π^0-MESON PRODUCTION IN A NUCLEAR COULOMB FIELD

V. V. BARMIN, Yu. S. KRESTNIKOV, E. V. KUZNETSOV, A. G. MESHKOVSKIĬ, Yu. P. NIKITIN, and V. A. SHEBANOV

Institute of Theoretical and Experimental Physics, Academy of Sciences, U.S.S.R.

Submitted to JETP editor May 17, 1962

J. Exptl. Theoret. Phys. (U.S.S.R.) **43**, 1223-1230 (October, 1962)

A xenon bubble chamber is used to investigate the creation of π^0 mesons by 2.8-BeV/c π^- mesons in the Coulomb field of the xenon nucleus ($\pi^- + \mathrm{Xe} \to \pi^- + \pi^0 + \mathrm{Xe}$). The cross section for this reaction with outgoing π^- mesons in the angular range $3° \le \theta \le 30°$ is $\sigma_c = 4.4 \pm 1.6$ mb. The angular distribution has a sharp peak in the region $\theta < 10°$. A relation is derived between the cross section σ_c and the cross section for the photoprocess $\gamma + \pi^- \to \pi^- + \pi^0$, which is thus calculated to have the average value 0.6 ± 0.2 mb in the interval $4m^2 \le w^2 \le 21m^2$ (w is the total energy of created mesons in their c.m.s.).

1. INTRODUCTION

SEVERAL recent theoretical papers [1-3] have considered a special type of inelastic interactions between a high-energy particle and a nucleus acting as a whole. These coherent interactions are characterized by very small momentum transfer to the nucleus and by the absence of any nuclear excitation. Several specific mechanisms have been proposed. For example, Pomeranchuk and Shmushkevich [1] and Good and Walker [2] have regarded a coherent interaction between a particle and a nucleus as an exchange of virtual photons. In another paper Good and Walker [3] discussed coherent processes in diffraction scattering on nuclei.

The present work was undertaken to detect and investigate experimentally a special case of coherent interaction in which a primary pion dissociates into two pions:

$$\pi^- + N_Z^A \to \pi^- + \pi^0 + N_Z^A. \tag{1}$$

This reaction can only occur through interaction of the pion with the Coulomb field of a nucleus N_Z^A, since the diffraction dissociation $\pi \to 2\pi$ is forbidden by angular momentum conservation and G parity. [3] The cross section for the process (1) is proportional to Z^2 and the energy threshold for heavy nuclei is about 1 BeV. In the present investigation we used π^- mesons having the momentum 2.8-BeV/c and impinging on xenon nuclei ($Z = 54$, $A = 131$).

We are aware of only one previous attempt [4] to study particle dissociation experimentally. With 14-BeV π^- mesons only one event was observed, which can be interpreted as the dissociation of a pion into three pions in the Coulomb field of an emulsion nucleus. From this single case the upper limit of the cross section for the $\pi \to 3\pi$ process is estimated at ~ 8 mb for a lead nucleus.

It is important to note that the cross section for particle production in a Coulomb field can be related to the cross section for the corresponding photoprocess. [1] Thus under certain conditions we can expect the experiments to furnish information regarding cross sections for interactions between γ quanta and unstable particles. Specifically, an investigation of the reaction (1) will enable a calculation of the cross section for the reaction

$$\gamma + \pi^- \to \pi^- + \pi^0. \tag{2}$$

2. THEORY

If the reaction (1) satisfies the condition

$$q^2 \ll m^2 A^{-2/3}, \tag{3}$$

where q^2 is the invariant square of the momentum transferred to the nucleus, m is the pion mass, and A is the atomic weight, the principal contributions to the amplitude of (1) come from diagrams associated with virtual photon exchange (Fig. 1). The differential cross section $d\sigma_c$ for (1) can then be determined by the Weizsäcker–Williams method: [1]

$$d\sigma_c = \frac{Z^2\alpha}{\pi}\frac{dw^2}{w^2 - m^2}\frac{dq^2}{(q^2)^2}\left[q^2 - \left(\frac{w^2 - m^2}{2E_L}\right)^2\right]|F(q^2)|^2 d\sigma_p(w). \tag{4}$$

Here w is the total energy of the two pions produced through (1) in their c.m. system, E_L is the

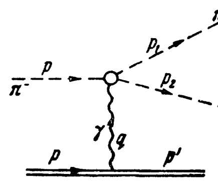

FIG. 1

π^- energy in the laboratory system before the collision, F is the electric form factor of the nucleus, and $d\sigma_p$ is the cross section for the photoprocess (2).

