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A SEARCH FOR THE ρ^0 MESON AND A CHECK OF THE DISPERSION RELATIONS IN π-N SCATTERING

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The total π^--p interaction cross sections (σ_t^-) were measured with an accuracy of 1.5 — 2% for about 50 pion energies between 140 and 360 Mev. The pion energy was known to within ±1%. No anomalies in the energy dependence of σ_t^- were found which could indicate the existence of a ρ^0 meson with a mass in the range of 270 to 410 Mev/c^2.

The data are inconsistent with the energy value $E_2 = 650$ Mev for the second maximum of σ_t^- found by Frisch et al.[7] but agree with the conclusion drawn by Brisson et al.[8] that it should be located at a lower energy ($E_2 \approx 610$ Mev). The data are in agreement with the dispersion relations for π^--p scattering. It is thus demonstrated that the Puppi-Stanghellini problem as such no longer exists and that it arose only as a result of an inaccurate knowledge of the total π^--p interaction cross section.

INTRODUCTION

THE energy dependence of the total cross section of the π^--p interaction σ_t^- has already been investigated in a wide energy interval several years ago. For energies up to 360 Mev, where the most precise data were obtained, the cross section was measured with a precision not exceeding ~ 5%, while the energy for which the cross section was being determined was known only within ±6 Mev. At the same time the precise measurement of this cross section with good energy resolution is of undoubted interest for several reasons.

First, as was already communicated earlier,[1] by determining the energy dependence of the total cross section σ_t^- very precisely it is possible in principle to observe a definite type of "threshold anomalies" which could furnish information on π-π interaction, or would indicate the existence of the still unknown ρ^0 particle.

Secondly, it is of definite interest to express the energy dependence of the total π-N cross section in the state with an isotopic spin $T = \frac{1}{2}\,[\sigma(\frac{1}{2})]$ with the aid of a small number of Breit-Wigner type of "resonance" curves. This requires experimental data of great precision.

Thirdly, some authors[2] doubt the validity of the dispersion relations for π-N scattering. From this point of view a more careful measurement of the σ_t^- than has been carried out to date in a sufficiently wide energy interval is essential for the precise calculation of the real part of the π^--p scattering amplitude.

In the present work we present the experimental investigations which we have undertaken in connection with the above.

Preliminary results were communicated at the Conference on the Physics of High-Energy Particles in Kiev in 1959.

THE EXPERIMENTS

a) The geometry of the experiment. The total interaction cross sections of negative pions with hydrogen were measured by the weakening of the meson beam passing through a hydrogen scatterer. The general setup for the experiment is shown in Fig. 1. The meson beam incident on the hydrogen target was formed by a rectangular collimator 3 cm wide (in the yoke of the synchrocyclotron magnet), by the deflecting magnet, and by counters 1 and 2 connected in coincidence. The mesons after passing through the scatterer were registered by counter 3, connected in coincidence with counters 1 and 2. The counters were made of scintillating plastic and were of the following dimensions: counter 1 — 0.8 × 3 × 6 cm; counter 2 — 0.5 × 3 × 6 cm; counter 3 — 1 × 10 × 10 cm (the last value for each counter gives the vertical dimension). The mean angle of registration by counter 3 was 10.5°. Liquid hydrogen in a foamed polysterol container (wall thickness 0.8 g/cm^2)

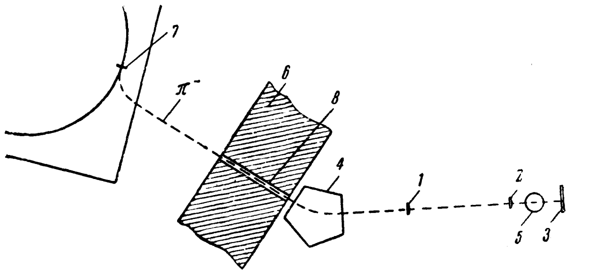

FIG. 1. Experimental setup (schematic): 1, 2, 3 — scintillation counters, 4 — deflecting magnet, 5 — hydrogen scatterer, 6 — yoke of the synchrocyclotron magnet, 7 — beryllium target inside the synchrocyclotron chamber, 8 — pion collimator.

served as the target.[3] The density of the hydrogen was taken as 0.0708 g/cm^2; the mean number of hydrogen nuclei in the path of the beam corresponding to this density amounted to $(0.4607 \pm 0.0023) \times 10^{24}$ nuclei/cm^2.

b) Electronic apparatus. The apparatus used in this experiment was essentially the same as in reference 3. FÉU-33 photomultipliers were used for the scintillation counters. To increase the counting efficiency and to decrease the role of the apparatus "drift," the resolving time of the coincidence circuits used was increased to 2×10^{-8} sec. Two scaling devices of the "Kalina" type, each preceded by an additional scale-of-4 scaler with a dead time of 0.1 μsec, were used for counting the transmitted mesons.

