INVESTIGATION OF INELASTIC COLLISIONS BETWEEN 2.8 BeV/c π^-*-MESONS AND PROTONS*

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The $\pi^- + p \rightarrow p + \pi^- + m\pi^0$ reaction on hydrogen was studied in a propane-xenon chamber for 2.8 BeV/c π^- mesons. It is shown that a ρ^- meson is formed with a cross section $\sigma = 0.30 \pm 0.07$ mb for a momentum transfer in the 0.2—0.4 BeV/c range. An irregularity in the distribution of residual masses is observed at the value $M_X = 1.00 \pm 0.01$ BeV with a half-width 60 ± 20 MeV, which corresponds to the final state π^-, π^0, π^0. The cross section for this process in the indicated region of momentum transfer to the proton is $\sigma = 0.16 \pm 0.05$ mb.

We investigated the reaction

$$\pi^- + p \rightarrow p + \pi^- + m\pi^0 \qquad (1)$$

on free and quasi-free protons with a π^--meson momentum of 2.8 BeV/c and a momentum scatter ±4%. The work was performed with a strong-focusing 7-BeV accelerator at the Institute of Theoretical and Experimental Physics. The measurements were carried out in a 17-liter bubble chamber without a magnetic field[1], filled with a propane and xenon mixture. The mixture density was 0.84 g/cm^3 (57.3% Xe and 46.3% C_3H_8 by weight).

The average efficiency of γ-quantum registration was close to 50%. Altogether we scanned 50,000 frames. In the scanning we selected two-prong stars with one gray track, ascribed to the π^- meson, and a black track, ascribed to the proton, under the condition that the proton stopped within the working volume of the chamber. In order to limit the background due to the reactions on complex nuclei, all two-prong stars with any additional visible track starting from stars which could result from evaporation protons of low energy were discarded. The minimum proton momentum measured with the required accuracy was 0.20 BeV/c.

For the primary analysis we selected 2,000 two-prong stars having 0, 1, 2, 3, and 4 electron-positron conversion pairs. From the known momenta of the protons and from the angles between their directions of emission and the primary direction of the π^- mesons in the laboratory system (l.s.) of coordinates we construct the spectrum of "residual masses." The measurements of the space angles of all the particles, including the pairs, and of the proton track lengths were made with stereo projectors. The angles and proton track lengths were accurate to ± 1° and ± 1 mm respectively. A preliminary analysis has shown that about half of the selected cases fall in the region in which the dominant role is played by elastic scattering. We have therefore left for subsequent analysis only those stars which give a residual mass higher than 0.4 BeV. For the case where the track was accompanied by pairs, no such limitation was imposed.

Figure 1 shows the summary distribution of 1092 events with 0—4 pairs. The investigation of the distribution given in Fig. 1 has shown the pres-

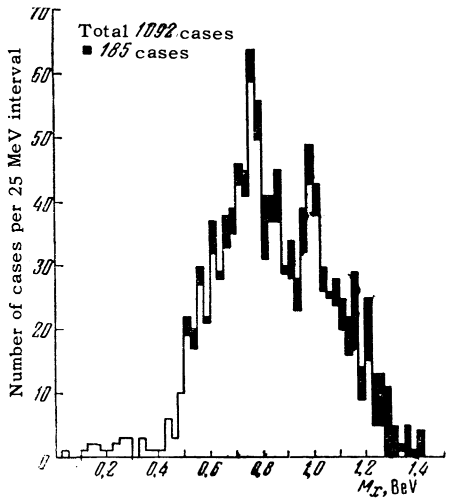

FIG. 1. Over-all distribution of events with 0, 1, 2, 3, and 4 registered pairs with respect to the residual masses M_x. Here and subsequently the areas shown in black in the figures are those corresponding to events with proton momentum greater than 0.4 BeV/c; in the remaining cases it is equal to 0.2 – 0.4 BeV/c.

ence of two irregularities. One, with good statistical reliability, is in the 0.7—0.8 BeV region of the residual masses. The second, with poorer reliability, is in the residual mass region 0.95—1.025 BeV.