Following [1], we integrate (4) over q^2 and w^2 within the limits

$$[(w^2 - m^2)/2E_L]^2 \leqslant q^2 \leqslant m^2/A^{2/3} \text{ and } 4m^2 \leqslant w^2 \leqslant m^2 + (2E_L/A^{1/3}),$$

assuming that $\sigma_p(w)$ does not vary much and without introducing the form factor. We thus obtain

$$\sigma_c = \frac{Z^2\alpha}{\pi}\bar{\sigma}_p\left[\ln^2\frac{2E_L}{3mA^{1/3}} - \ln\frac{2E_L}{3mA^{1/3}} + \frac{1}{2} - \frac{(3mA^{1/3})^2}{2\,(2E_L)^2}\right], \quad (5)$$

where $\bar{\sigma}_p$ is the average cross section for (2) in the given interval of w^2.

A prerequisite of the Weizsäcker–Williams method is the condition $\ln(2E_L/3mA^{1/3}) \gg 1$ in (5). However, for the xenon nucleus and the relatively low energy $E_L = 20\,m$ the logarithmic term in (5) equals ~ 1, so that this formula is correct only in order of magnitude. Thus the energy value 2.8 BeV lies only at the beginning of the interesting region of cross sections for interactions between γ quanta and unstable particles.

We improve the Weizsäcker–Williams approximation by introducing the form factor[1)]

$$F(q^2) = 1/(1 + q^2R^2/6), \quad (6)$$

where $R = A^{1/3}/m$ is the nuclear radius ($\hbar = c = 1$). In this case the effective value of the transferred momentum is $q \lesssim \sqrt{6}/R$, which amounts to $\sim m/2$ for the xenon nucleus, i.e., about 70 MeV/c. The condition $q < m/2$ is less rigorous than previously; in this case the pion can penetrate more deeply into the nucleus, since the process (1) will occur in a spatial region having a radius $> R/\sqrt{6}$. Thus the contribution of nuclear forces to (1) will generally be comparable to the Coulomb contribution. However, for the nuclear mechanism the essential region is $q \lesssim m$; we can consider that strong interactions still do not predominate over the Coulomb effect when $q < m/2$. Indeed, it will follow from our experiment that for $q < 70$ MeV/c and for scattered π^- angles $< 10°$ the effect depending on Z^2 is dominant.

We now integrate (4) using the form factor (6) and the new limits

$$[(w^2 - m^2)/2E_L]^2 \leqslant q^2 \leqslant 6m^2/A^{2/3},$$

$$4m^2 \leqslant w^2 \leqslant m^2 + (2E_L m\sqrt{6}/A^{1/3}). \quad (7)$$

For the xenon nucleus and our value of the energy we obtain the desired relation between the cross sections for (1) and (2):

$$\sigma_c \simeq 7.5\bar{\sigma}_p, \quad (8)$$

where $\bar{\sigma}_p$ is the average cross section for $\gamma + \pi^- \to \pi^- + \pi^0$ in the interval $4m^2 \leq w^2 \leq 21m^2$. In integrating, we assumed that $\sigma_p(w)$ varies very little in this interval.

The maximum angle of pion emission θ_{max} corresponding to the limit of q must now be determined. A kinematic calculation gives

$$\text{tg}\,\theta_{max} = w\,[(w^2 - 4m^2)/(4m^2E_L^2 - w^4)]^{1/2}, \quad (9)*$$

whence for $w^2 = 21m^2$ we obtain $\theta_{max} = 30°$ in our case. Thus in our experiment we must select events with pion emission angles less than 30° for $q < 70$ MeV/c.

