatment of the Coulomb dependence, Lepore's treatment is in agreement with that of Wolfenstein.[8] Calculations were made in 0.5-Mev intervals from 3.5 to 14.0 Mev by IBM-CPC machine using the phase shifts through d wave for low-energy proton-helium scattering.[11] Coulomb dependence was included. Phase shifts were extrapolated graphically in the region from 9.48 to 14.0 Mev. Computed polarizations for even integral energies are shown in Fig. 2. The complete set of curves is contained in reference 2. Our values are in good agreement with curves by Dodder[12] and with curves by Brinkworth and Rose.[5] The results are only in qualitative agreement with the curves of Marshall and Marshall.[4]

Figure 3 shows the weighted sums of the left vs right scattering, as a function of assumed polarization of the beam incident on the helium. The standard deviation indicated in this figure was obtained by computing

$$\sigma=\left[\sum_{\text{Right}}\left(\frac{P_i\cos\phi_i}{1+P^*P_i\cos\phi_i}\right)^2+\sum_{\text{Left}}\left(\frac{P_i\cos\phi_i}{1-P^*P_i\cos\phi_i}\right)^2\right]^{-\frac{1}{2}}. \quad (3)$$

[10] Frank Solmitz (private communication).

[11] D. C. Dodder and J. L. Gammel, Phys. Rev. 88, 520 (1952). We used the values listed as "A" in their tabulation.

[12] D. C. Dodder (private communication).

The higher order terms of our expansion gave

$$\sum \ln\sigma_i(P) = \text{const} - \left(\frac{\Delta P}{0.14}\right)^2 - \frac{(\Delta P)^3}{3}(4.92) - \frac{(\Delta P)^4}{4}(7.52) + \frac{(\Delta P)^5}{5}(0.99) + \cdots, \quad (4)$$

where $\Delta P \equiv P - P^*$.

DISCUSSION

Our computed polarization of +0.30 indicates that the nuclear polarization of 315-Mev protons scattered out of the Berkeley synchrocyclotron is in the direction predicted by spin-orbit coupling theory. If we consider our results statistically, we see that the sign could be reversed only if our data were in error by 2.8 standard deviations or more.

Our computed magnitude of polarization does not agree with the known magnitude of the original beam polarization.[9] The randomly distributed background would not lower the polarization from 70% to our observed value.

The effect of the background $h_i(\theta_i E_i)$ can be treated by adding this function h_i to Eq. (1). Following the argument presented in reference 2, we conclude that the polarization computed in the presence of background should be corrected by a factor of 1.1 or 1.2.

An unknown, but possibly large, source of error is in the choice of phase shifts. Predicted polarization is sensitively dependent on the choice of phase shifts taken from scattering data. For example, the errors of ±3° in S-wave and ±2° in P-wave shifts in the work of Kreger *et al.*[13] produce uncertainties of about 25% in double-scattering polarization in the experiment by Scott and Segel.[14]

Our phase shifts were extrapolated graphically in the region above 9.48 Mev. At 13 Mev our S_1^+ and S_1^- phase shifts were respectively −3° and +8° away from the corresponding shifts that would be obtained by linear extrapolation of the logarithmic derivative, (aY), of the P-wave functions.[15]

Recently Brockman has computed phase shifts from

[13] Kreger, Jentschke, and Kruger, Phys. Rev. **93**, 837 (1954).
[14] M. J. Scott and R. E. Segel, Phys. Rev. **100**, 1244 (A) (1955).
[15] D. C. Dodder and S. L. Gammel, (reference 11). We have adjusted the abscissa of their Fig. 1 by a factor of 5/4.

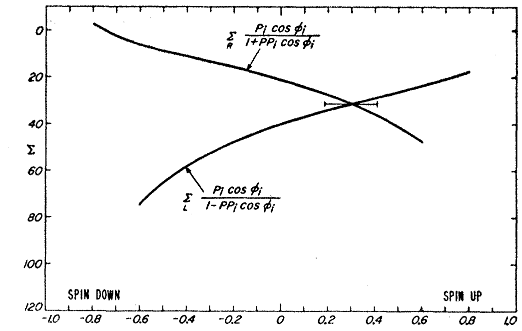

FIG. 3. Scattering of polarized beam in helium. Plot of weighted sums of left scattering and right scattering events *vs* assumed initial polarization P. A correction for background has been made. The maximum-likelihood value of P is at the intersection of the two curves, *viz.*, +0.30. The error shown (±0.108) is the statistical standard deviation σ, computed from Eq. (3).

17.5-Mev p-α scattering data.[16] If the linear relation between (aY) and energy is made to fit his 17.5-Mev p-wave shifts as well as the lower energy data, the resultant S_1^+ and S_1^- shifts at 13 Mev are found to be approximately −4° and +6° different from the values we used for computing polarizations. The differences between extrapolated and interpolated values for the other phase shifts have not been estimated; but the effect on the predicted polarization can clearly be large.

CONCLUSION

The direction of polarization produced by small-angle quasi-elastic scattering of protons on beryllium is found to agree with the predictions of spin-orbit coupling theory. The difference in magnitude between computed and previously measured polarization of the beam can probably be accounted for by uncertainties in the phase shifts for the proton-helium elastic scattering.

ACKNOWLEDGMENTS

The experiment was suggested by Edward Teller. The calculation of expected polarizations from phase shifts was done by Robert Johnston. Warren Heckrotte, Joseph Lepore, Myron Heusinkveld, and Frank Solmitz furnished much valuable counsel.

[16] K. W. Brockman, Jr., Phys. Rev. **102**, 391 (1956).