ELASTIC PROTON-PROTON SCATTERING AT 8.5 Bev

V. B. LYUBIMOV, P. K. MARKOV, E. N. TSYGANOV, CHENG P'U-YING, and M. G. SHAFRANOVA

Joint Institute of Nuclear Research

Submitted to JETP editor April 17, 1959

J. Exptl. Theoret. Phys. (U.S.S.R.) **37**, 910-916 (October, 1959)

Elastic p-p scattering at 8.5 Bev was studied using photographic emulsions. The geometry of irradiation was such that the incident protons were perpendicular to the plane of the emulsion. Sixty-six cases of elastic scattering were found. Scattering on quasi-free protons and other background effects comprised about 2%. The elastic scattering cross section was (8.4 ± 1.1) mb. The differential cross section down to 2.5° in the c.m.s. was obtained. Near 0° it turned out to be larger than would be expected on the basis of the purely absorbing proton model.

INTRODUCTION

THE study of the elastic scattering of particles at high energy is a convenient way of studying their structure. The optical model, which was first applied to the analysis of scattering of neutrons by nuclei,[1] has been used widely to analyze experimental data on the elastic scattering of π mesons and protons by nuclei at energies of 1 Bev and higher.[2-8] Recently, several authors,[9-11] employing somewhat simplifying assumptions, carried out a phase-shift analysis of experimental data on the elastic scattering of π mesons and protons by protons at various energies. It turned out that the available experimental results could be explained almost completely by diffraction scattering.

In the study of elastic scattering of high-energy π mesons and protons by nucleons, one encounters a series of experimental difficulties. Firstly, the cross section is small (5 — 10 mb). Secondly, the corresponding experiments demand detection of very small scattering angles (~ 1° in the laboratory system, designated l.s.), whereas in the work of references 2 — 8 scatterings through angles up to 5° in the l.s. were missed, and in the work of reference 12 the differential cross section was measured from an angle of 2° in the l.s. (E = 6.15 Bev). Thirdly, in work with photoemulsions, it is hard to segregate cases of scattering by protons bound in the nucleus,[2,3,5] since this requires a very high accuracy in measurement of angles.

An attempt was made in this work to avoid the difficulties indicated above.

EXPERIMENTAL ARRANGEMENT

In this work, the elastic scattering of 8.5 Bev protons by protons was studied using photoemulsions. Usually one scans along the track to find such events. However, with this method of search, the efficiency of detecting cases of scattering through small angles is low.[2] This is especially so for cases in which the scattering plane makes a large angle with the plane of the photoemulsion.[6] An azimuthal asymmetry is also observed in area scanning in the case of irradiation parallel to the plane of the photoemulsion.[13] Estimates using the optical model show that at 8.5 Bev almost all the scattering is concentrated in angles < 3° in the l.s. Therefore, the usual type of scanning along the track would introduce considerable distortion into the results. Also, the accumulation of statistics is exceedingly slow.

In studying elastic scattering at E = 8.5 Bev using photoemulsions, it is advantageous to direct the proton beam perpendicular to the plane of the emulsions and carry out area scanning. Since the recoil proton* in most cases has a small momentum, directed almost perpendicular to the incident proton, i.e., it lies almost in the plane of the photoemulsion, the efficiency of detecting the events of interest is high, and does not depend on the azimuth angle. The beam density employed in perpendicular irradiation can be several times higher than that used in parallel irradiation.[14] This increases the speed of accumulation of statistics. Also, with such geometry it turned out to be possible to measure angles of the scattered proton with high accuracy (~ 3′).

The enumerated advantages of such a method are considerable, and we believe that this method can be successfully used also at somewhat higher energies.

*We call the proton emitted at a large angle the recoil proton, and the one emitted at a small angle (relative to the incident beam) the scattered proton.

