HIGH PARTIAL WAVES IN THE PHOTOPRODUCTION OF π^0 MESONS ON PROTONS

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The angular distribution of π^0 mesons produced on protons by 181 ± 10 MeV photons was measured. The π^0 mesons were detected by counting coincidences between the two decay photons using scintillation counter telescopes. A comparison of the data with the results of calculations based on the one-dimensional dispersion relations shows a discrepancy which may indicate that resonance meson states contribute to the process under consideration.

1. INTRODUCTION

BALDIN and one of the authors of the present article[1,2] found a marked discrepancy between the experimental data on the π^0-meson photoproduction on protons and the solutions of the integral equations obtained in the static limit from one-dimensional dispersion relations for the amplitude of this process.[3] In this connection it is interesting to compare directly the experimental results with the exact dispersion-relation prediction [3,4] by substituting experimental data into the left- and right-hand sides of the equations. The first attempts of such a comparison met with difficulties.[1,2] However, a more accurate calculation removed the discrepancy to a great extent.[5,6] The remaining difference can be interpreted as due to a contribution from resonance meson interactions represented by diagrams a and b in Fig. 1 (see, e.g., [7]). It should be noted, however, that the uncertainty of the estimate of the dispersion integrals is of the same order of magnitude as the contribution of the resonance meson states to the photoproduction amplitude. It is therefore necessary to increase considerably the accuracy of the experiments over the whole energy range to estimate correctly the effects of the diagrams in Fig. 1.

Another way to assess these effects is to find such experimental quantities which can be calculated without the necessity of taking the dispersion integrals into account. In principle, this could be done by studying the high multipole amplitudes of π-meson photoproduction in the range of not too high energies. This is due to the peripheral character of the diagrams in Figs. 1a and 1b, the role of which increases with increasing orbital quantum number l, as compared to diagrams involving a nucleon or a nucleon and a meson in the intermediate state.

The study of π^0-meson photoproduction on protons near the threshold represents one of the ways to estimate the contribution of the processes under consideration. In this energy range the cross section for the process $\gamma + p \rightarrow p + \pi^0$ is considerably less than the cross section for $\gamma + p \rightarrow n + \pi^+$, while the possible contributions of the diagrams in Figs. 1a and 1b to both cross sections are of the same order of magnitude. In addition, in the π^0-meson photoproduction there is no contribution from a direct photon interaction between the photon and the charged meson, which imposes additional requirements on the accuracy of the experimental data on the π^+-meson photoproduction.

In the present article we describe an accurate measurement of the angular distributions of the π^0-meson photoproduction on protons near the threshold, and give an analysis of the results from the point of view of the effects discussed above.

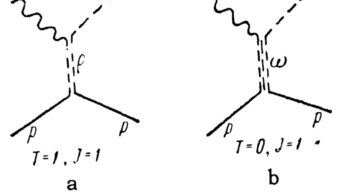

FIG. 1. Diagrams of interaction processes involving resonance states (J and T are the total angular momentum and isotopic spin of the intermediate particle).

2. EXPERIMENTAL METHOD

The experiments were carried out with the Physics Institute synchrotron with an arrangement which permitted us to detect simultaneously the two photons from the π^0-meson decay. A diagram of the experiment is shown in Fig. 2.

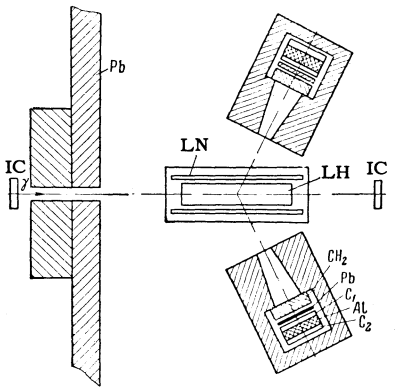

FIG. 2. Diagram of the experiment: IC – ionization chambers, LH – liquid hydrogen, LN – liquid nitrogen.

As a source of primary photons we used the bremsstrahlung from the accelerator. The synchrotron operation was chosen such that the maximum magnitude of the magnetic field in the magnet gap corresponded at the accelerator target to an accelerated-electron energy equal to 200 MeV. The duty cycle of the synchrotron was stretched to ~ 1000 msec to lower the chance coincidence counting rate. This caused the energy of the accelerated electrons at the target to vary within the limits of 196–200 MeV.

The collimated bremsstrahlung photon beam impinged on a liquid-hydrogen target made of foamed polystyrene. The background counting rate from the empty target amounted to 10% of the counting rate of $\gamma\gamma$ coincidences with full target.

