ELASTIC SCATTERING OF 2.8- AND 6.9 Bev/c π^- MESONS ON CARBON

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Elastic scattering of π^- mesons with momenta of 2.8 and 6.8 Bev/c on carbon nuclei was studied. The differential cross sections obtained are analyzed with the aid of the optical model. It is shown that the characteristics for elastic scattering of π^- mesons on carbon depend only on the momentum transfer in the energy range under investigation. The cross section for scattering of π^- mesons by neutrons into the back hemisphere in the laboratory system is also estimated: $\sigma_{\pi n}(\geq 90°) \lesssim 0.4$ mb (2.8 Bev/c) and $\sigma_{\pi n}(\geq 90°) \lesssim 0.1$ mb (6.8 Mev/c).

INTRODUCTION

THE aim of the present experiment was to measure the total and differential cross sections for elastic scattering of negative pions on carbon nuclei. The obtained data make possible, with the aid of the optical model, the determination of the magnitude and sign of the spin-independent real part of the pion-nucleon scattering amplitude, [1,2] which result from interference between Coulomb and nuclear scattering. These data yield information on the energy dependence of the elastic scattering differential cross section for the same momentum transfer.

1. EXPERIMENTAL METHOD

A. Measurements of 2.8-Bev/c π^- meson scattering. The scattering of π^- mesons of momentum 2.8 ± 0.15 Bev/c [3] was measured with a $37 \times 10 \times 10$ cm propane bubble chamber without a magnetic field. We selected for measurement tracks of relativistic particles entering the chamber at angles not greater than 2° relative to its horizontal axis (projected angle on the plane of observation) and lying in the effective region of the chamber of length 28.4 cm (60 mm on the film), where the distortion of the tracks is a minimum and approximately uniform in magnitude.

In order to speed up the selection of cases of scattering we measured under high magnification the deviation of the track from a straight line traced on a transparent rule which was aligned with the points of intersection of the track with the boundaries of the effective region. This method made it possible to select, with practically no loss, cases of scattering by an angle $\varphi \geq 1°$.* The use of the rule speeded up the selection of cases of scattering approximately ten-fold, and also decreased the number of stars lost in an ordinary scanning. Cases of scattering selected with the rule were measured twice on an MBI-9 microscope under a magnification of 3.5×15. The measurements were made with a 10-mm cell, which reduced to a minimum the error of the angle measurement due to multiple Coulomb scattering and dispersion of the track bubbles ($\sim 0.06°$). A reliable method of separating true scatters from cases of spurious scattering is to localize the scattering point. For all selected cases of scattering by an angle $\varphi \geq 1°$ the scattering point was determined visually within the limits of 1 mm in the chamber. The scattering points were uniformly distributed over the chamber length. A comparison of the number of cases of scattering on different sides (67 and 54) indicates that the selection of cases was independent of the sign of the scattering angle.

We examined a total of $\sim 1.49 \times 10^5$ cm of π^--tracks and selected more than 800 cases. After the microscope measurements, there remained 121 cases of scattering by angles from 1° to 10°

*By the angle φ we understand the projection of the space scattering angle ϑ on the plane of observation. In the present experiment we measured the projections of the scattering angles on the plane of the photograph, which provided considerably better accuracy than measurements of the space angles.

and 30 cases of scattering by angles greater than 10°.

B. Measurements of 6.8-Bev/c π^--meson scattering. We measured the elastic scattering of π^- mesons on carbon nuclei with the aid of a 24-liter propane bubble chamber placed in a magnetic field of 13 700 oe.* The π^- mesons entered the chamber with a momentum of 6.8 ± 0.6 Bev/c. The μ^--meson contamination was $(5 \pm 2)\%$. The details of the experimental arrangement have been dedescribed by Wang et al. [4]

For the measurements we chose an effective chamber region 42 cm long, where the distortion of the tracks was a minimum and approximately constant. We selected relativistic particle tracks passing through this region with an angle no greater than $\pm 0.6°$ relative to the beam axis. The scanning for cases of scattering and the measurements were performed on an MBI-9 microscope under a magnification of 6.3×15. The cell length on the film was 6 mm. After all tracks were measured once, the cases with scattering angles $\varphi \geq 0.33°$ were measured again with the cell shifted. This permitted a more accurate localization of the scattering point and increased the accuracy of the angle measurements from 0.15 to 0.09°. The scanning for cases of scattering with a reprojector showed that, for angles $\geq 0.5°$, more than 80% of the cases had a point of deflection in the region where, according to the microscope measurements, the point of scattering should have occurred. It was also shown that there was no correlation between cases of scattering and scattering on neighboring tracks. The points of scattering were uniformly distributed over the effective length of the chamber. A comparison of the number of cases of scattering on different sides (142 and 159) indicated that the selection of cases was independent of the sign of the scattering angle.