The present work was carried out with a camera of dimensions $10 \times 10 \times 2$ cm^3 consisting of layers of emulsion of type NIKFI-BR of thickness 400μ, irradiated by the internal beam of 8.5 Bev protons from the proton synchrotron of the Joint Institute, perpendicularly to the plane of the photoemulsion. Analysis on hydrogen content was carried out in control layers. It turned out that each cm^3 of irradiated emulsion contained $(2.90 \pm 0.06) \times 10^{22}$ atoms of hydrogen.

Area scanning was carried out with 630-fold magnification in the central part of the layers, of dimensions 2×2 cm. The mean beam density in this zone was $(1.97 \pm 0.05) \times 10^5$ particles/cm^2. In all, 1.53 cm^3 were scanned.

In order to determine the efficiency of detecting the events of interest and the reliability of results, the entire area was scanned twice. Approximately 9000 stars were found, including 451 two-pronged ones. From these two-pronged ones, stars were chosen, which looked like elastic p-p events. These cases were broken down into two groups: 1) cases with a black recoil proton ($I/I_{min} > 4$, $I_{min} \sim 40$ grains per 100μ), 2) cases with a grey recoil proton ($2 < I/I_{min} \leq 4$).

The detection efficiency in the first scanning turned out to be $(68.7 \pm 2.9)\%$ for events in the first group and $(34.5 \pm 9)\%$ for events in the second group. In the second scanning, the values were (84.0 ± 2.6) and $(56.5 \pm 12)\%$. The overall efficiency as a result of two-fold scanning was equal to (95 ± 1) and $(71 \pm 9)\%$ for events of the first and second groups, respectively. Since it subsequently turned out that the overwhelming majority of cases found (90%) belonged to the first group, the efficiency of detection for events of the second group was not investigated further. With such an efficiency, one scanner was able to scan 12 mm^2 in 6 hours, corresponding to ~ 10 m of track-length of incident protons.

ANALYSIS OF DETECTED EVENTS AND METHOD OF MEASUREMENT

In order to segregate cases of elastic scattering by free hydrogen the following criteria were employed.

1. The relation between the track length of the recoil proton R and its angle with respect to the incident proton φ should satisfy the kinematics of elastic scattering.

2. The angle γ between the direction of the primary proton and the plane defined by the secondary particles should be zero (condition of coplanarity).

3. The relation between the track length of the recoil proton R and the angle ψ of the scattered proton with the direction of the primary particle should satisfy the kinematics of elastic scattering.

4. At the point of scattering there should be no nuclear recoil and no β electron.

When the recoil proton did not stop in the camera and its momentum, determined from ionization measurements, was known only with large error, the relation between the angle of the scattered proton and that of the recoil proton was required to be fulfilled as in elastic scattering. The error in measuring the track length of the recoil proton R did not exceed 5%.

In order to determine the angle of the recoil proton, it is necessary to know the direction of the proton and the direction of the primary particle. Since the angular half-width of the beam of incident particles was $\sim 0.2°$, the direction of the beam was taken as the direction of the incident particle. In order to determine this at a given point in the emulsions, the angle of incident particles was measured from the values of projections along x and y axes. The x and y axes were chosen along lines marked by light, which were parallel to these axes to within $0.1 - 0.2°$. Measurements at a given point were carried out in 37 layers. Because of distortion of the emulsion, these measurements in different layers did not reproduce the same value for the angle, and were distributed with a half-width of $\sim 1°$. The mean value of the angle gave the true direction of the beam through the given point. The beam direction was determined at five such points — on the edges of the working zone and in the middle. The values obtained agreed to within 0.2°, the main error in determining the angle of the recoil proton came from inaccuracies in measuring the angle of dip. This error did not exceed $1 - 1.5°$ on the average, except for cases where the recoil proton had a short track-length ($\lesssim 500\mu$).

Measurement of the angle ψ of the scattered proton was carried out in two ways: 1) by measuring the angle between the mean direction of the incident particles and the scattered proton. This method gave an average accuracy of the order of the half-width of the beam, i.e., 0.2°. 2) Near the scattering act, at a distance of $20 - 30\mu$, one track of a noninteracting incident proton was chosen for calibration. To determine the scattering angle ψ, four measurements of the projections along the x and y axes in the plane of the photoemulsion of the line between the calibrating track and the track undergoing scattering were carried out. Two measurements were made before the scattering $\sim 2000\,\mu$ apart (through five plates) and two, at the same distance following the event. The projections were measured to an accuracy of $\sim 1\,\mu$. This made it possible to measure the scattering angle to an accuracy of $2'-3'$.