3. MEASUREMENT PROCEDURES AND TREATMENT OF RESULTS

A two-liter xenon bubble chamber [5] operated without a magnetic field was irradiated with a 2.8-BeV/c beam of π^- mesons from the proton synchrotron of the Joint Institute for Nuclear Research. About 10,000 stereoscopic photographs were scanned independently by three different persons, who searched for pion scattering in the angular range 3–30° accompanied by two electron-positron conversion pairs directed from the scattering point ($\pi^0 \to 2\gamma$ decay). We selected only events where the sole track emerging from the scattering point was that of the scattered π^- meson. It was difficult to detect π^- scattering at angles smaller than 3°.

The aforementioned selection criteria are, of course, an insufficient basis for assigning events to the reaction (1) and to small momentum transfer. The selected events could also be interpreted, for example, as π^0 creation resulting from a nuclear interaction where for some reason the photographs reveal no tracks of protons or other charged particles coming from the nucleus (e.g., only neutrons emerge). Another possibility is the reaction $\pi^- + n \to \pi^- + \pi^0 + n$ with small momentum transfer to a quasi-free nuclear neutron. An additional possible interpretation is the crea-

1)This possibility was pointed out to us by I. Ya. Pomeranchuk.

*tg = tan.

tion of two π^0 mesons, for each of which only one γ quantum was converted. In other words, our selected events must consist of the sought effect and a nuclear background.

The following kinematic selection procedure was adopted in order to determine the background. We write the relation

$$\mathbf{p} = \mathbf{p}_1 + \mathbf{p}_2 + \mathbf{p}_3 + \mathbf{q}. \quad (10)$$

in the laboratory system. Here $\mathbf{p}$ and $\mathbf{p}_1$ are the initial and final π^- momenta, $\mathbf{p}_2$ and $\mathbf{p}_3$ are the momenta of the two γ quanta from the decay of the created π^0 meson, and $\mathbf{q}$ is the momentum transferred to the nucleus. A coordinate axis is directed parallel to the momentum $\mathbf{p}$, and (10) is written for the axes as follows:

$$\begin{aligned} a_1p_1 + a_2p_2 + a_3p_3 &= p - a_4q, \\ b_1p_1 + b_2p_2 + b_3p_3 &= -b_4q, \\ c_1p_1 + c_2p_2 + c_3p_3 &= -c_4q, \end{aligned} \quad (11)$$

where a_i, b_i, and c_i are the direction cosines of the corresponding vectors. In each case a stereoprojector was used to determine the spatial orientations of $\mathbf{p}_1$, $\mathbf{p}_2$, and $\mathbf{p}_3$. All direction cosines in the left-hand sides of the equations (11) were thus determined experimentally and were known quantities.

The solution of the system (11) for p_1, p_2, and p_3 is given by

$$p_i = p_i' (1 - \Delta_i q/\delta_i p), \ i = 1, 2, 3, \quad (12)$$

where p_i' is a solution of

$$\begin{aligned} a_1p_1 + a_2p_2 + a_3p_3 &= p, \\ b_1p_1 + b_2p_2 + b_3p_3 &= 0, \\ c_1p_1 + c_2p_2 + c_3p_3 &= 0, \end{aligned} \quad (13)$$

Δ_i is a determinant derived from the principal determinant of (13) by replacing the i-th column with the column (a_4, b_4, c_4); δ_i is a minor of the principal determinant formed by striking out the first row and the i-th column and thus has only known direction cosines as its elements.

We now analyze the solution (12) for two cases.