The relative measurements of the primary photon beam incident on the target were carried out using two thin-walled ionization chambers placed in the beam before and after the hydrogen target. Absolute measurements of the beam were carried out by two methods: a) using a quantometer and b) by determining the induced activity in carbon-containing material [through the $C^{12}(\gamma, n)C^{11}$ reaction], placed at the center of the target. Both measurements gave results coincident within 6%.

To detect the π^0 mesons we chose the method of registering the coincidence of the two pion-decay photons. The photons were detected by two scintillation counter telescopes of the type described earlier[8], placed in the plane making an angle θ_π with the primary photon beam.

The angle θ_π determined the mean value of the angle of emission of the detected π mesons. The angle ψ between the telescopes determined the mean energy of the detected π^0 mesons. Because of the strong dependence of the energy of the produced π mesons on the angle of emission θ_π, the angle ψ was chosen for each angle θ_π in such a way that the mean energy of the detected mesons corresponded to a primary-photon energy of 181 MeV. The measurements were carried out using simultaneously three telescope pairs placed at three different angles θ_π.

Because of the strong dependence of the π-meson energy on the angle of emission, the spectrum of the π^0-decay photons incident on the telescopes was different for different θ_π. Thus, it was necessary to know the variation of the detection efficiency with the photon energy $\eta(E_\gamma)$. This was determined in a separate experiment consisting in the following: a lead target in which electron-positron pairs were produced was placed in the collimated bremsstrahlung beam from the synchrotron. Electrons of a given energy E_0 were selected from the beam by means of a magnetic field. The electrons produced in a second thin lead target placed in their path a bremsstrahlung photon with energy E_γ. A γ telescope, whose efficiency had to be determined, was placed in the path of the bremsstrahlung photons. The spectrum of the electrons from the second target was again analyzed by a magnet, and the electrons with a given energy E_e were detected by a telescope consisting of two scintillation counters. The γ telescope and the e telescope were connected in coincidence. The coincidence counting rate represented the detection by the γ telescope of photons with energy $E_\gamma = E_0 - E_e$ and the ratio of the γe coincidences to the number of electrons detected by the e telescope gave the detection efficiency of the γ telescope for photons of a given energy E_γ. The energy resolution of the system amounted to ~ 1%. The measured energy dependence of the photon detection efficiency of the γ telescope used in the main measurements of the angular distribution in π^0-meson photoproduction is shown in Fig. 3. A detailed description of the method of the γ-telescope efficiency determination was given earlier.[9]

In addition to the principal measurements, additional experiments were carried out to determine the counting rate of chance coincidences of the two

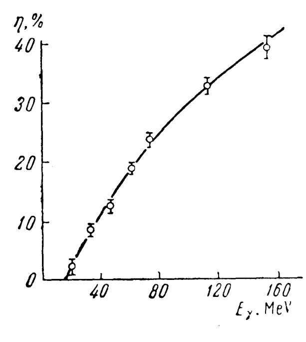

FIG. 3. Variation of the detection efficiency of the γ telescope with the photon energy.

γ telescopes and the contribution to the $\gamma\gamma$ coincidences from charged particle pairs. The experiments showed that the contribution from charged particle pairs is negligible. The rate of chance coincidences amounted to $\sim 3\%$ of the effect for π meson emission into the forward hemisphere; for emission into the backward hemisphere the correction could be neglected.

3. EXPERIMENTAL RESULTS

As a direct result of the experiments we obtained the yield, i.e., the number of $\gamma\gamma$ coincidences per unit primary photon beam intensity for six different angles θ_π. From the yields we determined the differential photoproduction cross section using Eq. (1) from our earlier paper.[8] For this it was necessary to know the quantity $\epsilon(\theta_\pi, \varphi_\pi, E_\gamma)$ representing the detection efficiency for π^0 mesons emitted in the direction θ_π, φ_π (in the l.s.) and produced by a photon of energy E_γ. The function $\epsilon(\theta_\pi, \varphi_\pi, E_\gamma)$, which determines also the energy and angular resolution of the system, was calculated by the Monte Carlo method using the Physics Institute electronic computer. The method of calculating $\epsilon(\theta_\pi, \varphi_\pi, E_\gamma)$ was described in detail in [10].

The energy resolution $dN(E_\gamma)/dE_\gamma$ for the mean π^0-meson emission angle of 25.8° in c.m.s. is shown in Fig. 4. It can be seen from the figure that the mean energy of detected π mesons corresponds to the energy of primary photons equal to 181 ± 10 MeV. Similar results were obtained for all remaining angles θ_π. In the same figure the l.s. angular resolution $dN(\cos\theta_\pi)/d\cos\theta_\pi$ of the system is also shown for mean angles of π^0-meson emission in this system equal to 19.3, 90, and 153.8°. An analysis shows that the angular resolution is determined mainly by the kinematics of the process and is little affected by the geometry of the measurements.