As a result of the measurement of 3.25×10^5 cm of π^--meson tracks, we found 301 cases of scattering by angles $\varphi \geq 0.33°$ (among them, 218 cases of scattering by angles $\varphi \geq 0.5°$).

2. CORRECTIONS TO THE EXPERIMENTAL DISTRIBUTIONS

We have to introduce corrections to the experimental material to take into account the character of the measurement procedure and the contribution of interactions whose nature is different from π^--meson scattering on carbon nuclei (see Table I).

The correction for one-prong stars associated with multiple production of π^0 mesons was taken into account by the extrapolation of the one-prong star distribution from the large angle region to the small angles. The extrapolation was based on the angular distribution of the products of multiprong stars, since measurements made on 2.8-Bev/c π^- mesons (see Table II) showed that the angular distribution of relativistic charged particles depended weakly on the number of particles in the star. A similar result was obtained for 6.8-Bev/c π^- mesons. Estimates of the one-prong star contribution based on the number of γ quanta from the decay of π^0 mesons produced in one-prong stars (by 6.8 Bev/c π^- mesons) confirmed the correctness of this procedure.

The most important correction is associated with the contribution from elastic scattering on quasi-free neutrons of the nucleus. In a number of reports [5,6] it has been shown that the angular dependence of the elastic and quasi-elastic scattering cross sections practically coincide. Since we cannot determine the effective number of quasi-free neutrons with sufficient accuracy, the correction was made by recalculating the background remaining after the introduction of other corrections for the small-angle region. Here we based ourselves on the differential cross sections of π^-p scattering measured at the same π^--meson energies. [4] This correction actually also takes into account the contribution from π^--meson inelastic scattering processes involving the excitation of the carbon nucleus, since the dependence of the excitation cross section [7] and the quasi-elastic scattering cross section on the momentum transfer do not differ from one another by more than a factor of 1.5. It should be noted that the correction used for quasi-elastic scattering corresponds to approximately one quasi-free neutron per carbon nucleus, which is in agreement with the estimate made by Birger et al. [8]

Another method of correction (for example, by linear extrapolation of the background from the large-angle regions) changes the final result very little.

3. CROSS SECTION FOR THE INELASTIC INTERACTION OF π^- MESONS ON CARBON

The available material made it possible to determine the inelastic scattering cross section of 6.8-Bev/c π^- mesons on carbon

$$\sigma_{in}(\pi^-, C) = 197 \pm 7 \text{ mb}.$$

*The authors are indebted to the bubble chamber group of the High Energy Laboratory of the Joint Institute for Nuclear Research under the direction of Professor Wang Kang-ch'ang for providing the chamber photographs.

Table I. Corrections to the experimental distribution of cases of scattering and differential cross section for elastic scattering of π^- mesons on carbon*

