PHYSICAL REVIEW VOLUME 85, NUMBER 1 JANUARY 1, 1952

The Production of Polarized Protons and the Inversion of Energy Levels of the $P_{\frac{1}{2}}-P_{\frac{3}{2}}$ Doublet in Li^{5}*[*]

M. HEUSINKVELD† AND GEORGE FREIER
Physics Department, University of Minnesota, Minneapolis, Minnesota

(Received September 17, 1951)

Spin-orbit coupling in the scattering of protons by helium is expected to result in polarization of the scattered proton beam. This effect has been established by performing a double scattering experiment, in the form of a polarizer-analyzer arrangement, and measuring the amount of polarization. These data, used in conjunction with the phase shift analysis of the single scattering differential cross-section data, give conclusive evidence that the $P_{\frac{1}{2}}$ and $P_{\frac{3}{2}}$ energy levels in the compound nucleus of Li^{5*} are inverted.

INTRODUCTION

WHEN a proton with spin $\hbar/2$ and a He^4 nucleus with spin 0 collide elastically with an orbital angular momentum of $\hbar$, there are two possible values of the total angular momentum, namely $j=\hbar/2$ and $j=3\hbar/2$. If there is an energy dependent spin orbit coupling involved in the nuclear forces which cause the scattering interaction, it is expected[1–3] that there will be selective scattering of protons; i.e., protons with a given spin orientation will be scattered more or less depending on whether the orientation is parallel or antiparallel to the orbital angular momentum vector with one unit of orbital angular momentum. Consequently an examination of a beam of protons which have been scattered by helium should reveal that this scattered beam is polarized or has more protons with one spin orientation than with the opposite orientation.

Furthermore, if these spin orbit forces are considered in establishing the energy levels of the compound Li^{5*} nucleus, the splitting of the $P_{\frac{1}{2}}$ and $P_{\frac{3}{2}}$ energy levels, if they are separated, will result in a strong interaction of one type when the interacting energy equals the energy of the $P_{\frac{1}{2}}$ level and a strong interaction of another type when the interaction energy equals the energy of the $P_{\frac{3}{2}}$ level which is either a higher or lower energy depending on whether the doublet levels are normal or inverted. The polarization of the protons scattered by the helium nuclei at one of these resonant energies will be opposite in sign to that at the other resonant energy.

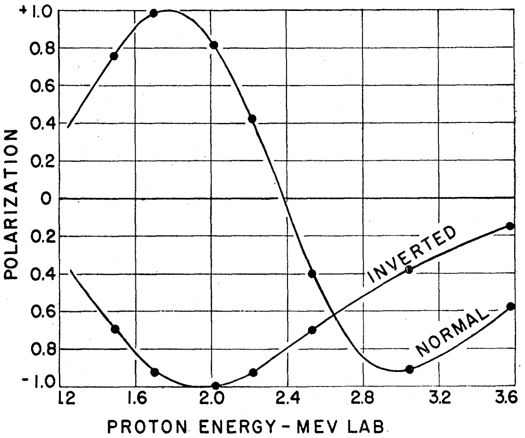

FIG. 1. Expected polarization of protons scattered from He^4 at 90° in the center-of-mass coordinate system as a function of incident proton energy. One curve assumes the normal $P_{\frac{1}{2}}-P_{\frac{3}{2}}$ doublet in Li^{5*} while the other assumes an inverted doublet.

A phase shift analysis of the proton-He^4 elastic scattering data in the energy range of incident protons from 0.95 to 3.58 Mev has been made by Critchfield and Dodder[4] from the experimental differential cross-section scattering data obtained by Freier, Lampi, Sleator, and Williams[5] at the University of Minnesota. The analysis shows that the data can be fitted by assuming that only $S_{\frac{1}{2}}$, $P_{\frac{1}{2}}$, and $P_{\frac{3}{2}}$ waves enter into the scattering interaction in the above energy range. However, the analysis does not establish uniquely the contribution of the $P_{\frac{1}{2}}$ and $P_{\frac{3}{2}}$ waves to the scattering interaction; i.e., two sets of phase shifts are obtained, one corresponding to the case of normal energy levels and the other for the case of inverted energy levels in Li^{5*}.

