ELASTIC SCATTERING OF 8.7-Bev PROTONS BY EMULSION NUCLEI

B. P. BANNIK, V. G. GRISHIN, and L. V. SIL'VESTROV

Joint Institute for Nuclear Research

Submitted to JETP editor January 24, 1961

J. Exptl. Theoret. Phys. (U.S.S.R.) **40**, 1653-1657 (June, 1961)

The angular distribution of 8.7-Bev protons scattered elastically in nuclear emulsion is measured. Comparison is made with the optical model theory.

1. EXPERIMENTAL PROCEDURE

THE present work was undertaken to improve our earlier measurements of elastic proton scattering in nuclear emulsion.[1] A pellicle stack was irradiated with an internal 8.7-Bev proton beam in the proton synchrotron at the High-Energy Laboratory of the Joint Institute for Nuclear Research. The stack consisted of 10×20 cm type-R NIKFI pellicles 400μ thick; the beam intensity was $\sim 3 \times 10^4$ protons/cm^2. The proton beam, with an angular spread of $\sim 0.1°$, traversed the stack at an angle of $0.1 - 0.2°$ to the plane of the emulsion. An MBI-9 microscope with 60×15 magnification was used to search for and measure scatterings.

For scanning we selected tracks satisfying the conditions of (1) relativistic ionization and (2) no visually perceptible angle between a track and the proton beam axis, nor track dip with respect to the emulsion plane.

Scattering events were searched for by accelerated on-track scanning.[2] We recorded track deflections for which the projected scattering angle φ on the emulsion plane was about 0.1° or larger. φ was measured with the accuracy $\Delta\varphi = 0.05°$ in track sections of length $l = 3$ mm.* All events with projected angle $\varphi > 0.17°$ were remeasured with $l = 1$ mm. In this way a 1-mm track section was determined within which scattering had occurred; the scattering point was then located.

All events exhibiting $\varphi > 0.17$ after the second measurement were remeasured relative to two or three close-lying tracks, with $l = 3$ mm. In addition to φ, we measured the projected angle θ on a plane perpendicular to the emulsion plane. The relative measurements were performed in order to exclude events resulting from distortions in the emulsion. The accuracy of the relative measurements was $\Delta\varphi = 0.04°$. An event was associated with distortion if a deflection with $\varphi \geq 0.1°$ was observed in a corresponding section of even one neighboring track. The great density of proton tracks insured high efficiency in excluding cases of distortion by means of the relative measurements.

The relative measurements of 331 events showed that 4 events resulted from distortions; $\varphi < 0.17°$ for 25 events; 2 events were induced by secondary particles; in 12 events $\varphi > 2°$ or $\theta > 2°$. Careful scanning showed that 16 events were stars. All of these events were excluded in plotting the angular distribution of elastic scattering in the range $0.17° < \varphi < 2°$.

A certain fraction of the plates was scanned for the purpose of recording track deflections with projected angles of at least 0.25°. These events were used to plot the angular distribution for $\varphi \geq 0.3°$. Thirteen of these events were excluded from the total data.

The efficiency of our on-track scanning technique for detecting scattering could differ from 100% at the beginning and termination of each track. In order to avoid scanning errors at the beginnings of tracks all events (17 instances) in the first three millimeters were excluded. A study of the distribution of scattering events along the lengths of tracks showed that scanning efficiency decreases at track terminations. We therefore excluded all events (41 instances) found in the last nine millimeters.

In estimating the scanning efficiency in the middle of a track it was assumed that events with $\varphi \geq 0.3$ were detected with 100% efficiency (see reference 2). The efficiency was estimated for φ in the range $0.2 - 0.3°$ by comparing the number of events having φ in this range with the number of events having θ in the range $0.2 - 0.3°$. The two results were identical within error limits. Assuming azimuthal symmetry of scattering, it therefore followed that the detection efficiency for events

*Angles were measured as described in reference 1.