Angular interval $\Delta\varphi$, deg	Number of one-prong stars	Corrections to experimental distribution						Total correction in given angular interval	Number of cases of elastic scattering of π^- mesons on C	Differential cross section of elastic scattering of π^- mesons on C, mb/rad
		Overlapping of intervals	Geometrical corrections	Coulomb scattering of μ^- mesons	Elastic and quasi-elastic π^-p scattering	Inelastic one-prong stars	Quasi-elastic π^-n scattering and scattering with excitation of nucleus			
1	2	3	4	5	6	7	8	9	10	11
2.8 Bev/c π^- mesons										
0.6–1	56									
1–1.4	28	–1.2	—	–0.5	–1	–0.5	–1.5	–4.7	23.3	1380±330
1.4–1.8	14	–0.7	—	–0.2	–0.7	–0.5	–1.5	–3.6	10.4	620±240
1.8–2.2	21	–0.9	–1.8	—	–0.3	–0.5	–1.5	–5	16	950±300
2.2–2.6	14	–0.6	–1.2	—	–0.2	–0.5	–1.5	–4	10	600±250
2.6–3.0	11	–0.4	–0.9	—	–0.2	–0.5	–1.5	–3.5	7.5	450±210
3.0–3.4	10	–0.4	–0.8	—	–0.2	–0.5	–1.7	–3.6	6.4	380±210
3.4–3.8	3	—	–0.2	—	—	–0.4	–1.8	–2.4	0.6	36^{+120}_{-26}
3.8–4.2	2	—	–0.2	—	—	–0.4	–1.4	–2	0	0±120
4.2–4.6	3	—	–0.3	—	—	–0.4	–1.5	–2.2	0.8	48^{+180}_{-48}
4.6–5	1	—	–0.1	—	—	—	–0.9	–1	0	0+80
1–5	107	–4.2	–5.5	–0.7	–2.6	–4.2	–14.8	–32	75	31.1±5.1**
5–10	14	—	–1.2	—	—	–4.7	–8.1	–14	0	0
10–180	30	—	–2.6	—	—	–27.0	–0.4	–30	0	0
1–180	151	–4.2	–9.3	–0.7	–2.6	–35.9	–23.3	–76	75	31.1±5.1**
6.8 Bev/c π^- mesons										
0.33–0.5	59	—								
0.5–0.7	62	+1.5	—	—	–1.7	–1.2	–1.7	–3.1	58.9	2940±400
0.7–0.9	46	–0.2	—	—	–1.5	–0.9	–1.9	–4.5	41.5	2080±360
0.9–1.1	26	–0.2	—	—	–1.0	–0.5	–2.0	–3.7	22.3	1120±270
1.1–1.3	15	–0.2	—	—	—	–0.3	–1.6	–2.1	12.9	640±210
1.3–1.5	10	–0.2	—	—	—	–0.2	–1.6	–2	8	400±170
1.5–1.7	10	—	—	—	—	–0.2	–1.5	–1.7	8.3	410±170
1.7–1.9	2	—	—	—	—	—	–1.4	1.4	0.6	30^{+90}_{-30}
0.5–1.9	171	+0.7	—	—	–4.2	–3.3	–11.7	–18.5	152.5	26.5±2.4**
1.9–5	31	—	—	—	—	–6.8	–24.2	–31	0	—
5–180	40	—	—	—	—	–4.0	—	–40	0	—
0.5–180	242	+0.7	—	—	–4.2	–50.1	–35.9	–89.5	152.5	26.5±2.4**

*Errors in the cross sections are statistical.

**Cross sections in millibarns.

Table II. Angular distribution of fast secondary prongs produced in propane by 2.8 Bev/c π^- mesons

Prong multiplicity		Percentage of cases in angular interval			Number of cases in angular interval 0–180°
black and gray	relativistic	0–5°	5–10°	10–180°	
0	2	17.0	14.7	68.5	401
1	2	11.1	13.5	75.5	126
2, 3, 4	2	14.5	10.0	75.5	200
0	3, 4	14.6	12.6	73.0	302
1, 2, 3, 4	3, 4, 5, 6	12.6	11.8	75.5	508
All stars:		14.2	12.6	73.2	1537

