SOVIET PHYSICS JETP VOLUME 11, NUMBER 5 NOVEMBER, 1960

ELASTIC SCATTERING OF 8.5-Bev PROTONS ON PROTONS

P. K. MARKOV, É. N. TSYGANOV, M. G. SHAFRANOVA, and B. A. SHAKHBAZYAN

Joint Institute for Nuclear Research

Submitted to JETP editor December 31, 1959

J. Exptl. Theoret. Phys. (U.S.S.R.), **38**, 1471-1475 (May, 1960)

Elastic pp scattering at 8.5 Bev was studied by the emulsion technique. The irradiation geometry employed was such that the incident-proton beam was perpendicular to the emulsion plane. A total of 145 elastic scattering events were detected, of which 66 have been previously reported.[1] The contribution of scattering on quasi-free photons and of other "background" events comprises approximatelt 1%. The total elastic cross section in the c.m.s. is found to be (8.6 ± 0.8) mb. A differential cross section down to one degree in the c.m.s. has also been obtained. The results can be made consistent with the model of a homogeneous semi-transparent ball with a refractive index not equal to unity.

SETUP OF THE EXPERIMENT

PRELIMINARY data on elastic pp scattering at 8.5 Bev have been published earlier.[1] The present work was performed with a $10 \times 10 \times 2$ cm chamber made up of type NIKFI-BR emulsions 400 microns thick and irradiated in the Joint Institute proton synchrotron by the internal 8.5-Bev proton beam, incident perpendicular to the emulsion plane. Special analyses made for the hydrogen content in control emulsions have shown that the hydrogen content was $(2.90 \pm 0.06) \times 10^{22}$ atoms per cubic centimeter of exposed emulsion.

Area scanning was carried out with an immersion objective at a magnification 630×, in the 2×2 cm central portion of the emulsion. The average flux density in this zone was $(1.97 \pm 0.05) \times 10^5$ particles per square centimeter. A total of 3.35 cubic centimeters of emulsion was scanned.

To determine the effectiveness of finding the investigated events and to increase the reliability of the results, the aforementioned volume was scanned twice. The stars outwardly resembling elastic pp scattering were separated from all the obtained two-prong stars. Their number was 799. These events were divided in the following three groups, depending on the range of the slow proton: 1) $10\,\mu \leq R < 100\,\mu$, 2) $100\,\mu \leq R < 20{,}000\,\mu$, 3) $R \geq 20{,}000\,\mu$.

The tracks of the slow protons in the first two groups were practically "black," since the sensitivity of the emulsion was high ($J/J_{\min} = 40$ grains/100 μ). The efficiency of the double scanning was found to be (85 ± 3) %, (92.5 ± 0.8) %, and (78 ± 5) % for events in the first, second, and third groups respectively.

ANALYSIS OF THE DETECTED EVENTS AND MEASUREMENT PROCEDURE

The following criteria were used to identify the cases of elastic scattering on free hydrogen:

1. The relation between the range R of the recoil proton and its angle with the direction of the primary photon, φ, satisfies the kinematics of elastic scattering.
2. The angle γ between the planes passing through the direction of the primary proton and the direction of emergence of the secondary particles is zero (coplanarity condition).
3. The relation between the range of the recoil proton and the angle ψ that the scattered proton makes with the direction of the primary particle satisfies the kinematics of elastic scattering.
4. No recoil nucleus or β electron is observed at the point of scattering.

The relation between the angle of the scattered proton and the angle of the recoil proton, which holds for elastic scattering, was used when the recoil proton did not stop in the chamber and its momentum, determined by ionization measurements, was known to be in considerable error.

The range of the recoil proton was measured accurate to 5%.

The principal error in the determination of the angle of emission of the recoil proton was due to the inaccuracy in the measurement of the dip angle. On the average this error does not exceed 1.5 or 2 deg, for cases when the recoil proton has a short range ($R < 500\,\mu$).

The angle of emission of the scattered proton, ψ, was measured in the following manner. A reference track of a primary proton that did not experience interaction was selected within 20 or 30 microns of the point of scattering. To determine the scattering angle ψ, four measurements were made of the x and y projections of the distance from the reference track to the scattered track, in the plane of the emulsion (parallel to the marker lines). We made two measurements to the point of scattering on a 2000-μ base (that is, through five emulsions), and two past this point, on the same base. The accuracy with which the projections were measured was approximately 1 μ, so that these scattering angles could be measured accurate to 2′ or 3′. To exclude random errors, independent measurements were made relative to the three reference tracks.