Angle range, deg	Distribution of N events in emulsion plane						Spatial distribution, $(dN/d\Omega) \times 10^{-4}$	
	From reference 1,* L = 151.6 m	Present work, L = 151.6 m	Total, L = 224.2 m	Calculated for L = 224.2 m: Re f = + 14.4 Fermi units	Re f = − 14.4 Fermi units	Re f = 0	Measured, L = 123 m	Calculated for Re f = 0, L = 123 m
0,2—0,3		66,5**±9	98±13	96.6	131.7	83.8	141±27	126,1
0,3—0,4	50.2±10	46±7	70±8	69.8	85.5	51,3	76±14	65.2
0,4—0,5	33.5±8	20±5	36±6	46.0	53.1	31.7	49.2±9.0	38.2
0,5—0,6	18.8±6	17±4	26±5	26.7	31.4	17.9	21.8±5.2	21.4
0,6—0,7	8.4±4	8.5±3	12.5±4	16.6	21.4	9.8	11,0±3.3	11.1
0,7—0,8	2.1	6,5	7.5	9.9	14.5	5.2	6,3±2.3	4.5
0,8—0,9	—	4.5	4.5	6.5	9.5	3,3	3.6±1.6	2.0
0,9—1.0	4,2	4.5	6.5	6.2	8,8	2.6	2.6±1.3	1.5
1.0—1.1	—	6	6	5,4	7.9	2.0	3.4±1.4	1.3
1,1—1.2	6.3	5	8	4.1	5.7	1.5	3.1±1.3	1.2
1.2—1.3	4.2	2	4	3,3	4.6	1.1	0.9±0,7	0.8
1.3—1.4	—	1	1	2.0	2.8	0.5	0.4±0.4	0.4
1.4—1.5	—	2	2				1.2±0,7	
1.5—1.6	—	1.5	1.5				—	
1.6—1.7	2.1	1.5	2,5				0.3±0.3	
1.7—1.8		2	3				0.6±0.5	
1,8—1.9		—	—				0.6±0.4	
1,9—2.0		—	—				0.3±0.3	

*Data obtained for L = 72.54 m and converted for L = 151.6 m.

**When a scattering angle equalled the angle at the end of a 0.1° interval of the table, one-half event was assigned to each of the adjoining intervals.

with φ in the range 0.2 — 0.3° was close to 100%.

A total of 201 scattering events remained after the exclusion of events at track ends. For $\varphi > 0.3°$ we used events recorded in the scanning of a total combined track length L = 151.6 m; for φ from 0.17° to 0.3°, L = 123 m.

2. DISCUSSION OF RESULTS

The distributions obtained in the present and earlier work are given in the accompanying table. Since the results of the two experiments agreed within error limits a combined angular distribution was plotted (see the figure).* The table also gives the solid-angle distribution of scattering events from the total scanned track length L = 123 m, assuming azimuthal scattering symmetry.

The figure includes theoretical curves for the dependence of the differential cross section on the projected scattering angle. The calculations were based on the optical model taking into account the interference of nuclear and Coulomb scattering† and assuming that in the laboratory system the real part of the nucleon-nucleon forward-scattering amplitude is Re $f_{NN}(0)$ = 0, +14.4, or −14.4 Fermi units.‡ In calculating the differential cross section corresponding to Re $f_{NN}(0) = 0$ we used the total nucleon-nucleon interaction cross section averaged over the nucleons within the nucleus ($\bar{\sigma}$ = 38 mb), computed from measurements of p-p and p-n scattering cross sections.[4] The differential cross section for Re $f_{NN}(0) = \pm 14.4$ Fermi units and $\bar{\sigma}$ = 38 mb was obtained by linear extrapolation, using the results for Re $f_{NN}(0) = 0$ and $\bar{\sigma}$ = 38 mb and for Re $f_{NN}(0) = 0$ or $\pm$ 14.4 Fermi units and $\bar{\sigma}$ = 34 mb.

We shall now estimate the sensitivity of the curves to the parameters used in the calculations. Measurements in the emulsion give $\bar{\sigma}$ with ±10% accuracy,* corresponding to ±7% shifts of the calculated curves for small angles.

According to Hofstadter,[7] the uncertainty of the radial parameter is ±2%, which for small angles results in ±2% inaccuracy of the calculated curves. For large angles ($\varphi > 1°$), up to 100% error results in the calculated curves.