If the energy levels in Li^5 form a normal doublet, the phase shift analysis implies that both levels are within the above energy range so that it should be possible to polarize a beam of protons in either of two opposite directions in this energy range. If the energy levels are inverted, the phase shift analysis indicates that only the $P_{\frac{3}{2}}$ level is in this energy range and the $P_{\frac{1}{2}}$ level is somewhere above 4 Mev so that only one direction of polarization should take place in the above energy range. The expected polarization of protons scattered from He^4 at 90° in the center-of-mass system of coordinates for the normal and inverted doublets are shown in Fig. 1.

If one measures the polarization with some form of polarizer-analyzer arrangement, it should be possible to determine the order of the energy levels of the $P_{\frac{1}{2}}-P_{\frac{3}{2}}$ doublet in Li^{5*}. A beam of protons with a selected energy can be scattered by helium, and the protons

---

[*] This program assisted by the joint program of the ONR and AEC.

† Now at the Radiation Laboratory, Berkeley, California.

[1] F. Bloch, Phys. Rev. **58**, 829 (1949)

[1a] Julian Schwinger, Phys. Rev. **69**, 681 (1946); **73**, 407 (1948).

[2] L. Wolfenstein, Phys. Rev. **75**, 1664 (1949).

[3] M. Hamermesh, Phys. Rev. **75**, 1281 (1949).

[4] C. L. Critchfield and D. C. Dodder, Phys. Rev. **76**, 602 (1949).

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

scattered at 90° can be scattered by helium again at some lower energy determined by the mechanics of the scattering process and loss by ionization of the intervening material between the two scattering helium nuclei. If the doublet should be inverted, the second scattering process would favor an azimuthal direction that makes the second scattering similar to the first; while if the doublet should be normal, the opposite azimuthal direction would be favored on the second scattering provided one selects the original laboratory energy of the protons to fall on one side of the cross-over point and the energy of the second scattering to fall on the other.

The variation in azimuthal intensity is given by the differential cross-section relation[6]

$$\sigma(\theta,\phi)=\sigma_{12}[1+P_1(E_1,\theta_1)P_2(E_2,\theta_2)\mathbf{n}_1\cdot\mathbf{n}_2].$$

The quantities $\mathbf{n}_1$ and $\mathbf{n}_2$ are unit vectors representing the planes of the first and second scattering interactions, P_1 and P_2 are the polarizations which would be given to an initially unpolarized beam of protons at the first and second interactions separately, and σ_{12} is the differential cross section which would be obtained for doubly scattered protons if the polarizing of the protons by the first scattering were neglected. This double-scattering differential cross section σ_{12} can be obtained simply as the product of the differential cross sections for the two individual scattering events, i.e.,

$$\sigma_{12}(E_1,\theta_1,E_2,\theta_2)=\sigma_1(E_1,\theta_1)\sigma_2(E_2,\theta_2).$$

Using the notation of Critchfield and Dodder, and considering only the S and P waves, the polarization can be obtained from the scattering amplitudes by the relation $P=A^*\sigma A/A^*A$, where σ here is the Pauli spin matrix and where the scattering amplitude A is understood to contain the spin factors in the correct weight. The calculations can be made most easily by rewriting the original incident beam and scattering amplitude in terms of eigenfunctions with eigenvalues ± 1 in the X-direction where the scattering interaction occurs in the $Y-Z$ plane, and then using the spin matrix $\begin{vmatrix}1 & 0\\ 0 & -1\end{vmatrix}$ in the formula for the polarization. The polarization curves of Figs. 2 and 3 were computed from the phase shift data for the $p-\mathrm{He}^4$ interaction as given by Critchfield and Dodder,[4] Fig. 2 giving the polarization assuming the existence of the inverted $P_{\frac{3}{2}}-P_{\frac{1}{2}}$ doublet and Fig. 3 giving corresponding curves for the normal doublet.

