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TRIPLE SCATTERING OF 660-Mev PROTONS II. ANGULAR DEPENDENCE OF DEPOLARIZATION

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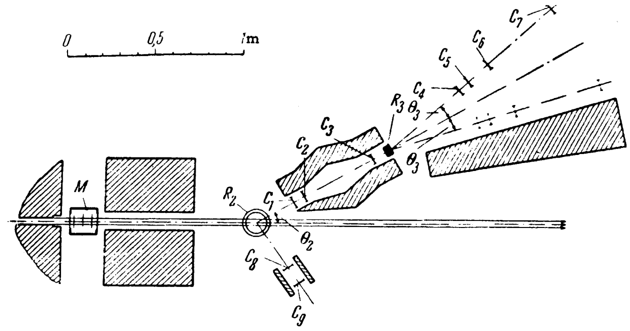
Results are presented on the measurement of the depolarization parameter for the scattering of a polarized beam of 640-Mev protons through 54, 72, 108, and 126° in the c.m.s. In scattering through 54, 72, and 90° the normal polarization component of the proton beam is changed slightly. The sum and difference of the values of the depolarization parameter for scattering angles that are symmetric about the 90° direction are interpreted in terms of the amplitude of the p-p scattering matrix.

OUR previous experiments[1] showed that the scattering of a polarized beam of 640-Mev protons by protons through an angle of 90° in the c.m.s. causes a weak depolarization of the beam. This result is evidence of the fact that at this energy the p-p interaction associated with elastic scattering at large angles is relatively rarely accompanied by a change in the spin orientation. Further information on the character of the p-p interaction can be obtained from experiments in which the depolarization parameter is measured at c.m.s. scattering angles both smaller and larger than 90°, which was done in this experiment. The results of such measurements give two independent relations between the amplitudes of the p-p scattering matrix supplemented by two relations embodying the data on the angular dependence of the differential cross sections and polarization.

The experiments described below were carried out on the six-meter synchrocyclotron of the Joint Institute for Nuclear Research as part of the program for studying the p-p interaction at ~660 Mev.

MEASUREMENT PROCEDURE AND RESULTS

The experimental arrangement is shown in the figure, its general features being the same as in the previous measurements (see Fig. 1a of reference 1). We used a proton beam with a degree of polarization $P_1 = 0.58 \pm 0.03$ and energy (640 ± 12) Mev, scattered inside the synchrocyclotron chamber to the left by an angle of 9° in a beryllium target-polarizer. The second scattering took place in a cylindrical vessel of diameter 12 cm filled with liquid hydrogen. The mean proton energy in the center of the liquid hydrogen target was 635 Mev, the intensity of the beam in a 3 cm diameter was 7×10^5 protons/cm²-sec.



Experimental setup (in plane of scattering). M – monitor; R_2 – second scatterer (vessel with liquid hydrogen); R_3 – third scatterer (graphite block 5×5 cm, 6 cm thick; C_1–C_9 – scintillation counters of dimensions (the first figure gives the horizontal dimension, and the second the vertical) 6.5×6.5; 6×7; 6×7; 6×6; 6×6.5; 6.5×7; 6.5×6.5; 7.5×12; and 8.5×13 cm and thickness 6 mm. The depolarization measurements at 126° were made without counters C_2 and C_5; a third scatterer of cross section 5×5 cm and thickness 3 cm was used here. The shaded areas indicate the position of the lead shielding.

The depolarization parameter D was measured every 18° over the scattering angle θ_2, beginning at 54° and ending at 126°. The beam of protons doubly scattered through an angle θ_2 on the same side (to the left) was picked up by a telescope consisting of three counters C_1, C_2, and C_3. In order to separate elastic p-p scattering from accompanying inelastic processes taking place in the liquid hydrogen target, the scattered protons and recoil protons were registered by telescopes ($C_1C_2C_3$) and (C_8C_9) working together, the angle between them corresponding to the kinematics of elastic p-p collisions.