1. We have at least one $p_i' < 0$. Then, since $p_i > 0$, we obtain $(1 - \Delta_i q/\delta_i p) < 0$, whence $q/p > \delta_i/\Delta_i$. The determinant Δ_i is composed of the direction cosines, i.e., $|\Delta_i|$ is the volume of the parallelepiped constructed on the unit vectors. Consequently, $|\Delta_i| \leq \sin\varphi_i$, where φ_i is the angle between a vector pair $(\mathbf{p}_2, \mathbf{p}_3)$, $(\mathbf{p}_1, \mathbf{p}_3)$, or $(\mathbf{p}_1, \mathbf{p}_2)$. Thus $q/p > \delta_i/\Delta_i > \delta_i/\sin\varphi_i$, whence

$$q > \frac{\delta_i}{\sin\varphi_i} p. \quad (14)$$

The right-hand side of the inequality (14) contains experimentally determined quantities. Thus, if the system (13) has negative solutions, the lower limit q_{min} of transferred momentum can be determined from (14). When $q_{min} > 70$ MeV/c the event must be rejected; when $q_{min} < 70$ MeV/c the event must be retained, since we can then not exclude the possibility of small momentum transfer.

2. We have all $p_i' > 0$. This means that the solution of (13) is physically meaningful, i.e., small momentum transfer is possible even if it cannot be calculated. Additional selection criteria for positive solutions were: a) energy balance; b) $\varphi_1 > \varphi_{min}$, where φ_1 is the angle between the vectors $\mathbf{p}_2$ and $\mathbf{p}_3$, and φ_{min} is the minimum possible angle between the two γ quanta for the given calculated π^0 momentum; c) the probability of having the angle φ_1 between the γ quanta is not under ~ 0.05 for the given φ_{min}.

The foregoing procedure will obviously select the following classes of events: 1) the sought π^0-meson creation in the nuclear Coulomb field, 2) nuclear interactions with small momentum transfer, and 3) nuclear interactions with large momentum transfer accidentally simulating small transfer for our selection criterion. The existence of the last class of events was proved as follows. We observed and measured a few events clearly involving large momentum transfer, in which small-angle π^- scattering was accompanied by three or four γ quanta, i.e., at least two π^0 mesons were created. From these events 18 arbitrary combinations of two γ quanta were formed and subjected to the foregoing calculation procedure. Three of the 18 combinations satisfied all selection criteria, i.e., they simulated small momentum transfer.

In order to determine the number of remaining background cases (the number of nuclear interactions involving small momentum transfer and the simulating events) we proceeded as follows. The same 2.8-BeV/c π^- beam was used to irradiate a freon bubble chamber [6] having the average $Z^2 = 136$ for the mixture. Since π^0 production in a Coulomb field is proportional to Z^2, we can expect that the Coulomb effect in a freon chamber will be at least 20 times smaller than in a xenon chamber. Therefore all events in freon that were observed and selected by our procedure must belong to the background. We shall show that under certain assumptions this background can be calculated from the results obtained with xenon.

4. RESULTS AND DISCUSSION

We scanned 9723 stereoscopic photographs of the xenon chamber showing a total of 8007 inelastic interactions, and 9928 stereoscopic photographs of the freon chamber containing 22,226 inelastic interactions. The xenon chamber yielded 48 instances of π^- scattering in the angular range 3–30° accompanied by two electron-positron pairs directed from the scattering point; the freon chamber yielded 31 such events.

All these events were measured with a stereoprojector and calculations were performed as described above. The average accuracy of angular measurements was $\pm 1°$. For xenon 33 events give negative solutions of the equations (13); 22 of these give $q_{min} > 70$ MeV/c and were rejected, leaving 11 events. For one of the other 15 events in xenon the angles could not be measured; this event was retained. Positive solutions of (13) were obtained for 14 events, one of which did not satisfy an additional criterion (having an improbable angle between the two γ quanta); the other events were retained. Thus 25 events in xenon were left. Following the kinematic analysis 13 out of 31 events in freon were left.

The true number n of events required to calculate the cross section σ_c for the reaction $\pi^- + Xe \rightarrow \pi^- + \pi^0 + Xe$ was determined from the formula

$$n = \frac{n_1}{\eta_1} - \frac{n_2 N_1}{\eta_2 N_2}, \quad (15)$$

where n_1, η_1, and N_1 are the number of observed events, the registration efficiency for two γ quanta from the decay of a single π^0 meson, and the total number of inelastic interactions in the scanned photographs for xenon; n_2, η_2, and N_2 are the analogous quantities for freon. The registration efficiency was computed for each event from the measured "potential lengths" and were then averaged, yielding $\eta_1 = 0.57$ and $\eta_2 = 0.33$.

