INELASTIC SCATTERING OF 300-Mev POSITIVE AND NEGATIVE π MESONS BY PHOTOGRAPHIC EMULSION NUCLEI

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Submitted to JETP editor March 29, 1958

J. Exptl. Theoret. Phys. (U.S.S.R.) **35**, 838-844 (October, 1958)

We report on the results of measurements of the inelastic scattering cross sections, angular distributions, and energy spectra of 300-Mev π^+ and π^- mesons inelastically scattered by photographic emulsion nuclei. Some other characteristics of inelastic scattering were also obtained.

A study of the interaction of π mesons with nuclei can yield important information about the spatial distribution and energy spectra of nucleons in the nucleus, as well as the magnitude of the potential for a meson-nuclear reaction and its dependence on π-meson energy. Moreover, experimental data on interactions between π mesons and nuclei can be used to check various model representations of the nature of π-meson interaction with nucleons in a nucleus. In particular, it is possible to evaluate the validity of the hypothesis that nucleons inside a nucleus and free nucleons interact with π mesons in an identical manner.

The interactions of π mesons of different energies (mostly π^- mesons) with various nuclei have been the object of a whole series of investigations.[1-9].

The present investigation dealt with the inelastic scattering of 300 ± 15 Mev π^+ and π^- mesons by emulsion nuclei. NIKFI-R and Ilford G-5 photographic plates $400\,\mu$ thick were used. For several reasons the NIKFI plates contained 1.6 times as many light nuclei (O, C) as the G-5 plates (per unit area). The number of nuclei per cm^3 in the NIKFI emulsion (minus hydrogen) was $\sim 7.5 \times 10^{22}$. The conditions under which the photographic plates were irradiated and examined were described before.[8] The results obtained are based on an analysis of 5000 inelastic interactions (stars), due to π^+ and π^- mesons, found when the photographic plates were examined "by area."

We classified as inelastic scattering those interactions (stars) in which, besides a scattered π^+ or π^- meson, the track of at least one other charged particle was observed (in this case the minimum energy transferred by the meson to the nucleus equals ~ 20 Mev). In this investigation the contribution of other $\pi^\pm$-meson interactions were included in the total cross section. The presence of a scattered charged π meson in a star with an energy > 60 Mev was determined by measuring the ionization (grain density) in the tracks of the secondary particles forming the star. To identify lower-energy π mesons and to determine the energies of the mesons identified by grain density, it was necessary to make still further measurements of Coulomb scattering. These measurements were reliable only for particle tracks $> 1500\,\mu$ long. Therefore, it was not possible to specify all stars containing inelastically scattered mesons (with an energy < 60 Mev).

Only tracks more than $2000\,\mu$ long, having a grain density corresponding to mesons with an energy over 10 Mev, were used to construct the energy spectra of the scattered mesons. Coulomb scattering was measured on a spring stand with a very low noise level, $\overline{D}_{noise}(200\,\mu) = 0.02\,\mu$, described by Belovitskii et al.[10] The total error attributed to false-scattering effects was $0.1\,\mu$. Third differences[11] were used for the calculation of multiple scattering angles. The average statistical accuracy in the energy measurement of scattered mesons was 16%.

1. DETERMINATION OF THE CROSS SECTION FOR INELASTIC SCATTERING OF 300-Mev π^+ AND π^- MESONS

Experimental data on the ratio of inelastically scattered mesons without charge exchange to the total number of inelastic interactions were obtained from a study of 1622 stars due to π^- mesons and 1377 stars due to π^+ mesons on NIKFI plates and 286 stars due to π^- mesons on G-5 plates. Inelastic scattering occurred in $(45 \pm 2)\%$ of π^- mesons and in $(40 \pm 2)\%$ of π^+ mesons. A value

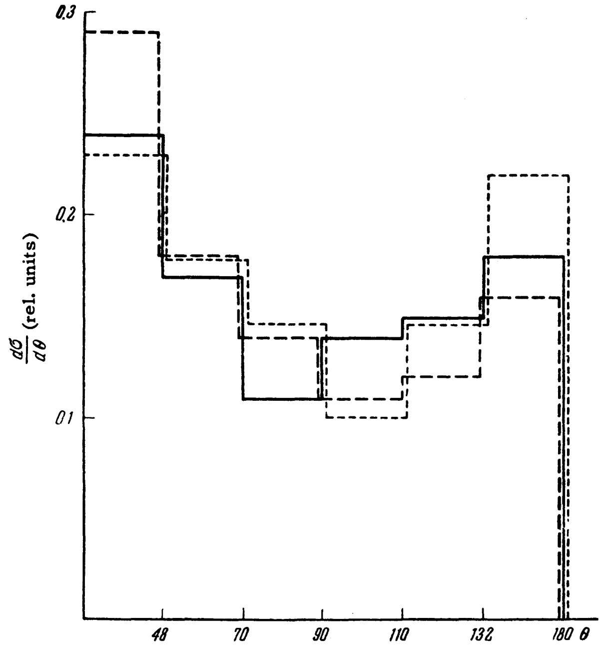

FIG. 1. The angular distribution for inelastically scattered mesons with energies > 60 Mev. The solid line is for π^- mesons (640 tracks), the broken line for π^+ mesons (481 tracks, NIKFI plates), and the dotted line for π^- mesons (95 tracks, G-5 plates).