Uncertainty regarding the form of the nucleon density distribution in the nucleus (trapezoidal, Fermi, or Gaussian distribution) results in ±2% inaccuracy of the calculated cross sections.

When calculating errors amounting to 3% are added, the total error of the calculated cross sections is of the order 10% for small angles φ.

*In the angle range $0.2° < \varphi < 0.3°$ some events were overlooked because of the selection criterion. This loss was estimated at ~ 5 events, for which the angular distribution was not corrected.

†Details of the calculation are given in reference 3.

‡This corresponds to an effective potential of 30 Mev for nucleon-nucleus interactions.

*From data kindly furnished by the authors of reference 5 we have estimated the mean free path for inelastic interactions of 8.7-Bev protons in the emulsion. From the result $\bar{R}_{inel} = 33.7^{+1.3}_{-1.6}$ cm it follows that $\bar{\sigma} = 38^{+4}_{-6}$ mb.[6] In our earlier paper we used $\bar{R}_{inel}$ = 34.7 ± 1.5 cm and, correspondingly, $\bar{\sigma}$ = 36 ± 5 mb. The measurements of $\bar{R}_{inel}$ in the emulsion thus are not inconsistent with each other or with the value $\bar{\sigma}$ = 38 mb used in the calculations.

A χ^2 test of goodness of fit between the experimental histogram and the theoretical curves indicated agreement with probability 0.3 for Re $f_{NN}(0) = +14.4$ Fermi units, with probability 0.001 for Re $f_{NN}(0) = 0$, and with probability < 0.001 for Re $f_{NN}(0) = -14.4$ Fermi units.

Taking into account the uncertainty of the calculated curves, we can conclude that the results exclude Re $f_{NN}(0) = -14.4$, that they perhaps do not exclude Re $f_{NN}(0) = 0$, and that they are in good agreement with Re $f_{NN}(0) = +14.4$.

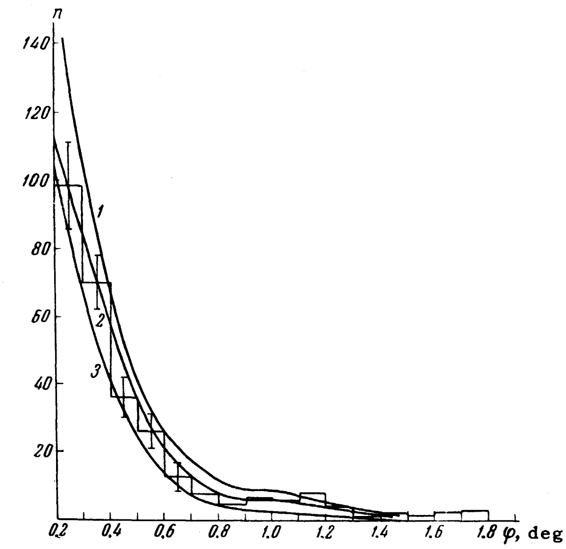
There also remains the possibility that some events taken to be elastic scatterings were actually inelastic interactions.* We estimated the contribution to the measured cross section from inelastic processes which could have been mistaken for elastic processes.

Quasi-elastic proton-neutron scattering was estimated from the measured cross section for quasi-elastic scattering of protons by bound protons.[8] Assuming identical cross sections for quasi-elastic scattering by bound protons and by neutrons, we estimated ~ 7 quasi-elastic neutron scatterings in 225 m of path within the emulsion. Two of these scatterings fall within the angle interval $0-1°$ and about five within the interval $1-2°$.†

In calculating nuclear excitation accompanying scattering it was assumed that the ratio $\sigma_{scat}/\sigma_{exc}$ of the elastic scattering cross section to the excitation cross section depends only on the transferred momentum. Using nuclear excitation measurements at E = 185 Mev,[9] for our experimental conditions we obtain $\sigma_{scat}/\sigma_{exc} \approx 100$ at scattering angles $0.2-0.6°$ and $\sigma_{scat}/\sigma_{exc} \approx 10$ at $1-2°$. The Coulomb excitation cross section was determined for $\varphi \lesssim 0.5°$, since Coulomb scattering falls off sharply above 0.5°. The contribution from Coulomb excitation was of the order 1% or less. The contribution from diffractive pion production[10] was calculated to be less than 1% of the total cross section and $\sim 10\%$ in the interval $1-2°$. From the angular distribution of secondary relativistic particles in nuclear reactions single-pronged stars were estimated to occur in 1% of the total number of events.