Obviously, the number of true events can be calculated from (15) only if it is assumed that the cross section for nuclear reactions of the type $\pi^- + N_Z^A \rightarrow \pi^- + \pi^0 + N_Z^{A'}$ with small momentum transfer is proportional to the cross section for all inelastic interactions of π^- mesons with nuclei. This hypothesis is supported by the experimental results for the reactions $\pi^- + p \rightarrow m\pi^0 + n$ (with the average $m = 2$) involving quasi-free protons of xenon or of the freon mixture and 2.8-BeV/c π^- mesons. The yields were $(0.50 \pm 0.20)\%$[2)] for xenon, and $(0.93 \pm 0.10)\%$[7] for freon, of all inelastic interactions. Thus the relative yields from the reaction $\pi^- + p \rightarrow m\pi^0 + n$ were approximately equal for light and heavy nuclei. Moreover, this hypothesis with the given method of background subtraction does not introduce a large error into our results, because the background was very small in the angular range accounting for most of the production cross section in a Coulomb field. This can be seen in the accompanying table giving the angular distribution of all events left following the kinematic analysis.

The table shows that the background (i.e., n_2N_1/η_2N_2) is only about 10% in the interval 3–10°, but increases greatly in the interval 10–30°. Thus most of the effect depending on Z^2 is concentrated in the small-angle region. This is especially clear in Fig. 2a, which shows the angular dependence of the differential cross section for the reaction $\pi^- + Xe \rightarrow \pi^- + \pi^0 + Xe$ that was calculated from our data. For comparison Fig. 2b gives the analogous dependence for light nuclei in the freon mixture (normalized to the results in xenon). Figure 2b shows that the angular distribution does not tend to rise sharply at small angles in the case of light nuclei, where the Coulomb effect is negligible.

π^--meson scattering angle, deg	n_1	n_2	n_1/η_1	n_2N_1/η_2N_2	n
3–10	12	2	21.0	2.2	18.8
10–17	7	7	12.3	7.6	4.7
17–24	4	1	7.0	1.1	5.9
24–30	2	3	3.5	3.3	0.2

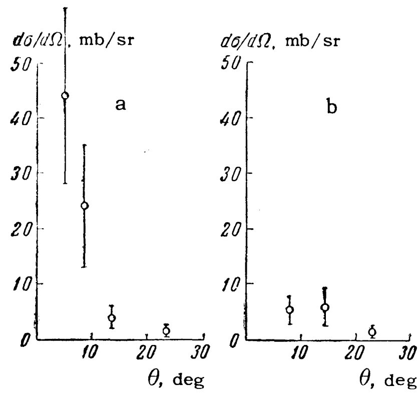

FIG. 2. a – differential cross section for π^0-meson production in the Coulomb field of the xenon nucleus: $\pi^- + Xe \rightarrow \pi^- + \pi^0 + Xe$; b – nuclear background for the same reaction from measurements on the freon mixture. θ is the π^--meson scattering angle.

It is also interesting to compare the angular distributions in xenon of events selected and excluded by our kinematic analysis. This comparison is shown in Fig. 3 in relative units for the number of events per unit solid angle. The distribution of excluded events is nearly isotropic, whereas the distribution of selected events ex-

[2)]Measured by E. V. Kuznetsov.

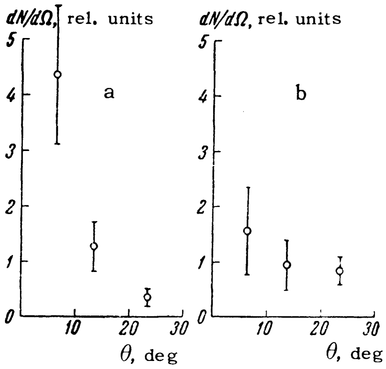

FIG. 3. Angular distribution of all events in xenon (per unit solid angle): a – events left following the kinematic analysis; b – excluded events. θ is the π^--meson scattering angle.

hibits a sharp peak at small angles. This further confirms the efficiency of the procedure developed for selecting Coulomb events, especially since the corresponding angular distributions for selected and excluded events in freon do not differ so strongly.