For the precision required of the total cross sections (2%) it was essential that the operating stability of the apparatus amount to about several hundredths of a percent. It was, therefore, desirable to have an objective criterion for the satisfactory quality of the operation of the apparatus. Such a criterion can be the reproducibility of the results over long periods of time (tens of hours). If we take, for example, the coincidence count of counters 1, 2, and 3 (the count of 1 and 2 is the monitor) and measure it a sufficient number of times then, in the absence of errors due to the apparatus "drift," the deviations of each measurement from the mean will obey a Gaussian distribution with a calculable dispersion. However, such a control consumes almost as much time as all the measurements. The information already accumulated in the course of measuring the total cross section was, therefore, employed for the control. The measurements were repeated 5 — 6 times for each energy. The deviations of the coincidence count N_{123} from its mean value with the hydrogen were summed for various energies. The result of this summation (Fig. 2) shows that the distribution of the deviations is in very good agreement with the Gaussian distribution (solid curve in Fig. 2) with a dispersion calculated on the assumption

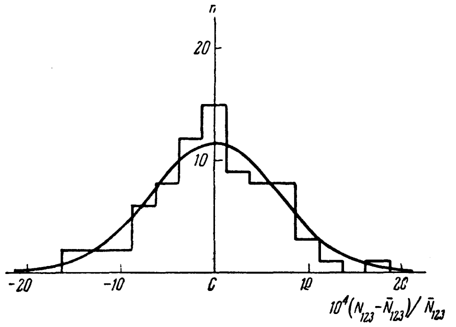

FIG. 2. The spread of the deviations of the normalized coincidence count N_{123} (with hydrogen) from the mean value; n is the number of measurements having a given deviation; the solid curve is the distribution function calculated on the assumption that the deviations are due only to statistical fluctuations.

of the absence of apparatus "drift" and other errors, except for the statistical fluctuations in the number of pion-interaction events after their registration by counters 1 and 2.

c) Determination of the negative-pion momentum. In the investigated range where the cross section depends rather strongly on the energy, the determination of the cross section with the above-mentioned precision makes sense only if the negative-pion momentum is measured with a precision of about 1%. Such a precision in the momentum determination is also essential for the possible observation of a ρ^0 meson, since the expected width of the anomalous region is small, and consequently cross-section measurements for pion energies differing by less than 5 Mev are required. For this purpose, the field of the deflecting magnet was stabilized during measurements at a given energy with a precision of 0.1% (by utilizing the Hall effect in a germanium disc), and at times even more precisely (by making use of the nuclear-resonance effect). The value of the field was determined from the current appearing in the germanium crystal owing to the Hall effect. The Hall current was measured with an instrument of the 0.5 class graduated with a precision of 0.5% directly in values of the negative-pion momentum by the method of the current-carrying filament. The required pion energy was obtained as follows. First the necessary field of the deflecting magnet was established, and then the beryllium target was positioned within the synchrocyclotron by remote control for maximum intensity of the pion beam.

Owing to the certain lack of precision entailed in the setting up of the meson target, the final precision of the mean value of the negative-pion momentum amounted to ~ 1%.

The energy spread of the beam depended on the collimator width in the yoke of the synchrocyclotron magnet, and according to graphically obtained estimates amounted to ±0.5 Mev/cm, i.e., ±1.5 Mev for a collimator 3 cm wide. The energy loss in the hydrogen was ~ 3 Mev.