From these polarization curves and from the formula for the differential cross section given above, the ratio is intensity between the forward double scattering and backward double scattering directions as applied to this experiment is obtained from the relation

$$R=(1+P_1P_2)/(1-P_1P_2),$$

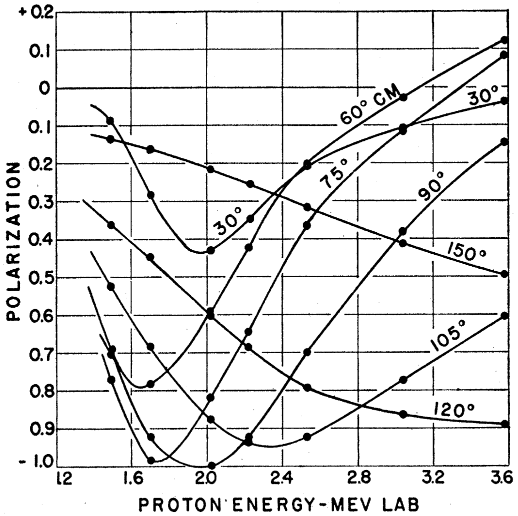

FIG. 2. Expected polarization of protons scattered from He^4 at various center-of-mass angles as a function of incident proton energy. All curves are for the case of in the inverted $P_{\frac{3}{2}}-P_{\frac{1}{2}}$ energy levels in Li^{5*}.

the term $\mathbf{n}_1\cdot\mathbf{n}_2$ being given only the values ± 1 for the geometry selected in this experiment.

EXPERIMENTAL APPARATUS AND PROCEDURE

The experimental polarizer-analyzer arrangement is shown in Fig. 4, which is a cross-section diagram of the double scattering chamber used. This chamber provided for double scattering at 90 degrees in the center-of-mass system for each of the two interactions, this angle giving, to a first approximation, the greatest polarization effect because of the maxima of the P waves at 90°. The collimating system between the two large gas volumes defined a beam of protons scattered at 90° in the first interaction, while selection of the protons scattered at 90° in the second interaction was made through analysis of the proton tracks in the nuclear

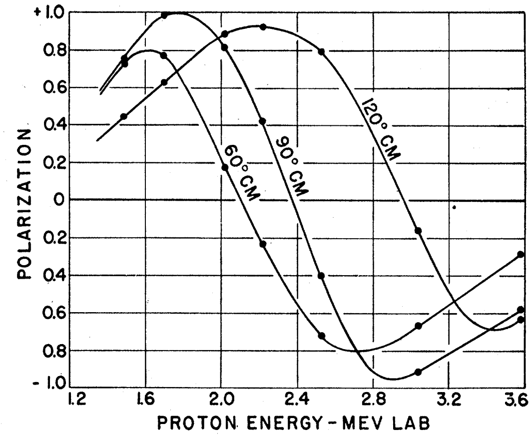

FIG. 3. Expected polarization of protons scattered from He^4 at various center-of-mass angles as a function of incident proton energy. All curves are for the case of the normal $P_{\frac{1}{2}}-P_{\frac{3}{2}}$ energy levels in Li^{5*}.

---

[6] J. V. Lepore, Phys. Rev. 79, 137 (1950).

emulsion plates used for measuring the yield. One nuclear emulsion plate was placed in a position to detect those protons scattered in a backward direction with respect to the incident proton beam, and another was placed in a position to detect those scattered in the forward direction.

The planes of the two scattering interactions were held nearly coplanar by the collimating system between the first and second scattering volumes, so that the expression $\mathbf{n}_1 \cdot \mathbf{n}_2$ took approximately the values ± 1.

The distance between the two effective scattering volumes was selected so that the stopping power of the gas in the chamber gave proper energy separation between the first and second scattering processes. Because of the low yield expected, the collimating systems were made to give broad resolution, and nuclear emulsion plates were used so that an integration of the yield over a long period of time could be obtained. The chamber was used with an atmospheric pressure of helium to provide a sufficiently high density of target nuclei for the double scattering process.[7]