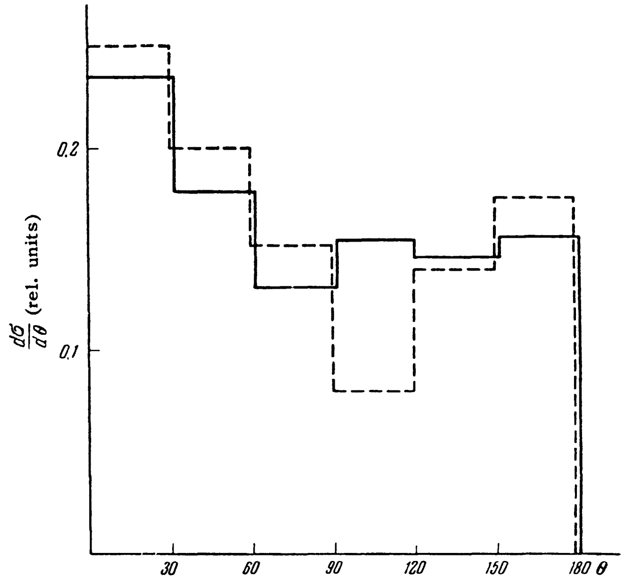

FIG. 2. The angular distribution for inelastically scattered mesons with energies over 10 Mev. The solid line is for π^- mesons (129 tracks), and the dashed line for π^+ mesons (85 tracks).

of (38 ± 4)% was obtained for π^- mesons in G-5 plates. Thus, the percentages of inelastically scattered π mesons of both signs were about the same for both kinds of emulsions.

Combining these data with the data of Dulkova et al.[8] on mean free paths for inelastic interactions of $\pi^\pm$ mesons of identical energy on identical photographic plates, we obtain 200 ± 32 and 185 ± 33 mbn for the cross section for inelastic scattering of π^- and π^+ mesons respectively. When the fraction of inelastically-scattered mesons was being computed, a correction was made for unidentified stars with tracks fue to π mesons with energies up to 60 Mev. In this connection, the fraction of mesons with energies of from 10 to 60 Mev was determined by comparing the number of 10- to 60-Mev mesons that had been identified by measuring grain density and Coulomb scattering with mesons of higher energy. The fraction amounted to (15 ± 5)% of the number of observed scattered mesons. In the case of π^- mesons, this correction should be increased by another 5% to account for slow π^- mesons with energies < 10 Mev. This last correction arose from the fact that in the stars due to π^- mesons we observed the emission of 11 π^- mesons that were stopped in the emulsion (with energy < 10 Mev) and in turn caused nuclear fission. No such correction was made where π^+ mesons were involved, because in the stars due to them not a single case was observed in which a π^+ meson was emitted and was stopped in the emulsion to bring about $\pi^+ \rightarrow \mu^+$ decay.

In order to obtain the total number of inelastic interactions involving π^- mesons, a correction was also made for the number of π^- mesons that "perished in flight" and hence were not observed during our examination of the area. This correction amounted to 5% of the total number of stars observed.[8]

It should be noted further that interactions in which only a scattered meson was detected were also predominantly inelastic. It was found that a considerable amount of energy (up to 200 Mev) could be transferred to a nucleus by a meson without any loss of heavy charged particles by the nucleus. Only the maximum value of the corresponding correction can be determined from the data of Dul'kova et al.,[8] this correction alters the inelastic scattering cross section only slightly.

2. ANGULAR DISTRIBUTIONS FOR INELASTICALLY-SCATTERED π^+ AND π^- MESONS

Figures 1 and 2 show the angular distributions for inelastically scattered π^+ and π^- mesons in the laboratory coordinate system (the data are related to equal solid angles). Figure 1 gives the distribution for mesons with energies > 60 Mev (NIKFI and G-5 plates), and Fig. 2 gives the distribution for mesons with energies > 10 Mev as identified by measuring Coulomb scattering and grain density (NIKFI plates). We see that the angular distributions presented in Fig. 1 and 2 have a similar shape for mesons of equal sign.