THE ENERGY VARIATION OF THE CROSS SECTIONS IN THE REGION OF MESON-PRODUCTION THRESHOLDS (150 — 180 Mev)

At an incident negative-pion energy of 150 Mev, three meson-production reactions by mesons are possible:

1. $\pi^- + p \rightarrow \pi^- + \pi^+ + n$ threshold 172 Mev,
2. $\pi^- + p \rightarrow \pi^- + \pi^0 + p$ threshold 165 Mev,
3. $\pi^- + p \rightarrow \pi^0 + \pi^0 + n$ threshold 160 Mev.

In principle, anomalies due to π-π interaction can be expected in the threshold regions. In so narrow an energy interval (~ 10 Mev), attention was chiefly paid only to the relative cross-section variation.

The energy of the primary beam of negative pions was held constant, and mesons of required energy were obtained by lowering the primary-meson energy in a graphite absorber. The relative cross-section variation was measured in steps of ~ 2 Mev. Figure 3 shows the results of two measurement series obtained on different days. It is seen that, within the precision of the experiment (~ 1.5%), no anomalies in the dependence of the cross sections on the energy were observed. It should be noted that the values of the "hydrogen difference" given are not proportional to the cross sections, since this method of energy "reduction" by means of a graphite absorber requires the introduction of strongly energy-dependent corrections.

It must be emphasized that the interaction in reactions 1, 2, and 3 can only lead to anomalies when two negative pions form a bound system.

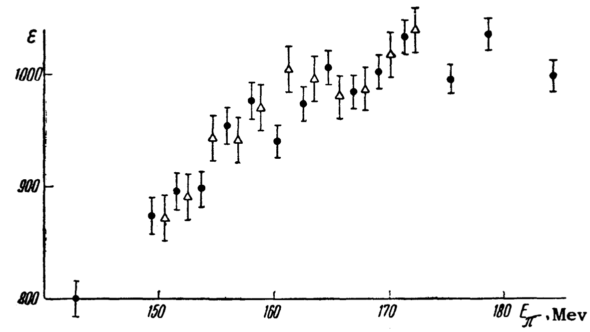

FIG. 3. The energy dependence of the effect of the hydrogen (ε) in relative units in the region of the thresholds of meson production (the results of two series of measurements made on different days).

Phenomenologically such a system is in itself a new particle. Therefore it is clear that the investigations must be conducted in a wider energy region, since the neutral boson, differing from the π^0 meson, can in principle have an arbitrary mass.

THE ENERGY VARIATION OF CROSS SECTIONS IN THE 160 — 360 Mev REGION

In this section we give not only experimental relative cross-section variations, but also the absolute values of the cross sections. The final results of the absolute measurements of the total cross sections are listed in Table I. It is not essential that we list the corrections made for all the energies. We merely state their nature:

1. A correction for the μ-meson admixture in the negative-pion beam, determined as usual from the negative-pion absorption curve in copper.

2. Account of the number of scattered negative pions and recoil protons incident on counter 3, on the basis of the known angular distributions.

3. The contribution of the Coulomb- and nuclear-scattering interference of negative pions, calculated from the formulas of Solmitz[4] and from the known phase shifts of π^--p scattering.

TABLE I. Total π^--p-interaction cross sections for different energies*

E_{π^-}, Mev	σ_t^-, 10^{-27} cm^2	E_{π^-}, Mev	σ_t^-, 10^{-27} cm^2	E_{π^-}, Mev	σ_t^-, 10^{-27} cm^2	E_{π^-}, Mev	σ_t^-, 10^{-27} cm^2
158.2	56.4±2.0	220.2	52.2±1.0	254.7	39.8±0.8	302.5	28.9±0.8
171.7	67.2±1.1	225.0	50.2±0.9	258.0	38.8±0.8	307.7	28.1±0.8
178.4	67.2±1.1	228.3	48.2±0.9	261.4	36.8±0.8	313.0	28.7±0.7
185.2	67.7±1.0	231.6	49.0±0.9	266.5	35.6±0,8	318.2	27.0±0.6
189.9	67.8±0.8	234.9	44.5±0.9	271.6	33.4±0.8	323.5	26.2±0,6
196.2	64.0±1.1	238.2	44.9±0.9	276.7	31,1±0.8	328.2	26.4±0.6
201.0	63.8±1.0	241.5	42.7±0.9	281.8	32.4±0.8	334.2	26.0±0.6
205.8	59.3±1.0	244.8	43.1±0.9	286.9	31.6±0.8	345.0	24.9±1.0
210.6	58.7±1.1	248.1	41.0±0.9	292.0	30.5±0.8	361.0	25,2±1.0
215.4	55.6±1.0	251.4	39.3±0.9	297.2	29.3±0.8		

*The indicated errors do not include those connected with the imprecise determination of the mean number of hydrogen nuclei in the path of the beam (±0.5%), and with the admixture of muons in the beam (±1.5%). These errors are statistical.