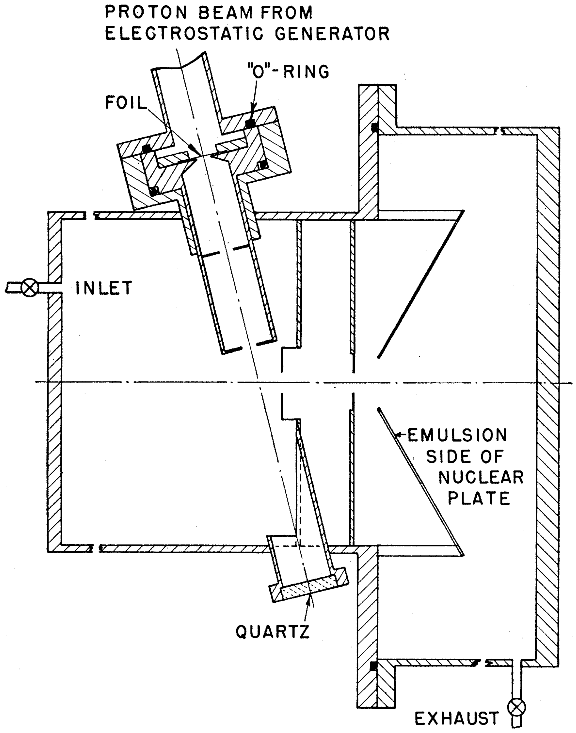

FIG. 4. Schematic diagram of double scattering chamber which uses nuclear emulsion plates as detectors of protons which have been scattered twice from He^4.

For elimination of wall scattering, the chamber was made of relatively large size, so that any protons scattered by the walls would not have enough energy left to pass through the high pressure helium and reach the nuclear emulsion plates. In addition, the plates were so oriented that no protons scattered by the slit edges could reach the emulsion side of the nuclear plates without additional $p-He^4$ collisions.

The atmospheric pressure of the helium was separated from the high vacuum of the electrostatic generator by a combination foil of 0.1-mil nickel and 0.2-mil Nylon placed over a hole $\frac{1}{4}$ inch in diameter but with a bar across its center for greater foil support. With the aid of the $Li^7(p,n)Be^7$ reaction threshold, the foil thickness was found to be 180 kilovolts at an initial proton energy of 2.062 Mev. The first collimating system consisted of the first round hole $\frac{1}{4}$ inch in diameter and the second hole $\frac{5}{16}$ inch in diameter, $3\frac{1}{2}$ inches from the first. An antiscattering slit of $\frac{5}{16}$-inch diameter was placed midway between these two defining slits. The second collimating system consisted of two rectangular slits $\frac{3}{8}$ inch long to provide sufficient intensity after the first scattering, and $\frac{1}{8}$ or $\frac{1}{4}$ inch wide to give sharper resolution in the plane of scattering.

The nuclear emulsion plates, 1 in.×3 in. in size, were held at one end on machined pedestals by spring clips at an angle of 60 degrees with respect to the central ray of the second collimating system. The plates chosen for detection of the protons were special C2 nuclear emulsion plates, made by Ilford, Ltd. In all the exposures made, after insertion of the plates into the chamber and replacement of the cover, the chamber was evacuated to a pressure of the order of 0.1 mm Hg. The helium was then let into the chamber, and the flow through the chamber was set at a rate of approximately six cubic feet per hour.

The relative intensity of the incident proton beam from the electrostatic generator was monitored with a 931-A photomultiplier tube which measured the light produced by the fluorescence of the quartz plate upon proton impact and the light produced by ionization and excitation of the helium. An absolute determination of the number of incident protons was not necessary.

To minimize blackening of plates by the light present in the chamber and to minimize peeling of the emulsions from the glass backing, C2 plates were obtained which contained a yellow screening dye to make the plates less sensitive to violet and ultraviolet light produced by the ionized helium, and with extra plasticizer added to improve the adherence of the emulsion to the glass. Ilford was able to supply these plates most conveniently with emulsions 100 microns thick. The proton tracks were easily visible in these plates, although these tracks may have been somewhat less dense than in the regular C2 plates.

DETAILS OF EXPOSURES

Two types of exposures were made, the first type being made with the emulsion in such a position as to determine the distribution of the singly scattered proton beam as collimated by the second slit system, and the second type being made to measure the intensities of the doubly scattered protons. No anomaly was found

---

[7] D. C. Dodder, Phys. Rev. 76, 683 (1949).

in the intensity pattern of the first scattered beam, the resulting distribution on the plates agreeing with that predicted by integrating the cross-section data available over the possible paths permitted by the collimation.