In determing the scattering angle ψ, effects of multiple scattering can be neglected. The error in the determination of the thickness of the layers was also small. In order to avoid errors, independent measurements were carried out simultaneously, relative to three calibrating tracks. It is possible to determine the angle of noncoplanarity from these measurements, knowing the direction of the recoil proton. The error in γ is determined mainly by the error in the angle of the scattered proton, and depends on the magnitude of this angle. Thus, $\Delta\gamma = 3°$ for $\psi = 1°$, if $\Delta\psi = 3'$.

Out of 451 two-pronged stars, 170 were discarded, since they obviously did not satisfy the selection criteria. For the remaining events, measurements of the track length R and angle φ of the recoil proton were carried out. All measurements were duplicated. Then the angle of the scattered proton was measured in the first way. These measurements were also duplicated. For a final separation of the elastic scattering cases, the angle ψ was measured in the second way, i.e., to an accuracy of $2'-3'$.

SELECTION OF CASES OF SCATTERING BY FREE PROTONS

One can try to estimate the expected contribution from quasi-elastic cases which would be counted as scattering by free hydrogen. It is well known[15] that the distribution of protons in the nucleus with momentum is near to $\exp\{-(p_x^2+p_y^2+p_z^2)/p_0^2\}$, where p_0 corresponds to an energy of ~ 20 Mev. The distribution of the projections of the proton momenta on an arbitrary axis will have the same form, with a p_0 corresponding to ~ 7 Mev.

We consider the influence of three mutually perpendicular momentum components on the kinematics of elastic scattering, if the x, y plane coincides with the scattering plane, and x is the direction of the initial proton. A momentum component p_x causes a violation, in the main, of the first criterion (R and φ), a component p_y, of the third criterion (R and ψ) and p_z destroys the coplanarity.

On Fig. 1 is shown the dependence of the angle φ of the recoil proton on its momentum for elastic proton-proton scattering, with momentum $p_x = 0$, ± 20, ± 42 Mev/c. Within the intervals $0-20$ Mev/c and $0-42$ Mev/c, fall 20 and 40%, respectively, of all quasi-free protons. From the figure it is clear that with the given accuracy of 3% in measuring the momentum and of $1-1.5\%$ in measuring the angle of the recoil proton, it is possible to segregate at least 80% of the cases of scattering by quasi-free protons using the first criterion. It is easy to show that with the second and third criteria it is also possible to segregate independently $\sim 80\%$ of the cases of scattering on quasi-free protons. Consequently, with the given accuracies of measurement, the contribution from quasi-elastic events will be on the order of a percent in the number of cases selected.

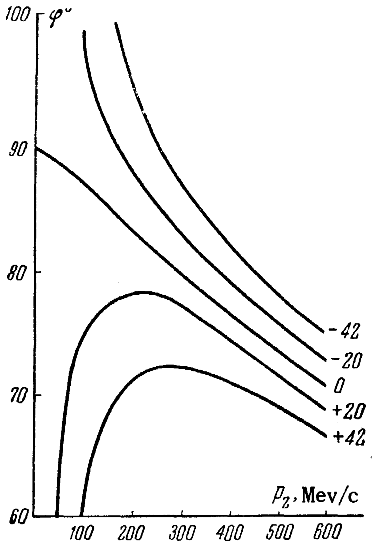


FIG. 1. Dependence of the recoil-proton angle φ (proton scattered through a large angle) on its momentum p_z for various values of the component p_x of momentum of a quasi-free proton, 0; ±20, ±42 Mev/c.