4. Account of the multiple Coulomb scattering of the pions in the hydrogen (its contribution is considerable when the beam diverges, which it always does, if only on account of the scattering in counter 2).

5. Control measurements of the difference between the target and the dummy, due to the fact that the experiments with the hydrogen and without it were conducted with different containers.

In Table II we have listed only the corrections corresponding to two energy values, in order to give some idea of their magnitude.

DISCUSSION OF RESULTS

a) Search for the ρ^0 meson. Here the ρ^0 is defined as a pseudoscalar meson with zero charge and isotopic spin. In the experiment whose results were cited in the preceding section we proposed to search for a relatively narrow anomaly in the energy dependence of the total cross section σ_t^-, inasmuch as such an anomaly can in principle indicate the existence of a ρ^0 meson. The idea[2] consists of the fact that in one or both of the $\pi^- + p \rightarrow \pi^0 + n$ and $\pi^- + p \rightarrow \pi^- + p$ reactions an anomaly can appear near the threshold of the hypothetical $\pi^- + p \rightarrow \rho^0 + n$ reaction. The width of this anomaly can be obtained from the condition $kR \ll 1$, where k is the momentum of the emitted ρ^0 meson in the c.m.s., and R is the interaction radius. If it is assumed that $R \sim \hbar/m_\pi c$, then the maximum peak width in the energy dependence turns out to be about 40 Mev in the laboratory system $m_{\rho^0} \sim 400$ Mev/c^2. Actually the width can be considerably smaller than this, and therefore a good energy resolution was employed in the experiments. The amplitude of the anomaly $\sigma(\pi^- p \rightarrow \rho^0 n)_{k=1/R}/\sigma_t(\pi^- p)$ can, in principle, approach several percent.

The obtained data indicate that in the 140- to 360-Mev energy region there exist no cross-section anomalies with an amplitude of, say, 3 — 4%. This means that we have not found a ρ^0 meson with a mass in the interval of 270 — 410 Mev/c^2. Of course this does not mean that such a meson does not exist. At the Kiev Conference on the Physics of High-Energy Particles in 1959 investigations[5] were reported in which different methods of searching for the ρ^0 meson also did not offer indications of its existence.

b) The total cross section in the state with $T = \frac{1}{2}$. Klepikov, Meshcheryakov, and Sokolov[6] analyzed in 1959 the body of information on the total cross sections of the π-N interaction on the basis of all the published data, and also on the basis of the data of this work. The "total" cross sections in states with an isotopic spin of $T = \frac{3}{2}$ $[\sigma(\frac{3}{2})]$ and $T = \frac{1}{2}[\sigma(\frac{1}{2})]$ were approximated by resonance formulas of the Breit-Wigner type; the method of maximum likelihood was used. Thus all the curve parameters and the corresponding error ranges were found. It should be noted that in the energy region of 250 — 1500 Mev it was impossible to describe the energy dependence of $\sigma(\frac{1}{2})$ in terms of Breit-Wigner curves, if simultaneous use was made of the data of this work and of the data of reference 7, where two maxima in the energy dependence of the cross section σ_t^- had been observed at $E_2 \sim 650$ Mev and $E_3 \sim 950$ Mev. Apparently this difficulty was connected with an error in the determination of the pion energy in the experiments of the American authors and confirms the conclusion of the French group[8] that the maxima are at $E_2 \approx 610$ Mev and $E_3 \approx 880$ Mev.

c) Pion-nucleon scattering and the dispersion relations. At the Conference on the Physics of High-Energy particles in 1958 the position concerning the application of the dispersion relations to the π^+-p and π^--p processes was summed up as follows:

1. The body of information on the π^+-p and π^--p scattering processes is fully compatible with the dispersion relations and makes it possible to determine the coupling constant of meson-nucleon interaction f^2, which turns out to be 0.08, within a precision of 10%.