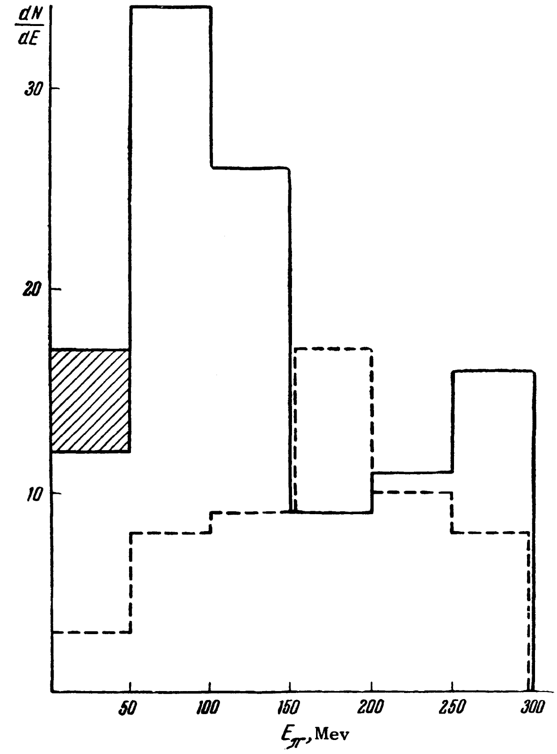

FIG. 3. The energy spectra of inelastically scattered mesons. The solid line is for π^- mesons, the dashed line for π^+ mesons.

The ratio of forward scattered mesons, (angles < 90°) to back scattered (angles > 90°) ones was 1.48 ± 0.14 and 1.5 ± 0.33 for π^+ mesons for both energy groups and 1.15 ± 0.1 and 1.19 ± 0.23 for π^- mesons. From these ratios it follows that the preponderance of forward scattering is notably greater for π^+ mesons than for π^- mesons. The angular distributions should also have included the cases mentioned above where the inelastic scattering of mesons was not accompanied by charged-particle emission. Inclusion of these examples would somewhat increase the proportion of mesons scattered forward.

3. THE ENERGY SPECTRA OF INELASTICALLY-SCATTERED π^+ AND π^- MESONS

Figure 3 shows the energy spectra for inelastically scattered π^+ and π^- mesons. Energy is plotted along the abscissa, the number of occurrences dN/dE along the ordinate. The π^- spectrum was corrected for slow π^- mesons with energies < 10 Mev (the shaded part of the histogram in Fig. 3). No such correction was made for the π^+-meson spectrum. The π^--meson energy spectrum has a maximum for E = 50 to 100 Mev. The maximum in the π^+ meson spectrum is shifted toward the larger energies. The average energy was 133 and 168 Mev for scattered π^- and π^+ mesons respectively.

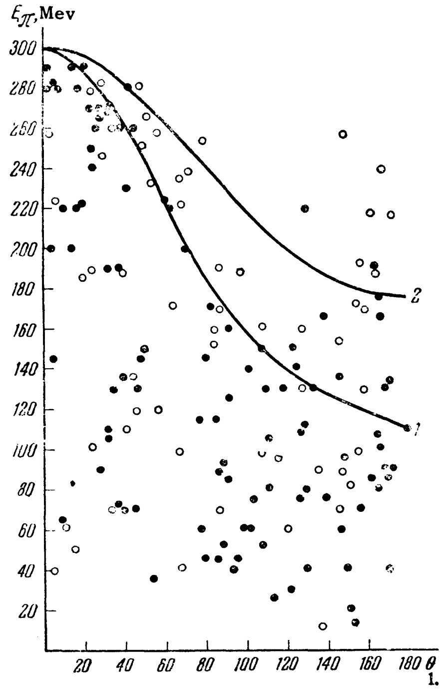

FIG. 4. Relation between the energy of a scattered meson and the scattering angle (laboratory coordinate system). Experimental data: ● is for π^- mesons; and ○ – for π^+ mesons. Curves 1 and 2 were computed for the elastic scattering of 300-Mev π mesons by protons and deuterons respectively.

The average meson energy for three angular intervals is presented in the table. A significant difference is seen to exist between the π^+ and π^- mesons. The average energy of scattered π^+ mesons changes only slightly from one angular interval to another. In the case of π^- mesons, on the other hand, the average energy doubles in the same range. It should be noted, however, that the data for π^+ mesons is based on less statistical material and therefore lacks sufficient accuracy.