For each case that was measured, the errors in the measurement were estimated, and cases satisfying the kinematics within three standard errors were retained. Distributions for these cases plotted against $|\Delta\varphi|$, $\Gamma = |\gamma/\Delta\gamma|$ and $|\Delta\psi|$ are given on Fig. 2. From Fig. 2a it was found that the root mean square error in the measurement of the angle φ was $\sim 1.5°$. From the distribution of the selected cases with Γ, it is clear that the errors in the angles of noncoplanarity were correctly estimated.

The distribution of cases with $|\Delta\psi|$ is given in Fig. 2c. For this histogram, cases were selected in which the recoil proton stopped and where the kinematics were satisfied to within three root mean square errors in the first two criteria. Cases of scattering on quasi-free protons with momentum p_y fall in this figure, since these cases are not segregated by the first two criteria. A considerable proportion of these cases fall in the region $|\Delta\psi| > 12'$ (i.e., beyond three times the half-width

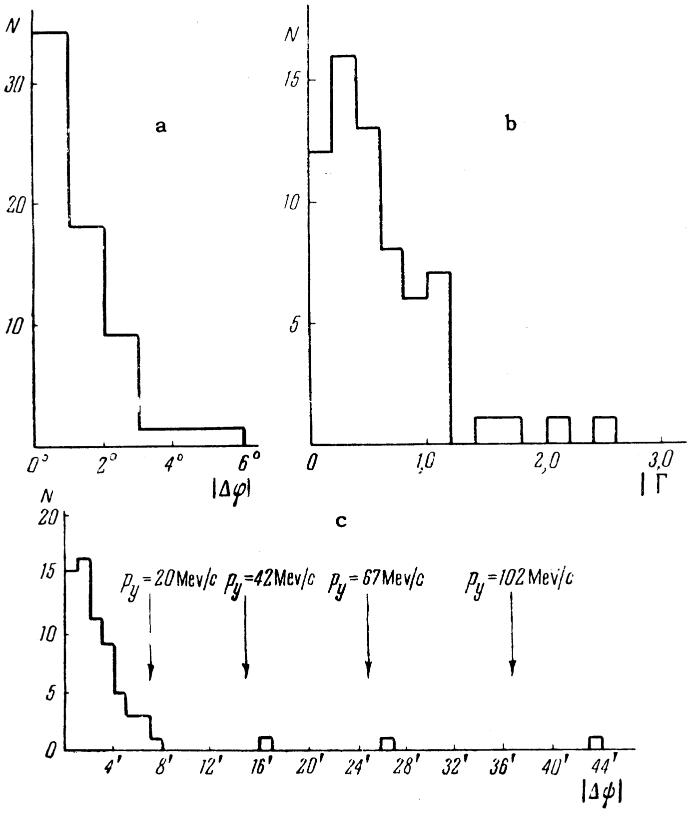


FIG. 2. a: distribution of cases of elastic scattering with $|\Delta\varphi|$, where $\Delta\varphi$ is the difference between the measured angle of the recoil proton and the angle corresponding to its track length according to the kinematics; b: distribution of cases of elastic scattering with Γ, where $\Gamma = |\gamma/\Delta\gamma|$, γ is the angle of noncoplanarity and $\Delta\gamma$, the error in it; c: distribution of cases chosen by the first two criteria (R vs φ and coplanarity) vs $|\Delta\psi|$.

of the distribution), where there are no cases of scattering on free protons. From the number of such cases it is possible to estimate the contribution of quasi-elastic cases of scattering and other cases belonging to the background in the region $|\Delta\psi| \leq 12'$. This contribution was $\sim 2\%$.

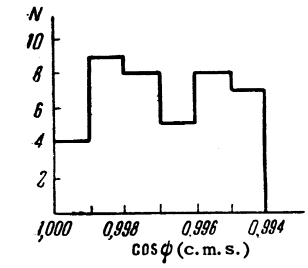
RESULTS

The selection criteria were satisfied, within the limits of three rms errors, in 66 cases. Of these, in only two did the recoil proton leave the emulsion camera.

The angular distribution in the center of mass system for the cases in which the angles were $\leq 6.3°$ is given in Fig. 3.