Figure 2 shows histograms with differing numbers of registered pairs, from zero to 4. In order to identify the peripheral collisions, we separated cases with momentum transfer from 0.2 to 0.4 BeV/c (the regions corresponding to cases with momentum transfer from 0.4 to 0.6 BeV/c are shown in black). A noteworthy fact is that the irregularity in the region of masses of 0.75 BeV appears only on the histograms where the number of pairs registered does not exceed 2.

The same irregularities appear also in Fig. 3, which shows the summary histogram for 1 to 4 registered pairs, when the peak in the mass region 0.65—0.8 BeV went beyond the phase curve in six points by more than three standard deviations, while the peak in the region of masses near 1 BeV has an excess of four standard deviations in two neighboring points. The reason why events without an accompanying electron-positron pair were excluded is indicated below.

It is natural to assume that the peak near the 0.75 BeV mass belongs to the ρ^- meson, which breaks up into π^- and π^0 mesons. To prove this, we investigated the angular distribution of the π^-

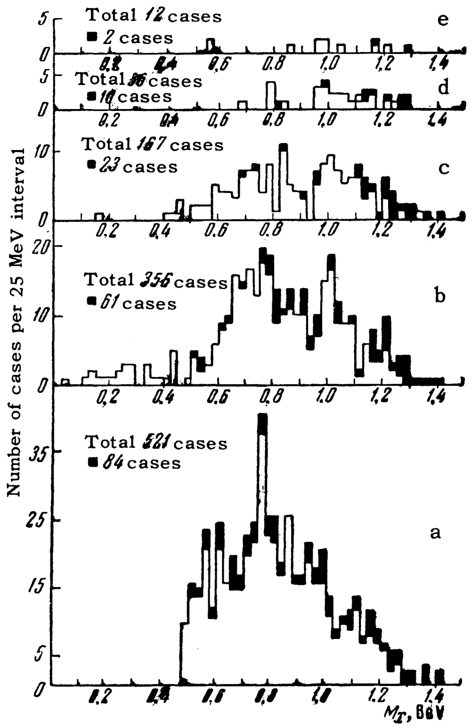

FIG. 2. Distribution of events with different numbers of registered pairs.

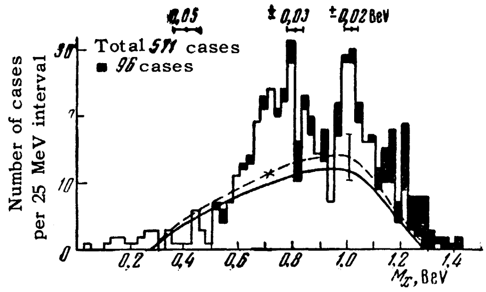

FIG. 3. Summary distribution of events with 1 to 4 registered pairs. Smooth curves—summary phase curves, normalized by two different methods.

mesons in the ρ^- meson rest system. It is known [2] that the ρ meson has unity spin. This causes the angular distribution of the π^- mesons in the ρ-meson rest system to obey the law $a + b\cos^2\theta^*_{\pi\rho}$ where $\theta^*_{\pi\rho}$ is the angle between the directions of motion of the π meson and the ρ meson in the ρ-meson rest system. From work done with liquid-hydrogen chambers it follows that a is close to zero.

Figure 4 shows the angular distributions of π^- mesons in the c.m.s. for four regions of residual masses. It must be emphasized that if only two pions are emitted, then the angular distribution of the π^- mesons in the c.m.s. of the emitted pions is determined uniquely from the known momentum and proton emission angle and emission angle of the secondary π^- meson.