The normal component of the polarization vector of the doubly scattered protons was determined by measurements of the left-right asymmetry ϵ_{3n} of the emitted charged particles in the direction $\theta_3 = 12°$ (in the laboratory system) from a carbon target-analyzer R_3. These measurements involved the registration of nine-fold coincidences of counter pulses grouped in telescopes ($C_1C_2C_3$), (C_8C_9), and ($C_4C_5C_6C_7$), the last registering triply scattered protons. Corrections to the number of nine-fold coincidences took into account chance nine-fold coincidences ($\sim 1\%$) and the effect of the empty vessel ($\sim 3\%$). In order to check that the angles θ_3 measured to the left and right were actually equal to one another, and therefore to exclude the possibility of the appearance of a false asymmetry owing to the zero mark on the θ_3 angular scale not coinciding with the effective axis of the secondary beam, the "profile" of the beam of doubly scattered protons was measured carefully for all angles. The procedure involved in these measurements was similar to that used earlier by the Berkeley group.[2]

The value of the depolarization parameter $D(\theta_2)$ was found from the relation[3]

$$D = \frac{\varepsilon_{3n}}{\varepsilon_3}(1 + P_1P_2) - \frac{P_2}{P_1}, \qquad (1)$$

where P_1 is the initial polarization of the beam, and P_2 is the polarization arising in the scattering on hydrogen of an unpolarized proton beam through a given angle θ_2. The value and angular dependence of P_2 are known from previous measurements.[4]

The value of ϵ_3 represents the experimentally observed left-right asymmetry of emission from the carbon target of charged particles under the action of a proton beam of polarization P_1 and energy equal to the energy of the protons scattered in hydrogen through an angle θ_2. In measuring the value of this asymmetry, we used the same apparatus as in the measurements of ϵ_{3n}. Counters C_1, C_2, C_3 and the carbon target were set in the primary polarized proton beam whose energy was degraded, by means of a filter consisting of lead and polyethylene plates, to the energy of the doubly scattered proton beam. Particles emitted from the carbon target in the direction of ± 12° were registered by the telescope ($C_4C_5C_6C_7$) connected in coincidence with the telescope ($C_1C_2C_3$); the intensity of the primary beam was reduced here to 1/50 — 1/100 of its former value. It should be noted that measurements made with filters having different ratios of thickness of lead and polyethylene layers were in agreement, within the limits of standard deviations of the value of ϵ_3.

At each angle of observation, of the depolarization, we made 10 — 12 independent repeated measurements of the asymmetries ϵ_{3n} and ϵ_3. In the overwhelming majority of cases the results of the repeated measurements were in agreement, within the limits of error, with the mean values. The data on the mean energies, and also the angular and energy spread of the protons in the secondary beam, are given in the table, along with the values found for the asymmetries ϵ_{3n} and ϵ_3 and their statistical errors. The table lists also the values obtained for the depolarization parameter, for various scattering angles.

DISCUSSION OF RESULTS

According to Wolfenstein,[3] the depolarization parameter can vary in the limits of $-1 + 2|P_2| \leq D \leq +1$. The results obtained in our experiment indicate that the depolarization parameter corresponding to p-p scattering through 54, 72, 90, 108, and 126° is a positive quantity. Moreover, for scattering angles of 54, 72, and 90° the depolarization parameter was found to be close to +1. By comparing the asymmetries ϵ_{3n} and ϵ_3 obtained for angles of 54, 72, and 90°, it can be seen that in p-p scattering at those angles the normal component of the polarization does not undergo large changes.

Thus far, systematic measurements of the depolarization parameter in p-p scattering were

Values of the Asymmetries ϵ_{3n} and ϵ_3 and Depolarization D
(the results for 90° are taken from ref. 1)

$\theta_2 \pm \Delta\theta_2$, deg	$E_2 \pm \Delta E_2$, Mev	$\varepsilon_3 \pm \Delta\varepsilon_3$	$\varepsilon_{3n} \pm \Delta\varepsilon_{3n}$	$D \pm \Delta D$
54±4	490±20	0,121±0,005	0,161±0,024	0,99±0.25
72±4	416±21	0,173±0,008	0,1[illegible]4±0,029	0.69±0,20
90±5	315±20*	0,216±0,012	0,200±0,032	0,93±0,17
108±5	219±27	0,198±0,011	—0,023±0,033	0.28±0.16
126±5	125±21	0,157±0,015	—0.009±0.036	0,57±0,20

*In the previous work[1] the energy spread of the protons was erroneously given as ±40 Mev.

carried out at energies of 315 (reference 5) and 143 (reference 6) Mev for angles less than 90°. In both cases the values obtained for the depolarization parameter were of positive sign.* Comparison of the available data for triple scattering of protons indicates that the depolarization parameter discloses a tendency to increase with an increase in energy from 143 to 635 Mev in the scattering angle interval $50° \leq \theta_2 \leq 90°$. This characteristic of p-p interactions in the considered energy region would be brought out still more convincingly if the depolarization parameter were to be measured with greater accuracy and over smaller energy intervals.