The angle of non-coplanarity γ was determined from these measurements. The error in γ was due essentially to the error of measurement of the angle of the scattered proton, and dependent on the value of this angle. Thus, for $\psi = 1$ deg, the error in the non-coplanarity angle is 3 deg if $\Delta\psi = 3'$. As shown earlier,[1] at the prevailing measurement accuracies the contribution of the number of quasi-elastic scatterings should be approximately 1%.

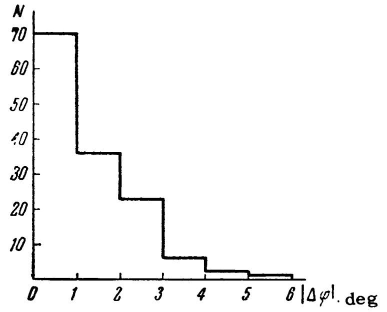

FIG. 1. Distribution of |Δφ| in scattering events: Δφ – difference between the measured angle of the recoil proton and the angle that corresponds to its range in the elastic scattering kinematics.

The measurement errors were estimated for each measured event and the events satisfying the kinematics of elastic scattering within the tripled errors were selected. Figures 1 to 3 show the distributions of $|\Delta\varphi|$, $\Gamma = |\gamma/\Delta\gamma|$, and $|\Delta\psi|$ for these events. It follows from Fig. 1 that the mean-square error in the measurement of φ amounts to ~ 2 deg.

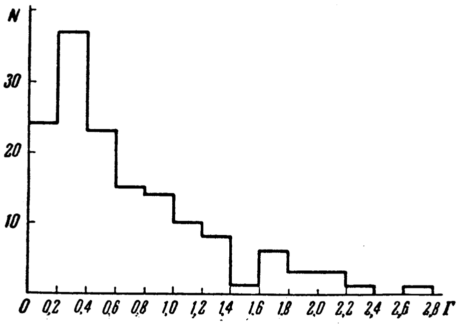

FIG. 2. Distribution of $\Gamma = |\gamma/\Delta\gamma|$ in elastic scattering events; where γ is the non-coplanarity angle and $\Delta\gamma$ is the error in its determination.

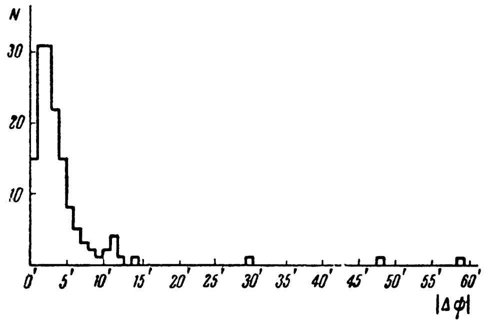

FIG. 3. Distribution of $|\Delta\psi|$ in events chosen in accordance with the first two criteria (ratio of R to ψ and the coplanarity). $\Delta\psi$ – difference between the angle of the scattered proton and the angle corresponding to the range of the recoil proton in the elastic scattering kinematics.

From the distribution of Γ in the selected cases it is seen that the errors in the distributions of the non-coplanarity angle $\Delta\gamma$ have been correctly estimated. For the histogram of Fig. 3, we selected, by the first two criteria, the cases satisfying the kinematics of elastic scattering within the limits of the tripled mean-square error. The histogram includes also those cases of scattering by quasi-elastic protons, for which the momentum lies in the scattering plane and is perpendicular to the incident proton, inasmuch as such cases were not identified by the first two criteria. A considerable fraction of such cases falls within the region $|\Delta\varphi| > 12'$ (that is, past the tripled half-width of the distribution), where there are no cases of scattering by free protons. From the number of such events one can estimate the contribution of quasi-elastic cases and other background in the region $|\Delta\varphi| < 12'$. This contribution is found to be approximately 1%.

RESULTS AND DISCUSSION

The technique employed (irradiation of emulsions at right angle to their plane) and the corresponding measurement procedure have made it possible to obtain the c.m.s. differential cross sections down to 1 deg, to separate reliably the quasi-elastic events from the background, and to accumulate considerable data in a relatively short time.

A total of 145 events satisfied the selection criteria within the limit of tripled mean-squared errors. This is several times more than in other emulsion investigations of elastic scattering in the energy range $\gtrsim$ 1 Bev (see references 2—4).