In the entire investigated angular range 3–30° the reaction $\pi^- + \text{Xe} \to \pi^- + \pi^0 + \text{Xe}$ accounts for the fraction $n/N_1 = (3.7 \pm 1.3) \times 10^{-3}$ of all inelastic interactions. In order to calculate σ_c we must know the total cross section σ_{inel} for inelastic interactions between 2.8-BeV/c π^- mesons and nuclei. This cross section, which is not known from experiment, was calculated on the optical model of a nucleus with nonuniform nucleonic density.[8] From the result $\sigma_{\text{inel}} = 1200$ mb we obtain $\sigma_c = 4.4 \pm 1.6$ mb.

A somewhat larger value of σ_c is calculated from the xenon-freon difference, disregarding the kinematic selection procedure, as follows. The scanning of freon photographs detected at least seven π^0 creation events in which a proton was ejected having an energy of about 10 MeV. These events were, of course, not included in the statistics. However, protons having this amount of energy cannot be emitted from xenon nuclei because of the Coulomb barrier; therefore similar events in xenon must have been included in the statistics when proton tracks were not detected by scanning. Charged-particle ranges in the xenon chamber are shorter than in the freon chamber; therefore a low-energy proton track might be detected in the freon photographs but not in the xenon photographs. These and other reasons could account for the fact that the number of nuclear events in freon appeared disproportionately smaller than in xenon. We therefore used the kinematic analysis in order to obtain more reliable results than from the difference method alone.

Equation (8) can be used to calculate the cross section for the reaction $\gamma + \pi^- \to \pi^- + \pi^0$. The result, $\bar{\sigma}_p = 0.6 \pm 0.2$ mb, is greater than $\sigma_p \cong e^2/m^2 = 0.15$ mb, which can be expected in the energy region where $\pi\pi$ resonances are absent. The large value of σ_p very possibly indicates the effect of $\pi\pi$ resonances. Indeed, the limit $w^2 = 21m^2$ is very close to the ρ resonance region. In addition, it has recently been indicated that $\pi\pi$ resonance can exist for $w^2 = 17m^2$.[9] It is therefore of considerable interest to analyze π^0 creation events in nuclear Coulomb fields with respect to the value of w, in order to obtain a functional relation $\sigma_p(w)$. This cannot be done in the present work because of our small statistics and the large errors involved in calculating w. It would also be very interesting to perform experiments with pions > 10 BeV; in this case the Weizsäcker–Williams approximation could furnish more reliable results for calculating γ-π interaction cross sections.

We are greatly indebted to I. Ya. Pomeranchuk for valuable discussions, to V. P. Rumyantseva for assistance, and to Yu. D. Bayukov, G. A. Leksin, and Ya. Ya. Shalamov, who found the number of squares with the desired events on some of the freon photographs.

[1] I. Ya. Pomeranchuk and J. M. Shmushkevich, Nuclear Phys. **23**, 452 (1961).

[2] M. L. Good and W. D. Walker, Phys. Rev. **120**, 1855 (1960).

[3] M. L. Good and W. D. Walker, Phys. Rev. **120**, 1857 (1960).

[4] Baldassarre, Caforio, Ferraro, Ferilli, Merlin, Perkins et al, Nuovo cimento **21**, 459 (1961).

[5] E. B. Kuznetsov and I. Ya. Timoshin, PTÉ No. 4, 40 (1959).

[6] Blinov, Lomanov, Meshkovskiĭ, Shalamov, and Shebanov, PTÉ No. 1, 35 (1958).

[7] Ya. Ya. Shalamov and V. A. Shebanov, JETP **39**, 1232 (1960), Soviet Phys. JETP **12**, 859 (1961).

[8] Cronin, Cool, and Abashian, Phys. Rev. **107**, 1121 (1957).

[9] Barloutaud, Heughebaert, Leveque, Meyer, and Omnes, Phys. Rev. Letters **8**, 32 (1962).

Translated by I. Emin
215