*The possible background of inelastic interactions at small φ lends support to the exclusion of Re $f_{NN}(0) = -14.4$, but makes it more difficult to choose between Re $f_{NN}(0) = 0$ and Re $f_{NN}(0) = +14.4$.

†Quasi-elastic proton-neutron scattering can produce an excited nucleus decaying by the emission of β rays with a few Mev. A corresponding track should then be observable at the scattering point. In the present work, in 201 scatterings within the range $0.2° < \varphi < 2.0°$ not a single event of this type was observed.



Angular distribution of 8.7-Bev protons scattered elastically in nuclear emulsion. Theoretical curves 1, 2, and 3 correspond to Re $f_{NN}(0) = -14.4$, $+14.4$, and 0, respectively. n is the number of events in a 0.1° interval.

Multiple scatterings on 37 tracks were measured as a control. The distribution of mean second differences for each scattered particle was compared with the analogous distribution for the primary protons. The parameters of the distributions were identical within error limits.

A strikingly large number of scatterings occurred at angles from 1 to 2°, totaling 27 events (including some events involving nuclear recoil), whereas the optical model indicates ~ 7 events for Re $f_{NN}(0) = 0$. The observed discrepancy cannot be accounted for solely by the inelastic reactions, which amount to 40% according to the estimates given above. It can reasonably be assumed that the discrepancy results from inaccuracy of the calculated cross sections at large angles.

The authors are deeply indebted to M. I. Podgoretskii for numerous valuable discussions and very considerable assistance, and to I. M. Gramenitskii and V. N. Strel'tsov for assistance and suggestions.

The authors also wish to thank the laboratory assistants G. A. Nurusheva, G. P. Tyupikova, T. A. Zhuravleva, É. V. Esina, and M. A. Varganova for performing measurements and scanning; also O. V. Kol'ga and M. I. Filippova for assistance with the calculations.

[1] Bannik, Grishin, Danysh, Lyubimov, and Podgoretskii, JETP **37**, 1575 (1959), Soviet Phys. JETP **10**, 1118 (1960).

[2] B. P. Bannik and M. I. Podgoretskii, Приборы и техника эксперимента (Instrum. and Exptl. Techniques) No. 3, 36 (1960).

[3] B. P. Bannik and V. G. Grishin, JETP **39**, 94 (1960).

[4] Von Dardel, Frisch, Mermod, Milburn, Piroué, Vivargent, Weber, and Winter, Phys. Rev. Letters **5**, 333 (1960); Perez-Mendez, Atkinson, Hess, and Wallace, Bull. Am. Phys. Soc. **4**, 253 (1959).

[5] Wang Shu-Fen, Vishki, Gramenitskii, Grishin, Dalkhazhav, Lebedev, Nomofilov, Podgoretskii, and Strel'tsov, JETP **39**, 957 (1960), Soviet Phys. JETP **12**, 663 (1961).

[6] V. S. Barashenkov, Usp. Fiz. Nauk **72**, 53 (1960), Soviet Phys.-Uspekhi **3**, 689 (1961).

[7] R. Hofstadter, Revs. Modern Phys. **28**, 214 (1956).

[8] V. A. Nikitin and É. N. Tsyganov, JETP **40**, 1027 (1961).

[9] T. A. J. Maris and H. Tyrén, Nuclear Phys. **3**, 35 (1957); H. Tyrén and T. A. J. Maris, Nuclear Phys. **6**, 82; 446 (1958).

[10] I. Ya. Pomeranchuk and E. I. Feĭnberg, Doklady Akad. Nauk SSSR **93**, 439 (1953).

Translated by I. Emin
282