After estimating the contribution of quasi-elastic processes, discarding the cases of scattering by small angles ($\leq$ 1 deg in the c.m.s.), and estimating the scanning efficiency, the value obtained for the cross section of elastic interaction was found to be $\sigma_{el} = 8.5 \pm 0.8$ mb.

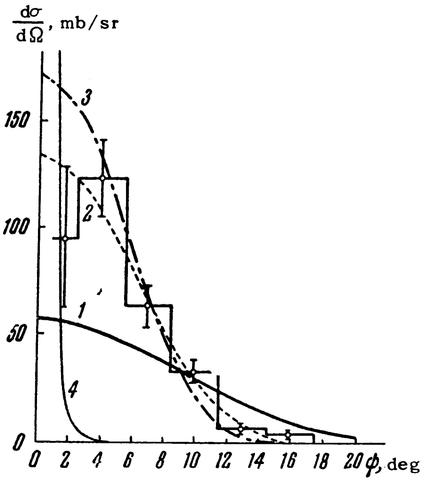

FIG. 4. Differential cross section of elastic pp scattering at 8.5 Bev (histogram). ψ – scattering angle in c.m.s. Calculated curves: 1 – Coulomb scattering, 2 – disc for R = 0.94 f and a = 0.453; 3 – homogeneous semi-transparent sphere, R = 1.5 f, $k = 0.12 \times 10^{13}$ cm^{-1}, $k_1 = 0.15 \times 10^{13}$ cm^{-1}, U = 34 Mev, and V = 27 Mev; 4 – homogeneous semi-transparent sphere, R = 1.7 f, $k = 0.12 \times 10^{13}$ cm^{-1}, $k_1 = 0.12 \times 10^{13}$ cm^{-1}, U = 22 Mev, and V = 22 Mev.

Figure 4 shows, in the form of a histogram, the differential cross section for elastic pp scattering in the c.m.s. The heavy solid curve shows the angle of distribution obtained by using the model of a purely-absorbing disc with the following parameters: disc radius $R = 0.94 \times 10^{-13}$ cm, amplitude of passing wave A = 0.453, cross sections for elastic and inelastic interaction $\sigma_{\mathrm{el}} = 8.5$ mb and $\sigma_{\mathrm{in}} = 22$ mb. It is seen from the figures that the experimental data cannot be explained within the framework of this model. Nor can these data be explained by any other model of a purely absorbing proton, when, without allowance for the spin dependence, the differential cross section at zero angle is given by the optical theorem

$$|\operatorname{Im} f(0)|^2 = (\sigma_t / 4\pi\lambda\!\!\!^{-})^2$$

and is found to be considerably less than the experimental value. In this respect, our results disagree with the conclusions of other experiments carried out at lower energies. Thus, for example, in the work by Cork et al.,[5] in which elastic scattering at 6.15 Bev is investigated, the differential cross section is extrapolated from 7.6 deg to the value for 0 deg given by the optical theorem. However, if we plot $k_c \sin\theta$ vs. $k_c^{-2} d\sigma/d\Omega$ instead of our differential cross section (as is usually done to compare experiments at different energies) the experimental data of reference 5 and ours are found to be in satisfactory agreement. The point is that our experimental data disagree with the proton model proposed by the authors of reference 5 only in the range of angles from 0 to 7.6 deg, for which there are no experimental data in reference 5.

The agreement with the data of Kalbach et al.[3] and the model of the purely-absorbing disc may be due to the insufficient statistical accuracy.

In view of the results obtained, we see no full justification for approaching the analysis of the data on elastic scattering of protons by protons by assuming a pure imaginary scattering amplitude.[6]

In reference 7 it has been shown that the model of the purely absorbing proton, in the energy range above 6 Bev, does not contradict the available experimental data. Our data, obtained at smaller scattering angles, indicate that it is also necessary to take into account the real part of the scattering amplitude.

We have performed the calculations using the model of the homogeneous sphere with a complex coefficient of refraction.[6] As seen from Fig. 4, the experimental data are in satisfactory agreement with the calculations for a sphere having the following parameters:

$$R = (1.5 \text{ to } 1{,}7) \cdot 10^{-13}\,\mathrm{cm}$$

$$k = (0.191 \text{ to } 0{,}125) \cdot 10^{13}\,\mathrm{cm}^{-1}, \quad k_1 = (0{,}155 \text{ to } 0.125) \cdot 10^{13}\,\mathrm{cm}^{-1},$$

$$U = (34.1 \text{ to } 22.3)\,\mathrm{Mev}, \quad V = (27{,}5 \text{ to } 21.8)\,\mathrm{Mev},$$

where R is the radius of the sphere, k and k_1 describe the absorption and refraction coefficients respectively, and U and V are the imaginary and real parts of the potential inside the sphere.