It follows from Fig. 4b that the distribution in the 0.65—0.85 BeV region of residual masses is essentially anisotropic and corresponds to the case when the π^- meson is emitted predominantly forward or backward, and the probability of emission in both directions is the same within the limits of statistical error and can be described by the law $a + b\cos^2\theta^*_{\pi\rho}$ with a criterion $\chi^2 \leq 4$. For all the remaining regions, the distribution can be regarded as isotropic (in the worst case of Fig. 4c

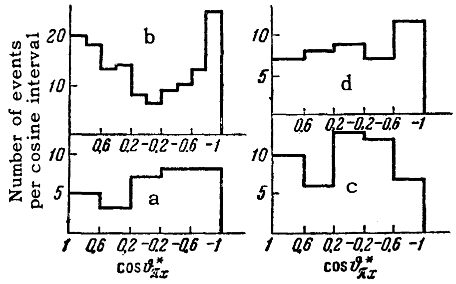

FIG. 4. Angular distribution of π^- mesons in the rest system of the emitted pions for four regions of the histogram of Fig. 3. a—for 0.55–0.65 BeV, b—for 0.65–0.85 BeV, c—for 0.95–1.05 BeV, d—for 1.05–1.15 BeV.

we have $\chi^2 \leq 4$). Thus, the angular distribution corresponds to the assumption that the irregularity in the distribution in the mass region 0.65–0.85 BeV can be ascribed to the ρ^- meson.

Assuming that the excess over zero in the region of values of $\cos\theta^*_{\pi\rho} = 0$ is due to the background, and assuming that the background has an isotropic distribution (the latter statement follows from the analysis of the angular distributions in the neighboring regions of Fig. 4), we can find the total background, obtain the ordinate of the phase curve [1)], and calculate the cross section of the reaction

$$\pi^- + p \rightarrow p + \rho^- \qquad (2)$$

To estimate the cross section for the generation of the ρ^- meson it is necessary to subtract the contribution of the nonresonant processes. The summary phase curve for reaction (1) with m = 1 and m = 2 is shown in Fig. 3, where the ratio of the channels with m = 1 and m = 2 is taken to be 3:1 (based on the ratio of the areas in the histogram of Fig. 2), and where allowance is made for the γ-quantum registration efficiency. Figure 5 shows the phase curves (I and II) calculated for the case when the photons with momenta from 0.2 to 0.4 BeV/c were registered in the fiducial volume of the chamber.

The phase curve on Fig. 3 was normalized by two methods. The dashed curve was normalized at the point designated by the cross to the value of the background obtained from Fig. 4b by the method indicated above. The solid curve was normalized to the total area of the histogram with the peaks subtracted. It can be seen from Fig. 3 that both methods of normalization give nearly equal results.

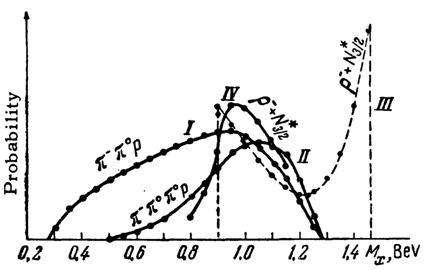

FIG. 5. Phase curves: I and II–for momentum transfer 0.2–0.4 BeV/c, III and IV–for all momentum transfers. Curve III–for masses ρ and $N^*_{3/2}$, equal respectively to 0.75 and 1.24 BeV, without account of the width of distribution over the masses, curve IV–with account of the width $\Delta m = 150$ MeV for the ρ meson.

The cross section of reaction (2) for a 2.8 BeV/c primary π^- meson was determined in the momentum transfer region 0.2–0.4 BeV/c by two methods. First, on the basis of the data on the cross section of the reaction $\pi^- + p \rightarrow m\pi^0 + n$ [3] and from a comparison of these data with ours in a series of 7,000 frames. Second, by a direct method with allowance for the number of passages of π^- mesons through the chamber and the number of registered events, corrected for the efficiency of registration of the given reaction in the chamber and for the efficiency of registration of the γ quanta. In the second method it was assumed [4] that there is a 35% contribution of the reaction $\pi^- + p \rightarrow p + \pi^- + \pi^0$ on quasi-free nucleons of complex nuclei in the working medium of the chamber. Both methods gave similar results for the ρ^--meson production cross section: $\sigma = 0.30 \pm 0.07$ mb.