2. Data relating only to π^+-p scattering allow a sufficiently precise determination of f^2.

3. The information relating only to π^--p scattering was less satisfactory in the sense that it turned out difficult to reconcile with the value of f^2 obtained from π^+-p-scattering experiments (the so-called Puppi-Stanghelli problem).

One can say that it had always been natural to

TABLE II. Corrections introduced in the determination of the total cross sections (in percent)

Energy of π^- mesons, Mev	Admixture of μ^- mesons	Forward-scattered π^- mesons and protons	Interference of the Coulomb and nuclear scattering	Coulomb multiple scattering in the hydrogen	Difference between the dummy and the target
201.0±2	6.5±1.5	3.1±0.4	—0.3	—1.2±0.3	—0.3±1.0
297.2±3	3.5±1.5	3.5±0.4	+0.3	—0.8±0.2	—0.2±1.3

regard with caution the possibility of the "revolutionary" inference of Puppi and Stanghellini (which has been particularly emphasized by a number of other authors) not only in view of its far-reaching theoretical consequences, but particularly in view of certain logical contradictions inherent in it. These contradictions consisted of the following: experimentally nothing was known about the interaction of states with T = ½, and it is therefore incomprehensible how in the absence of such information a real contradiction of the dispersion relations could arise.

In 1959 there appeared some theoretical work which indicated the lack of serious difficulties in the application of the dispersion relations to π-N scattering.[10] The most convincing results were cited in reference 6, where the data of the present work together with other published data had been used. On the basis of the total cross-section curves, obtained as indicated in the preceding section, the authors of reference 6 calculated the real part of the π^--p forward-scattering amplitude and obtained the corresponding range of errors. Figure 4 shows the calculated curve of the real part of the forward-scattering amplitude, obtained from the "dispersion integral," and its particular values obtained for certain energies from the angular distribution of the π^--p scattering and from the total cross sections. It must be emphasized that in plotting the points given in Fig. 4, values of the total cross sections obtained from "calculated curves" (reference 6) were employed. The use of a calculated $\sigma_t^-(E)$ curve leads to a smaller error than the use of a separate total cross-section measurement, since the width of the error region of $\sigma_t^-(E)$ is small.

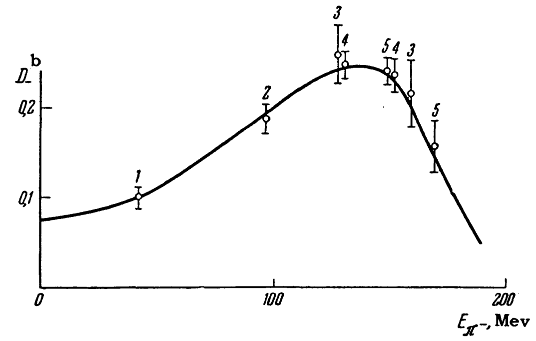

FIG. 4. The real part of the π^--p forward-scattering amplitude D_-^b in $\hbar/m_\pi c$ units. The solid curve was calculated by Klepikov et al.[6] on the basis of all the total cross-section measurements: 1 – Barnes et al. (Rochester),[11] 2 – Edwards et al. (Liverpool),[12] 3 – Budagov et al. (Dubna),[13] 4 – Kruse and Arnold (Chicago),[14] 5 – Ashkin et al. (Carnegie).[15] All points in the figure are plotted with account of the latest data on total cross sections.

As can be seen, it is difficult to expect better agreement of the calculated D_-^b curve and the values obtained from angular distributions and total cross sections. Inasmuch as the Puppi-Stanghellini problem has been widely discussed, albeit, in our opinion, not quite thoroughly, it is appropriate to pose the question why it arose. It is at present perfectly clear that the Puppi-Stanghellini "discrepancy" was simply due to an inexact knowledge of the total π^--p cross sections which entered both in the "dispersion integral," and also in the "experimental" values of the real part of the forward-scattering amplitude. More precise measurements of σ_t^- and better methods of processing the experimental data for the calculation of the dispersion integral remove this discrepancy. This is obvious if only from the fact that the π^--p interaction data of Ashkin et al.[15] for energies of 150 and 170 Mev, which were in 1956 the main source of the discrepancy, fit the present D_-^b curves excellently (cf. Fig. 4) if use is made of the latest data on total cross sections.

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