Figure 4 shows also the differential cross section of the Coulomb interaction (thin solid line). It is seen that at angles greater than 2.5 deg the effect of the Coulomb interaction is very small and can be neglected. In the interval from 1.0 to 2.5 deg, experiment yields a differential cross section somewhat smaller than that predicted by the model of the homogeneous sphere, although the efficiency of finding the scattering is sufficiently high here and is known with good accuracy. If the result is confirmed after the statistical errors have been reduced, it will be possible to attribute it to the interference of the Coulomb interaction with the nuclear interaction.

The large value of the differential cross section at 0 deg does not contradict the model of a purely absorbing proton, if a great difference is assumed in the interaction cross sections for the singlet and triplet states. It is therefore of interest to investigate the role of the spin interactions in elastic pp scattering at 8.5 Bev. This has been done in simplest form by one of the authors (Shakhvazyan)[9] for the model of a purely absorbing proton (pure imaginary scattering phase shifts) with allowance for the spin-spin interaction.

In this case the scattering matrix is independent of the total angular momentum J (see reference 6) and has the form

$$R_l = \eta_l - 1, \quad 0 \leqslant \eta_l \leqslant 1.$$

The last inequality yields expressions for the upper limits of the coefficients of the curve that approximates the experimental points. A phase-shift analysis[9] carried out under the same assumptions both for different mixtures of singlet and triplet states, and for purely singlet states, leads to values of η_l which do not satisfy the inequality. This circumstance allows us to state that in the approximation of reference 6 the experimental results cannot be explained by the model of a purely absorbing proton which allows for the spin-spin interaction.

The authors are very pleased to express deep gratitude to D. I. Blokhintsev, V. I. Veksler, M. Danysz, M. I. Podgoretskiĭ, I. Ya. Pomeranchuk, Ya. A. Smorodinskiĭ, and K. D. Tolstov for numerous valuable discussions of the results and for interest in the work. The authors thank the proton synchrotron crew of the Joint Institute for Nuclear Research for irradiating the emulsion chamber, and the staff of the emulsion scanning section of the High-Energy Laboratory of the Joint Institute for Nuclear Research. The authors also thank L. G. Popova, V. A. Nikitin, and V. A. Sviridov for aid in processing the experimental data, to the crew of the "Ural" computer (Laboratory of Technical Physics, Joint Institute for Nuclear Research) and also T. F. Grabovskaya and O. A. Ignatenko for scanning and measurements.

[1] Lyubimov, Markov, Tsyganov, Cheng, and Shafranova, JETP **37**, 310 (1959), Soviet Phys. JETP **10**, 219 (1960). Preprint, Joint Inst. Nuc. Res. R-339.

[2] W. D. Walker, Phys. Rev. **108**, 872 (1957). W. D. Walker and J. Crussard, Phys. Rev. **98**, 1416 (1955); Phys. Rev. **104**, 526 (1956).

[3] Kalbach, Lord, and Tsao, Phys. Rev. **113**, 330 (1959).

[4] Duke, Lock, March, Gibson, McEwen, Hughes, and Muirhead, Phil. Mag. **2**, 204 (1957).

[5] Cork, Wenzel, and Causey, Phys. Rev. **107**, 859 (1957).

[6] Ito, Minami, and Tanaka, Nuovo cimento **8**, 135 (1958); **9**, 208 (1958). V. G. Grishin and I. S. Saitov, JETP **33**, 1051 (1957), Soviet Phys. JETP **6**, 809 (1958). V. G. Grishin, JETP **35**, 501 (1958), Soviet Phys. JETP **8**, 345 (1959).

[7] Grishin, Saitov, and Chuvilo, JETP **34**, 1221 (1958), Soviet Phys. JETP **7**, 844 (1958). V. S. Barashenkov and Huang Nen-Ning, JETP **36**, 832 (1959), Soviet Phys. JETP **9**, 587 (1959).

[8] Fernbach, Serber, and Taylor, Phys. Rev. **75**, 1352 (1949).

[9] B. A. Shakhbazyan. Analysis of Elastic Proton-Proton Scattering at 8.5 Bev. Preprint, Joint Inst. Nuc. Res. D-450, 1959.

Translated by J. G. Adashko
283