Figure 6 shows the angular distribution of the π^- mesons in the c.m.s. of the emitted pions in the residual-mass region 0.65–0.85 BeV for cases without observed pairs (see Fig. 2a). The strong asymmetry with predominant emission of the π^- mesons forward can be attributed essentially to the elastic scattering of the π^- mesons by quasi-free nucleons. The magnitude of this background from the reactions on complex nuclei was estimated from a comparison of the number of events with a different number of registered pairs. Whereas the histograms of Fig. 2 with 1–4 pairs more or less satisfy the ratios of the probabilities of the registration of the different number of γ quanta, there is a considerable excess of events (approximately $2/3$ of the total) in the histogram of Fig. 2a as compared with the calculated value. The presence of a large background from an entirely different reaction was the reason why the cases without pairs were discarded from the very outset.

Let us consider now the irregularity in the 0.95–1.025 BeV residual mass region. In our opinion, the phase curves indicate that this irregularity is statistically well founded. A comparison

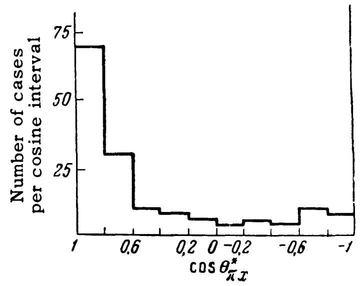

FIG. 6. Angular distribution of π^- mesons in the rest system of the emitted pions for the region 0.65–0.85 BeV of the histogram in Fig. 2a.

[1)] This method of normalizing the phase curve was suggested to us by A. I. Alikhanov.

of the histograms of Fig. 2 shows apparently that this irregularity is due essentially to the reaction

$$\pi^- + p \rightarrow p + \pi^- + \pi^0 + \pi^0. \qquad (3)$$

A more rigorous proof of this statement was obtained in the following manner. It follows from the 50% efficiency for registering a single γ quantum that when two π^0 mesons are produced the greatest probability of registering this event is in the channel with registration of two pairs (37%). The efficiency of registration of two γ quanta from π^0 mesons is 25%. Consequently, under our assumption that the irregularity is due to the $\pi^-\pi^0\pi^0$ channel, the relative contribution of the latter compared with the $\pi^-\pi^0$ channel should be the largest on the histogram of Fig. 2c. With our procedure it was possible in many cases to separate in Fig. 2c the $\pi^-\pi^0\pi^0$ and $\pi^-\pi^0$ events by measuring the emission angles of both pairs. Indeed, knowing the momentum and the proton emission angle, we know the momentum and the direction of emission of the pion system. If, further, the pion system consists of two pions, then they should lie in a plane passing through the direction of motion of the system. The direction of the secondary π^- meson is known. We deal in the experiment with the decay products of π^0 mesons—two pairs. If a reaction has occurred via the $\pi^-\pi^0$ channel, then the pairs should be registered on both sides of the plane passing through the direction of motion of the system of the pions and the π^- meson. If the pairs were registered on one side of this plane or the direction of the π^- meson and both pairs lies on one side of the direction of the momentum of the pion system, then the case does not belong to the $\pi^-\pi^0$ channel, and belongs apparently to the $\pi^-\pi^0\pi^0$ channel.

The contribution of the channels with a large number of π^0 mesons can be regarded as insignificant, since only one case with five pairs was registered, and this case is furthermore doubtful. Such a small contribution of channels with more than two π^0 mesons is explained by the fact that, owing to the finite dimensions of the instrument, part of the protons are not stopped in the chamber and strong cutoff occurs in the region of large residual masses, i.e., in that region where the phase-volume curve for five particles has a maximum.

The distribution of events belonging only to the $\pi^-\pi^0\pi^0$ channel, namely with three and four pairs, and sometimes with two pairs, clearly not corresponding to the $\pi^-\pi^0$ channel, is shown in the histogram of Fig. 7, where the irregularity in the 1-BeV region is quite clearly seen. Thus, we can regard it as established that the irregularity in the 1-BeV region which has been disclosed on the histogram of Fig. 3, is due to reaction (3). Two explanations can be proposed for this irregularity.

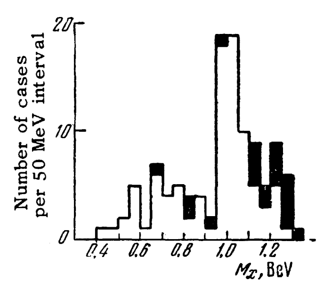

FIG. 7. Histogram of events pertaining to the $\pi^-\pi^0\pi^0$ channel.