Within the range $0 - 2.5°$ a somewhat smaller number of cases was observed than in the neighboring intervals. This probably resulted from the fact that some of the cases in which the path length of the recoil proton $R \lesssim 10\,\mu$ were missed in the scanning. Therefore, in the angular interval $0 - 2.5°$ a correction of 3.4 ± 1 cases was introduced,

FIG. 3. Angular distribution of cases of elastic scattering for angles <6.3° in the c.m.s.



under the assumption that the differential cross section in this interval is equal to the mean differential cross section in the interval $2.5 - 6.3°$. Calculations show that the influence of Coulomb scattering on the differential cross section for angles larger than 2.5° was negligible. To evaluate the effect of Coulomb scattering for the angles less than 2.5°, much better statistics would be necessary.

On the basis of estimates of the contributions of quasi-elastic cases, omission of cases of scattering through small angles, and efficiency of scanning, the total number of cases of elastic scattering on free protons turned out to be equal to 73.9 $\pm$ 9.1. Thus, the cross section for elastic scattering was found equal to

$$\sigma_e = (8.4 \pm 1.1)\,\text{mb}.$$

According to reference 16 the cross section

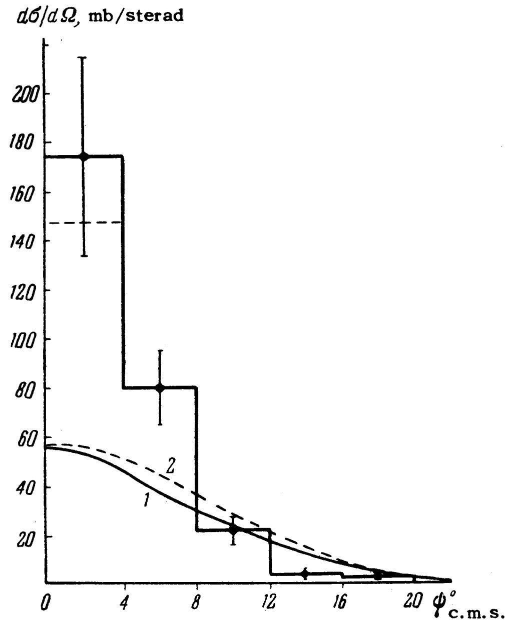


FIG. 4. Differential cross section for elastic scattering of 8.5-Bev protons by protons in the c.m.s. The dashed line in the first interval indicates the differential cross section without correction for the omission of cases at small angles. Curves 1 and 2 were calculated from the optical model for a purely absorbing proton and different assumptions about the dependence of the absorption coefficient on radius.

for elastic scattering at E = 9 Bev is equal to (10 ± 4) mb.

The differential cross section for elastic p-p scattering in the c.m.s. is given on Fig. 4 in the form of a histogram. The solid curve was constructed from the data of Barashenkov and Huang Nen-Ning.[11] In their work the optical model was employed and, for energies of the incident proton greater than 5 Bev, the index of refraction was assumed to be unity, and the dependence of the coefficient of absorption on radius was taken from the work of Grishin.[10] The dashed curve was calculated for the model of a purely-absorbing disc with constant coefficient of absorption. In this, the total proton-proton interaction cross section was taken equal to 30 mb.[17]

The differential cross section obtained cannot, apparently, be made to agree with the model of a purely absorbing proton. According to this model, with neglect of spin, the differential cross section at 0°, as obtained from the optical theorem, is

$$(d\sigma / d\Omega)_{0^\circ} = (k\sigma_t / 4\pi)^2,$$

where k is the wave number of the colliding protons in the c.m.s. and σ_t is the total cross section for p-p interaction. For $\sigma_t = 30$ mb, the differential cross section at 0° is equal to 57 mb/sterad, whereas, from Fig. 4 it can be seen that in the region near to 0° the differential cross section is significantly greater.

Optical-model calculations can be made to agree with experimental results if one assumes that the index of refraction is different from unity, i.e., there is potential scattering. It is possible that agreement would also be obtained if the interaction cross section were assumed different in the singlet and triplet states. The present work is being continued, and a more detailed analysis of the experimental data will be made after better statistics have been obtained.