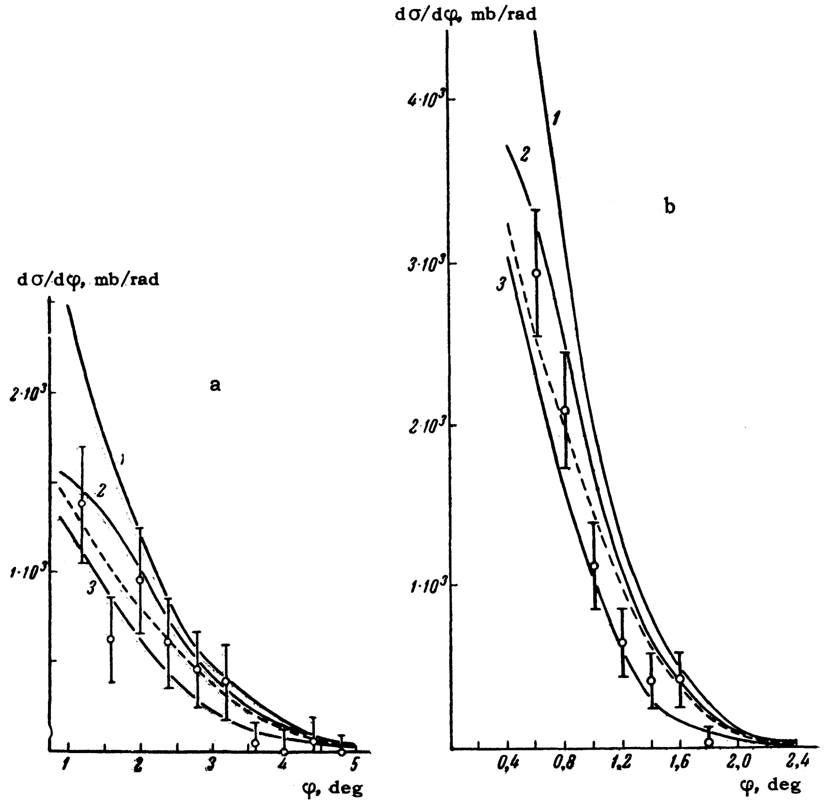

FIG. 1. Elastic scattering differential cross sections: a – for $p_\pi = 2.8$ Bev/c, b – for $p_\pi = 6.8$ Bev/c.

We used here the total cross section of the π^-p interaction $\sigma_t = 28$ mb.[9] The total π^--meson interaction cross section with a bound nucleon of the nucleus obtained from $\sigma_{in}(\pi^-, C)$ with the optical model, was 28.5 ± 1.5 mb, i.e., the same as the interaction cross section on a free nucleon.

This result was used to determine the μ^--meson contamination in the 2.8-Bev/c beam. Here we used the pion-nucleon total cross section $\sigma_t = 30 \pm 1.5$ mb.[9] The calculation showed that the cross section for the inelastic scattering of π^- mesons on carbon at this energy is 202 ± 5.6 mb. Knowing the total number of events in the chamber, we thus found that the μ^--meson contamination in the 2.8-Bev/c beam was $(27 \pm 4)\%$.

4. DISCUSSION OF RESULTS

Figures 1a and 1b show the experimental differential cross section for the scattering of 2.8–6.8-Bev/c π^- mesons in the projection on the plane of observation.* Curves 1–3 are calculated from the optical model of the nucleus, under the assumption that the real parts of the pion-nucleon forward scattering amplitude are†

*It was shown that the difference between the central and orthogonal projection is negligible under our conditions.

†The values $\mathrm{Re}\, f_{\pi N}(0) = 3.39 \times 10^{-13}$ cm ($p_\pi = 2.8$ Bev/c) and $\mathrm{Re}\, f_{\pi N}(0) = 6.9 \times 10^{-13}$ cm ($p_\pi = 6.8$ Bev/c) correspond to the effective potential ~ 30 Mev.

$+3.39\cdot10^{-13}$ cm, $-3.39\cdot10^{-13}$ cm, 0 for $p_\pi = 2.8$ Bev/c; $+6.9\cdot10^{-13}$ cm, $-6.9\cdot10^{-13}$ cm, 0 for $p_\pi = 6.8$ Bev/c.

According to the optical theorem, the imaginary part of the pion-nucleon scattering amplitude is

$$\mathrm{Im}\, f_{\pi N}(0) = \frac{k\sigma_t}{4\pi} = \begin{cases} 3.39\cdot10^{-13} \text{ cm for } p_\pi = 2.8 \text{ Bev/c}; \\ 7.96\cdot10^{-13} \text{ cm for } p_\pi = 6.8 \text{ Bev/c}. \end{cases}$$

In the calculations we took into account the anisotropy in pion-nucleon scattering at these energies [10,4] (in Figs. 1a and 1b the dotted lines represent the results of the calculations with $\mathrm{Re}\, f_{\pi n}(0) = 0$ with no allowance for this effect).

The experimental and calculated values of the elastic scattering total cross section are shown in Table III. On the basis of these data we can limit the possible values of the real part of the scattering amplitude to

$$+3.39\cdot10^{-13} \text{ cm} > \mathrm{Re}\, f_{\pi N}(0) \geqslant -3.39\cdot10^{-13} \text{ cm} \quad (p_\pi = 2.8 \text{ Bev/c}),$$

$$+6.9\cdot10^{-13} \text{ cm} > \mathrm{Re}\, f_{\pi N}(0) \geqslant -6.9\cdot10^{-13} \text{ cm} \quad (p_\pi = 6.8 \text{ Bev/c}).$$