Energy and pion charge	Scattering angle in degrees		
	0–60°	60–120°	120–180°
π^+—300 Mev	188	163	152
π^-—300 Mev	194	103	95

Figure 4 presents a more detailed independence between the meson energy E and its scattering angle θ. Here every scattered meson has a corresponding point in the (E, θ) plane. Also shown on the figure are the computed curves for the elastic scattering of 300-Mev mesons by free nucleons and deuterons. For scattering angles less than 90°, not a single case was observed where the energy of a meson noticeably exceeded the energy of a meson scattered by a free nucleon, whereas for scattering angles > 120° the fraction of such cases is fairly high, attaining ~ 20%.

4. DETERMINATION OF THE EXCHANGE-SCATTERING CROSS SECTION

Among the 5000 stars produced by π^+ and π^- mesons, three electron pairs due to $\pi^0 \rightarrow e^+ + e^- + \gamma$ decay were observed. According to Lindenfeld et al.[12] one such π^0 meson decay occurs per 80 $\pi^0 \rightarrow 2\gamma$ decays. Hence, the cross section for exchange scattering is

$$\sigma_{\pi^\pm \rightarrow \pi^0} \approx \left(\frac{3 \times 80}{5000}\right) 450 \approx (20 \pm 12)\,\text{mbn},$$

which is $\sim 5\%$ of the inelastic scattering cross section. It is easy to explain why the exchange scattering cross section is so small in comparison with the total scattering cross section, on the basis of the known cross sections for free nucleon scattering of π mesons, by assuming that the ratio of the free nucleon scattering cross section to the corresponding cross section for bound nucleon scattering remains unchanged.

5. ANALYSIS OF THE RESULTS

The pronounced foward scattering of 300-Mev $\pi^\pm$ mesons by free nucleons[13] is absent from the angular distributions for scattered mesons (Figs. 1 and 2). Also, the average energy of the scattered mesons proved to be substantially less than that computed ($\sim$ 220 Mev) on the assumption that the mesons experience one collision in the nucleus. All of this is indicative of the fact that a considerable number of the scattered mesons experience more than one collision in the nucleus.

Mesons were observed among the scattered mesons that had been formed as the result of the absorption of a primary π meson by a nucleon pair, with subsequent internal production of a π meson by one of the nucleons. It was possible to identify such examples during the analysis of the interactions of π^+ mesons with nuclei. In particular, the emission of slow π^- mesons, generated mostly through the above mechanism, was observed in stars due to π^+ mesons. We found that $\sim 10\%$ of the inelastically scattered π mesons were created in this way.

The existence of some kind of difference between the interactions of π^+ and π^- mesons with nuclei, as indicated in the table, is of considerable interest. This difference may be due to the unequal number of protons and neutrons in the heavy nuclei composing the emulsion (Ag, Br). Because of this inequality, the number and geometric arrangement of the collisions experienced by π^+ and π^- mesons in heavy nuclei may prove not to be identical. If this is so, then it would be natural to expect a noticeable difference between the angular distributions and energy spectra for π^+ and π^- mesons, as was actually observed in our experiment (see Figs. 1, 2, and 3). The difference between the π^+ and π^- meson spectra in the low energy region ($E < 10$ to 15 Mev) appears to have been caused by the influence of the nuclear Coulomb barrier.

Some information concerning the nature of the interaction of π mesons with nuclei, and possibly information concerning the momentum distribution of nucleons in the nucleus, can be derived from an analysis of the data in Fig. 4. It is obvious that a good number of the back scattered mesons (angles > 90°) possess substantially greater energies than would be expected if each meson collided with a free nucleon at rest (Fig. 4, Curve 1). This result could be due to single collisions by mesons with transitory complexes of two, three, or more nucleons, or could be due to the influence of nucleonic movement or, finally, to simultaneous action by both of these factors. According to the preliminary data obtained by us, the probability of collisions between 300-Mev mesons and a deuteron in the nucleus amounts to ~ 2 to 3% of the total cross section for inelastic scattering, or about half of the observed effect.

If the second hypothesis is correct, it must follow that nuclear nucleons can possess a maximum kinetic energy of 50 to 60 Mev. This value is twice the magnitude usually taken for the nuclear model (the degenerate Fermi gas of non-interacting particles). Evidence that high-energy nucleons exist in the nucleus is also provided by several experiments with high-energy particles.[14] Therefore, it is not improbable that the observed effect is caused by the combined action of the factors described above.

It is our intention to compute the inelastic scattering of 330-Mev π mesons by emulsion nuclei with the Monte Carlo method, the assumption being that there are individual meson-nucleon collisions in the nucleus. The angular and energy distributions obtained in this way will be compared with the experiment.

In conclusion, the author wishes to express his gratitude to I. M. Frank for several helpful suggestions made when the investigation was being performed and to A. P. Lagena and O. N. Pavlova for their help with the measurements.

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Translated by A. Skumanich
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