The measured differential cross sections of the process investigated are shown in Fig. 5 as a function of the π^0-meson emission angle in the c.m.s. The errors shown include the statistical errors of

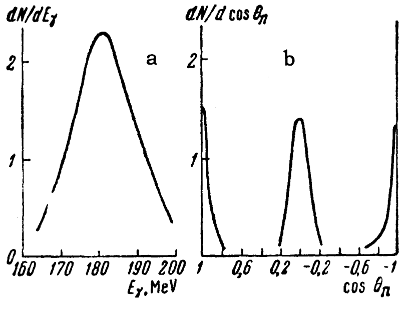

FIG. 4. Energy (a) and angular (b) resolution of the system.

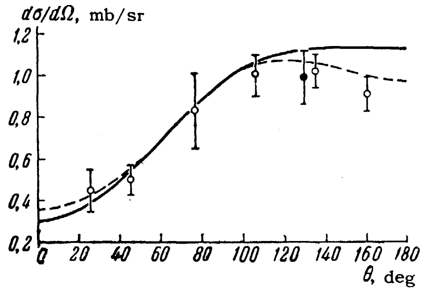

FIG. 5. Differential cross sections of the π^0 meson photoproduction on protons at E_γ = 181 ± 10 MeV.

the yield and errors in the value of $\epsilon(\theta_\pi, \varphi_\pi, E_\gamma)$ calculated by the Monte Carlo method. The black point in the figure represents the results of a measurement of the differential cross section at 135° by the emulsion method.[11] It can be seen that there is a good agreement of this result with our data.

4. DISCUSSION OF RESULTS

It is interesting to compare the obtained angular distribution with the results of the dispersion-relation calculations. The dashed curve in Fig. 5 is the result of calculation of the differential cross section of the $\gamma + p \rightarrow p + \pi^0$ process according to the formula

$$d\sigma/d\Omega = A + B\cos\theta + C\cos^2\theta + D\cos^3\theta \qquad (1)$$

with coefficients A, B, C, and D obtained in [6] neglecting the contribution of resonance meson states. The presence of the factor D is due to the photoproduction of mesons in a state with $l = 2$ (D wave). As can be seen from Fig. 5, the calculated and experimental cross sections are in good agreement. However, the contribution of the D wave due to the recoil of the proton and of the isobar was not fully taken into account in [6]. The fact that the authors of [6] limit themselves to the first two terms in the expansion of the invariant photoproduction amplitude F_i ($i = 1, 2, 3, 4$) in terms of powers of $\cos\theta$ ($F_i = \Sigma_k F_{ik} \cos^k\theta$) is equivalent to neglecting a substantial part of the contribution of states with $l = 2$ to the amplitude F_1.

We therefore calculated from the one-dimensional dispersion relations the quantity $F_{12} = F_{12}^B + \delta F_{12}^{(+)}$, where the first term represents the pole term, and the second the dispersion integral. The calculations were carried out using the same assumptions as in [6]. The dispersion integral was calculated in the pole approximation for the resonance amplitude $M_{1+}^{3/2}$. From a comparison of the results of the calculations given in Table I with Table II taken from [6] we can see that the ampli-

Table I. Amplitude F_{12} [in units of $(\hbar/\mu c) \times 10^{-3}$; W and M are respectively the total energy in c.m.s. and the nucleon mass in units $\hbar = \mu = c = 1$, where μ is the π-meson mass]

$W - M$	1	1,1	1,2	1,3	1,4	1,5
$\delta F_{12}^{(+)}$	0	—0.00869	—0.0200	—0.0343	—0.0521	—0.0718
F_{12}	0	—0.258	—0.530	—0.813	—1.110	—1.423

Table II. Angular distribution coefficients (in mb/sr) for the π^0 meson photoproduction on protons at 181 MeV

n*	A	B	C	D
3	0.93±0.08	—0.32±0.05	—0.33±0.13	—
4	0.90±0.08	—0.51±0.18	—0.26±0.13	0.28±0.26
Dispersion theory	0.94	—0.41	—0.25	—0.006

*n is the number of parameters in the approximation of the differential cross section by Eq. (1).

tude F_{12} is comparable with the amplitudes F_{21}, F_{31}, and F_{40}; this should manifest itself strongly in effects in which the determining role is due to partial waves with $l = 2$ and, in particular, in the magnitude of the factor D. As can be seen from Table I, the contribution of the dispersion integral to the amplitude F_{12} amounts to 4—5% only. This, on the one hand, justifies the use of the pole approximation in the calculation and, on the other, illustrates the claim made above concerning the possibility of decreasing the uncertainty in the higher-multipole amplitudes due to the evaluation of the dispersion integrals.