The first consists of an assumption that resonance was observed; then we must assign to it an isospin $T \geq 1$, a half width 60 ± 20 MeV, and a mass 1.00 ± 0.01 BeV. The cross section for the production of this resonance, determined by comparison with the cross section for the production of the ρ^- meson, was $\sigma = 0.16 \pm 0.05$ mb with 0.2—0.4 BeV/c momentum transfer to the proton. If such a resonance exists, then it should be observed in reactions with hydrogen having different isospin projections, namely in reactions with production of $\pi^+\pi^+\pi^-$, $\pi^+\pi^0\pi^0$, $\pi^0\pi^0\pi^0$, $\pi^-\pi^+\pi^0$, and others.

An analysis of the experiments performed at energies close to 2.8 BeV has shown that in all the published reports the detection of the resonance was made difficult by one cause or another. In fact, Maglic [5] investigated the combinations $\pi^+\pi^+\pi^-$ and $\pi^-\pi^-\pi^+$ in the annihilation of an antiproton into five pions. If we assume that the cross section for the production of the resonance at 1 BeV should correspond in this case to the cross section for $\pi^-\pi^0\pi^0$ production, then the resonance could not be different from a statistical peak. Selove [6] does not present a distribution for the $\pi^-\pi^0\pi^0$ system. Alff et al. [7] studied the reactions on a π^+ meson beam. According to Carmony et al. [8] the resonance at 1 BeV should be located close to the creation threshold.

Among the investigations with light nuclei, resonance in the 1 BeV region was first observed by Shalamov and Grashin [9] in a freon bubble chamber; the authors assigned it to the two-pion system $\pi^-\pi^0$.

Another possibility of explaining the irregularity was suggested by V. V. Vladimirskiĭ and B. L. Ioffe. It is based on the fact that the observed peak could be imitated by reaction $\pi^- + p \rightarrow N^*_{3/2} + \rho$.

It is known [5] that the $\pi^- + p \rightarrow N^*_{3/2} + \rho$ reaction has a rather large cross section. For our case there are no published data. On the other hand, if the reaction $\pi^- + p \rightarrow N^*_{3/2} + \rho^-$ does take place, and the ρ^- meson is produced aligned (i.e., the spin projection of the ρ meson which is emitted at a small angle to the direction of the primary pion in the direction of its motion is equal to zero), then the isobar should also be produced "aligned." The phase curves plotted for the case of complete "alignment" are shown in Fig. 5 (curves III and IV). The curve III pertains to the case with fixed masses of ρ and $N^*_{3/2}$ (0.75 and 1.24 BeV, respectively) and without account of the instrument geometry. Curve IV corresponds to decay with allowance for the ρ-meson width $\Delta m = 150$ MeV. We see that the latter curve is a rather sharp peak in the mass region of 1 BeV. Attention should be called to the similarity between the theoretical and experimental curves, which is manifest in a rapid rise on one side and a smoother descent on the other. Since there is no information at present concerning the angular distribution of the ρ^- mesons in the reaction $\pi^- + p \rightarrow N^*_{3/2} + \rho^-$, we were unable to estimate the contribution of this reaction to the peak on the histogram of Fig. 3.

Thus, in collisions between 2.8 BeV/c π^- mesons and protons a peak is observed in the distribution of the residual masses in the region of 1 BeV. If we assume that the contribution of the simultaneous production of the isobar and of the ρ^- meson is small, then we can conclude that in this region there is observed a resonance in the $\pi^-\pi^0\pi^0$ system with mass 1.00 ± 0.01 BeV, half width 60 $\pm$ 20 MeV, isospin $T \geq 1$, and cross section $\sigma = 0.16 \pm 0.05$ mb in the 0.2–0.4 BeV/c region of momentum transfer to the proton.

The second result of the work is that the cross section for the production of the ρ^- meson in the $\pi^- + p \rightarrow p + \rho^-$ reaction amounts to $\sigma = 0.3 \pm 0.07$ mb in the region of momentum transfer 0.2–0.4 BeV/c to the protons.

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