(The values are considered to be in disagreement if the experimental values differ from the theoretical values by more than two standard deviations. The corresponding values of the effective potential of the interaction lie in the limits

$$-30 \text{ Mev} < V_{\text{eff}} \leqslant 30 \text{ Mev} \ (p_\pi = 2.8 \text{ Bev/c});$$
$$-30 \text{ Mev} < V_{\text{eff}} \leqslant 30 \text{ Mev} \ (p_\pi = 6.8 \text{ Bev/c}).$$

As is known, a small real part for the pion-nucleon scattering amplitude was also obtained with the aid of the dispersion relations,[11,12] which predict the following values of the real part of the πN scattering amplitude $\mathrm{Re}\, f_{\pi N}(0) = \frac{1}{2}[\mathrm{Re}\, f_{\pi^- p}(0) + \mathrm{Re}\, f_{\pi^+ p}(0)]$:

$$\mathrm{Re}\, f_{\pi N}(0) = \begin{cases} -0.49\cdot10^{-13};\ -0.36\cdot10^{-13} \text{ cm} & (2.8 \text{ Bev/c}); \\ -0.33\cdot10^{-13} \text{ cm} & (6.8 \text{ Bev/c}). \end{cases}$$

The data obtained in the present experiment are not sufficiently accurate for a quantitative comparison with conclusions drawn on the basis of the dispersion relations, but are in agreement with them within the limits of error.

The agreement of the differential cross sections $d\sigma/dq$, where q is the projection of the momentum transfer on the plane of observation (Fig. 2) indicates that, within the limits of error, the elastic scattering in the investigated energy interval is determined only by the momentum transfer. From the point of view of the optical model this means that the optical parameters of the πN interaction in this region do not change with energy. Our data allow us to make this conclusion for momentum transfer from 60 to 200 Mev/c. The available data on the π^-p scattering lead to the same result in the momentum transfer region ≥ 200 Mev/c (see, for example, [4]).

5. ESTIMATE OF THE π^-n SCATTERING CROSS SECTION IN THE BACK HEMISPHERE

Among the one-prong stars found by us we did not observe any cases in which a π^- meson, after interaction, was emitted in the back hemisphere in the laboratory system (l.s.). Hence, as an estimate of the upper limit of the scattering cross section of 2.8- and 6.8-Bev/c π^- mesons on neutrons in the back hemisphere, we obtain $\sigma_{\pi^- n}(\geq 90°) \lesssim 0.4$ mb and $\sigma_{\pi^- n}(\gtrsim 90°) \lesssim 0.1$ mb. (We assumed that the number of quasi-free neutrons in the carbon nucleus is not less than one.[5,8])

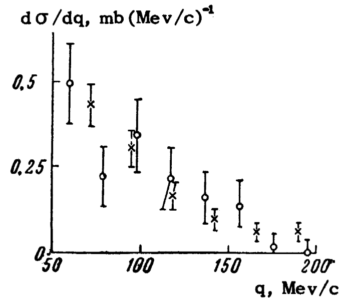

FIG. 2. Differential cross sections for π mesons with a momentum of: o – $p_\pi = 2.8$ Bev/c, x – $p_\pi = 6.8$ Bev/c.

Table III. Comparison and experimental theoretical cross sections for the elastic scattering of π^- mesons on carbon

p_{π^-}, Bev/c	$\Delta\varphi$, deg	Experimental cross section, mb	Calculation with optical model*: $\alpha=0.9$, $V_{\text{eff}}\approx-30$ Mev	$\alpha=0.5$, $V_{\text{eff}}\approx-15$ Mev	$\alpha=0$, $V_{\text{eff}}=0$	$\alpha=-0.9$, $V_{\text{eff}}\approx30$ Mev
2.8	1–5	31.1±5.1	51.2	36.5	25.3	40
6.8	0.5–1.9	26.5±2.4	43	30.4	21.3	34

* $\alpha = \mathrm{Re}\, f_{\pi N}(0)/\mathrm{Im}\, f_{\pi N}(0)$.

Pomeranchuk has drawn attention to the existence of the diagram in Fig. 3, which can lead to an increase in the $\pi^+ p$ and $\pi^- n$ scattering cross sections in the back hemisphere (in the l.s.) at high energies to ~ 1 mb. The estimate of Bayukov et al.[13] and the results of the present experiment indicate that the contribution of this diagram is evidently offset by other diagrams.

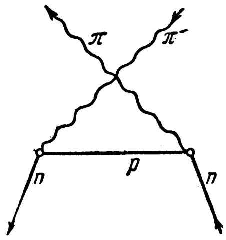

FIG. 3

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