Several exposures were made to measure the comparative densities of the doubly scattered protons. The first was at an initial proton energy of 3.25 Mev, giving a computed proton energy at first scattering of 2.91 Mev. The slits in the second collimating system were $\frac{1}{8}$-inch wide, and a 24-hour continuous exposure was made with an incident proton beam intensity of the order of three microamperes.

A second exposure was made with the same geometry and at 3.50-Mev initial proton energy, giving a proton energy at first scattering of 3.17 Mev, for study of energy-dependent effects.

A third exposure was made at an initial proton energy of 3.25-Mev, but with a slit width of $\frac{1}{4}$ inch for study of resolution-dependent effects.

A background exposure was made by filling the chamber with deuterium. If the incident proton made two collisions with deuterium in such a fashion that it could pass through all collimating slits, it would then have insufficient energy to reach the photographic plates. The complete absence of tracks in the emulsion indicated there was no gas to wall scattering effects.

ANALYSIS OF PLATES

In analyzing the plates we chose to accept only those tracks of protons arriving along paths making an angle of less than 32 degrees with the plane of the plate, this giving equal angles on both sides of the central ray after the second scattering at 76 degrees from the axis of the chamber, or 16 degrees from the plane of the plate. However, because of the considerable statistical change in direction of the protons through multiple small-angle scattering after entering the emulsion, it was decided to place greater reliance on the energy of the protons as indicated by the lengths of the tracks in the emulsion as a criterion in selecting protons which had not been scattered through too large an angle in the second scattering.

The various possible proton paths in this broad-resolution application were traced through, and the energies and angles at which these protons arrived at the plates were then used as the standards of acceptance. The setting of these criteria was not of greatest importance because these same criteria were to be applied for the backward and forward plates alike, and it was only the ratio of the number of tracks and not the absolute number of tracks which was being studied.

The results obtained by counting proton tracks in equivalent strips in the forward and backward plates are given in Table I.

TABLE I. Ratio of proton tracks in equivalent strips in the forward and backward plates.

	No. of tracks on backward plate	No. of tracks on forward plate	Ratio—backward to forward	Theoretical ratio for ideal ray	
				Inverted doublet	Normal doublet
3.25 Mev $\frac{1}{8}$-in. slits	364	191	1.9	2.6	1/20.2
3.25 Mev $\frac{1}{4}$-in. slits	220	156	1.4	2.6	1/20.2
3.50 Mev $\frac{1}{8}$-in. slits	61	33	1.85	1.9	1/6.6

A comparison of the experimental backward to forward ratios with the two possible theoretical values shows that the doublet is inverted. The effect of changing from $\frac{1}{8}$-inch slits to $\frac{1}{4}$-inch slits indicates that the lack of exact agreement between theoretical and experimental results can be attributed to the broad geometry used in the experiment as described below. The theoretical ratios for an ideal ray are plotted in Fig. 5 for a range of energy values and show that for the normal doublet, the forward plate would have had by far the greater number of tracks in the neighborhood of the energy used. Because of low yield in the 3.50-Mev exposure and consequent poor statistics, no reliable deductions can be made in comparing the ratios at 3.50- and 3.25-Mev initial proton energy.

ERRORS AND CORRECTIONS

Possible sources of error considered were metal-to-gas or gas-to-metal collisions by the protons, generation of free neutrons which might lead to spurious acceptable proton tracks in the emulsions, contamination of the plates before exposure or after exposure and before development, mechanical alignment, helium purity, accuracy of control of energy of the initial proton beam,

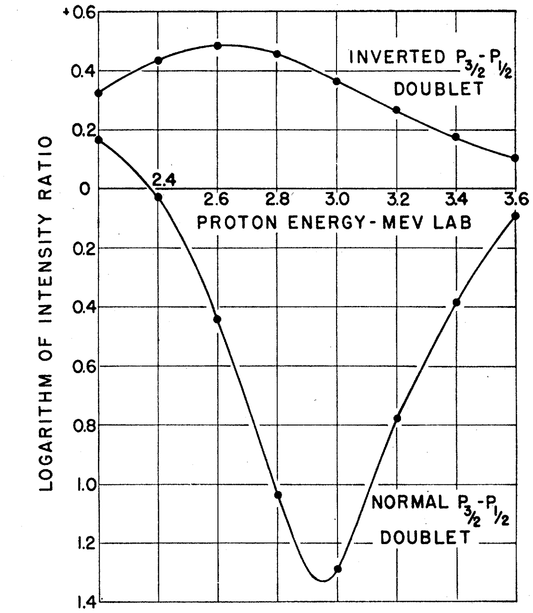

FIG. 5. Expected ratio of intensities on backward plate to forward plate for 90° center-of-mass double scattering of protons by He^4 as a function of incident proton energy before the first scattering.