In conclusion, the authors would like to express the gratitude to the entire crew of the proton synchrotron of the Joint Institute for irradiating the emulsion camera, and the photoemulsion processing group of the High-Energy Laboratory of the Joint Institute for the chemical processing of the photoemulsion. The authors are very grateful to Prof. D. I. Blokhintsev, Acad. V. I. Veksler, and to M. Danysh, M. I. Podgoretskiĭ and K. D. Tolstov for valuable remarks in discussions and for interest in the work. We would like to thank M. F. Rodichev for determining the hydrogen content of the dry emulsions, L. G. Kriventsov for determining the moisture content and specific weight of the photoemulsion, and also to the group of laboratory assistants for scanning and measurement.

[1] Fernbach, Serber, and Taylor, Phys. Rev. **75**, 1352 (1949).
[2] W. D. Walker, Phys. Rev. **108**, 872 (1957).
[3] W. D. Walker and J. Crussard, Phys. Rev. **98**, 1416 (1955); **104**, 526 (1956).
[4] Maenchen, Fowler, Powell, and Wright, Phys. Rev. **108**, 850 (1957).
[5] Duke, Lock, March, Gibson, McKeague, Hughes, and Muirhead, Phil. Mag. **46**, 877 (1955).
[6] Duke, Lock, March, Gibson, McEwen, Hughes, and Muirhead, Phil. Mag. **2**, 204 (1957).
[7] Chretien, Leitner, Samios, Schwartz, and Steinberger, Phys. Rev. **108**, 383 (1957). Cester, Hoang, and Kernan, Phys. Rev. **103**, 1443 (1956). Fowler, Shutt, Thorndike, Whittemore, Cocconi, Hart, Block, Harth, Fowler, Garrison, and Morris, Phys. Rev. **103**, 1489 (1956).
[8] Kalbach, Lord, and Tsao, Phys. Rev. **113**, 330 (1959).
[9] S. Z. Belen'kiĭ, JETP **30**, 983 (1956), Soviet Phys. JETP **3**, 813 (1956); JETP **33**, 1248 (1957), Soviet Phys. JETP **6**, 960 (1958). 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). Grishin, Saitov, and Chuvilo, JETP **34**, 1221 (1958), Soviet Phys. JETP **7**, 844 (1958). Blokhintsev, Barashenkov, and Grishin, JETP **35**, 311 (1958), Soviet Phys. JETP **8**, 215 (1959).
[10] V. G. Grishin, JETP **35**, 501 (1958), Soviet Phys. JETP **8**, 345 (1959).
[11] V. S. Barashenkov and Huang Nen-Ning, JETP **36**, 832 (1959), Soviet Phys. JETP **9**, 587 (1959).
[12] Cork, Wenzel, and Causey, Phys. Rev. **107**, 859 (1957).
[13] Dul'kova, Romanova, Sokolova, Sukhov, Tolstov, and Shafranova, Dokl. Akad. Nauk SSSR **107**, 43 (1956), Soviet Phys.–Doklady **2**, 154 (1956).
[14] Lonina, Tolstov, and Tsyganov, Приборы и техника эксперимента (Instrum. and Meas. Engg.) **2**, 37 (1956).
[15] Cladis, Hess, and Moyer, Phys. Rev. **87**, 425 (1952). J. M. Wilcox and B. J. Moyer, Phys. Rev. **99**, 875 (1955). E. M. Henley, Phys. Rev. **85**, 204 (1952). McEwen, Gibson, and Duke, Phil. Mag. **2**, 231 (1957).
[16] Bogachev, Bunyatov, Merekov, and Sidorov, Dokl. Akad. Nauk SSSR **121**, 617 (1958), Soviet Phys.–Doklady **3**, 785 (1959).
[17] V. S. Barashenkov and Huang Nen-Ning, JETP **36**, 1319 (1959), Soviet Phys. JETP **9**, 935 (1959).

Translated by G. E. Brown
183