In the notation of Wolfenstein,[3] the p-p scattering matrix can be written

$$M = BS + C(\sigma + \sigma_t)\mathbf{n} + \tfrac{1}{2}G[(\sigma\mathbf{k})(\sigma_t\mathbf{k}) + (\sigma\mathbf{p})(\sigma_t\mathbf{p})]T + \tfrac{1}{2}H[(\sigma\mathbf{k})(\sigma_t\mathbf{k}) - (\sigma\mathbf{p})(\sigma_t\mathbf{p})]T + N(\sigma\mathbf{n})(\sigma_t\mathbf{n})T, \quad (2)$$

and the differential cross section $\sigma_0(\theta)$ for the scattering of an unpolarized beam of protons on protons and the depolarization parameter $D(\theta)$ can be expressed in terms of the complex amplitudes B, C, G, H, N in the following way:

$$\sigma_0(\theta) = \tfrac{1}{4}|B|^2 + 2|C|^2 + \tfrac{1}{4}|G-N|^2 + \tfrac{1}{2}|N|^2 + \tfrac{1}{2}|H|^2, \quad (3)$$

$$\sigma_0(\theta)[1 - D(\theta)] = \tfrac{1}{4}[G - N - B]^2 + |H|^2. \quad (4)$$

Then, since B, $C/\sin\theta$, and H is an even function of $\cos\theta$, while G and N are odd, it is not difficult to show that the values of the depolarization parameter for angles symmetric with respect to the 90° direction are connected with the scattering matrix amplitudes by the two following independent relations:

$$\sigma_0(\theta)[D(\theta) + D(\pi - \theta)] = 4|C|^2 + |N|^2 - |H|^2, \quad (5)$$

$$\sigma_0(\theta)[D(\theta) - D(\pi - \theta)] = \mathrm{Re}\{[G - N]B^*\}. \quad (6)$$

From this it is seen that the product of the differential cross section $\sigma_0(\theta)$ and the sum $[D(\theta) + D(\pi - \theta)]$ is represented in terms of the triplet amplitudes C, N, and H, while the product of the differential cross section $\sigma_0(\theta)$ and the difference $[D(\theta) - D(\pi - \theta)]$ depends only on the singlet-triplet interference.

*The Harwell group[7] carried out observations of the depolarization in p-p scattering at 142 Mev and found negative values of the depolarization parameter for angles in the interval $50° \leqslant \theta_2 \leqslant 90°$. This result, however, has not been confirmed (see reference 6). It should be noted that the sign of the depolarization parameter is extremely sensitive to the model used for the nuclear potentials. Thus, the values of the depolarization parameter found in reference 6 are in agreement with the results of the calculations of Gammel and Thaler,[8] who used the statistical potential with the addition of an LS term, while use of the Signell–Marshak potential[9] leads to values of the depolarization parameter differing even in the sign from that given by experiment.

On the basis of the results of the present experiment, it may reliably be shown that in p-p scattering at 640 Mev the sum $[D(\theta) + D(\pi - \theta)]$ is not equal to zero. This means that the basic role in the p-p scattering matrix is played by the triplet terms $C(\sigma + \sigma_t)\mathbf{n}$, $H[(\sigma\mathbf{k})(\sigma_t\mathbf{k}) - (\sigma\mathbf{p})(\sigma_t\mathbf{p})]$, $N(\sigma\mathbf{n})(\sigma_t\mathbf{n})$. As has already been noted,[1] from the fact that $D(90°)$ is close to $+1$ it follows that the main contribution to scattering at an angle of 90° is given by the term $C(\sigma + \sigma_t)\mathbf{n}$.

In order to see if the observed difference between the values of $D(\theta)$ and $D(\pi - \theta)$ are significant or accidental, it was necessary to analyze the character of the distributions of all the errors of measurement of the asymmetries ϵ_{3n} and ϵ_3 and polarizations P_1 and P_2. The results of the statistical analysis were that the probabilities of non-zero differences in moduli $[D(54°) - D(126°)]$ and $[D(72°) - D(108°)]$ are 80 and 86%, respectively. Both differences between the observed values of the depolarization parameter are practically independent of each other and the probability that both these differences are simultaneously chance deviations from a mean value of zero is only ~3%.

Thus, although the data of the present experiment are not marked by a high accuracy, they all indicate that in the energy region and scattering angles under consideration singlet-triplet interference occurs. It thus follows that the final state of the p-p system includes some mixture of the singlet states.

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