and the broadness of the resolution in the scattering chamber. None of these except the last were found to have appreciable effect on the experimental ratio of number of proton tracks.

As seen in the results in Table I, however, the broadness of the resolution had a large effect on the correlation between the ratios as found experimentally and the ratios as predicted for the ideal proton path, i.e., the path involving two nuclear scatterings at exactly 90 degrees each in the center-of-mass system of coordinates. A numerical integration was then carried through for the case of incident proton energy of 3.25 Mev and slit width of $\frac{1}{8}$ inch. Factors included were the variation of cross section and energy with angle of scattering and variation of polarization with energy and angle of scattering. This summation gave a ratio in yield at the upper plate to that at the lower plate of 2.2 to 1, rather than the ideal path ratio of 2.6 to 1. Still neglected was the azimuthal variation of the paths of the protons such that the dot products $\mathbf{n}_1 \cdot \mathbf{n}_2$ were not exactly ±1.

CONCLUSIONS

The theoretical values are also subject to the experimental errors in the data from which the original phase shifts were calculated. With this additional correction, the ratio, as obtained experimentally, is considered to be in a statistical agreement with the ratio as obtained from the phase shift data for the inverted doublet and consequently shows that the $P_{\frac{3}{2}}-P_{\frac{1}{2}}$ doublet in the compound Li^5 nucleus is inverted. Any corrected theoretical ratio for the normal doublet would still be in complete disagreement with the experimental results.

This conclusion is in agreement with Adair's[8] considerations of the inversion of the P states in the mirror nuclei Li^5 and He^5. By assuming that the single level formula of nuclear dispersion theory held in this case, he showed that the phase shift variations for the inverted doublet as calculated by Critchfield and Dodder[4] could be fitted with an appropriate choice of nuclear parameters. He then used these same parameters corrected for the absence of the coulomb field and calculated the $n-\alpha$ total cross sections which were in substantial agreement with the experimental data.

It is expected that differential $p-\mathrm{He}^4$ cross-section measurements when extended to proton energies of 5 or 6 Mev would show the presence of the $P_{\frac{1}{2}}$ wave resonance. At this energy the scattered protons would have a polarization opposite in sign to the polarization found in this experiment. An experiment similar to this one would then give a further check on the order of energy levels in Li^{5*}. By selecting the first scattering to take place at the $P_{\frac{1}{2}}$ energy level and the second scattering to take place at the lower $P_{\frac{3}{2}}$ energy level, there should then be a reversal of the backward to forward ratios found in this experiment.

With the development of ion sources capable of high beam intensities and with improvement of electrostatic generator techniques, double process experiments are becoming more feasible. Interactions such as the $p-\mathrm{He}^4$ interaction described in this report can be used to polarize the protons in a single scattering process, and the polarized beam produced can be used in other scattering and disintegration experiments in which the angular momenta are of special interest. If there should be strong polarization near the $P_{\frac{1}{2}}$ level resonance of this inverted doublet, the applicability of this experimental device would be extended to higher energy ranges. After the beam has been polarized it can be degraded in energy to any desired value by ionization losses in passing through a material medium without appreciably changing the polarization.

ACKNOWLEDGMENTS

This work was begun by Mr. D. C. Dodder, who made preliminary calculations and suggested the geometry of the chamber to be used to decrease the background to a minimum. We also wish to thank Professor J. H. Williams for his interest and advice and the members of the electrostatic generator group for their cooperation in obtaining the exposures.

This research was materially assisted by the University of Minnesota Technical Research Fund.

---

[8] R. K. Adair, Phys. Rev. **82**, 750 (1951).