The solid line in Fig. 5 represents the variation of the differential cross section with θ, calculated taking the amplitude F_{12} into account. It can be seen that a more accurate account of the D wave leads to a discrepancy between the calculated and experimental values of the differential cross sections at large π^0-meson emission angles, and to a worse fit at small angles.

We therefore analyzed the data shown in Fig. 5 to obtain information on the π^0-meson production in a state with $l = 2$. This was done by determining the coefficient D in Eq. (1). Using the least-squares method, we obtained the values of the coefficients A, B, C, and D given in Table II.

An analysis of the data, limited to the three first terms of Eq. (1), leads to values of the coefficients which agree, within the limits of statistical errors, with the results of our earlier article[12], in which the angular distributions were measured by detecting only one photon from the π-meson decay.

In the last row of Table II are given the values of the angular distribution coefficients obtained from one-dimensional dispersion relations (the calculations included the amplitude F_{12}). The values of the coefficients C and D given in [6] change when the amplitude F_{12} is taken into account. The coefficient C decreases in absolute value by 10%; the greatest variation, however, is in the coefficient D, which decreases in absolute value by a factor of 20 and changes sign. A more accurate calculation, involving terms up to $\cos\theta$ in the amplitude expansion, does not change the conclusion that D is small. It can be seen from Fig. 2 that the accuracy of the basic experimental data was insufficient for an exact determination of the D-wave.

It should be noted, however, that some discrepancies between the experimental result and the calculations remain, both in the coefficient D and in the graph in Fig. 5. If we interpret these discrepancies in terms of contributions from diagram a in Fig. 1, then we obtain negative values for the constant Λ of the $\gamma\pi\rho$ interaction.[1)]

In order to find the contribution of high-multipole amplitudes to the π^0-meson photoproduction at higher primary-photon energies, we analyzed the angular distribution near the $(3/2, 3/2)$ resonance, obtained in [14] and summarized in [15].

[1)]After the present article had been written, we received a preprint[13] containing the results of exact measurements of differential cross sections for the $\gamma + p \to n + \pi^+$ reaction, which give a value $\Lambda = -(1.2 \pm 0.4)$ ef.

Table III. Angular distribution coefficients (in mb/sr) and the total cross section σ_t for the process $\gamma + p \rightarrow p + \pi^0$ in the energy range 270—400 MeV

Photon energy, MeV	A	B	C	D	σ_t, mb
270	16.5±1.0	—1.1±2.0	—11.3±2.6	2.1±4.4	160±3
295	23.3±0.5	—1.2±1.2	—15.5±1.1	0.9±2.2	228±3
320	27.3±0.8	0.9±2.9	—16.9±1.9	2.0±4.7	272±3
360	21.1±0.5	—1.1±1.5	—14.4±1.3	4.6±2.7	205±2
400	13.8±0.5	—0.8±1.2	—10.4±1.0	3.6±2.1	130±2

The results of a four-parameter approximation of the differential cross section are given in Table III.

It can be seen from Table III that the factor D is positive over the whole energy range under consideration. At present we can only say that it is different from zero at energies > 360 MeV. More exact measurements of the differential cross sections at small (< 30°) and large (> 150°) angles of emission of the π^0 meson are necessary to reach more definite conclusions. Also needed are calculations based on the dispersion theory of differential cross sections in the region of the ($^3/_2$, $^3/_2$) resonance, with the D wave taken into account.

The analysis of our data, using the three-term approximation of the angular distribution, gives results for the coefficients A, B, and C which agree with those given in [15], but the total cross sections calculated according to the equation $\sigma_+ = 4\pi(A + C/3)$ are 7% smaller than the cross sections given in [15]. This is manifest in the π-meson photoproduction amplitude calculated from the experimental data.

CONCLUSIONS

The main results of the present work are:

a) More accurate data on the angular distribution of the $\gamma + p \rightarrow p + \pi^0$ process near threshold.

b) More accurate calculations based on one-dimensional dispersion relations (with the amplitude F_{12} taken into account).

c) The detection of some discrepancy between the experiment and the dispersion-theory calculations without account of the resonance meson states. We tend to interpret this discrepancy as an indication that the resonance interactions contribute to the process investigated. For more definite conclusions it is necessary to carry out more precise measurements of the differential cross section of the π^0-meson photoproduction on protons and more exact calculations based on the dispersion theory.

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[1] A. M. Baldin and B. B. Govorkov, Nucl. Phys. **13**, 193 (1959).

[2] A. M. Baldin, JETP **38**, 579 (1960), Soviet Phys. JETP **11**, 416 (1960). A. M. Baldin, Proc. 1960 Ann. Intern. Conf. on High-Energy Physics at Rochester, Rochester Univ., 1961, p. 325.

[3] Chew, Goldberger, Low, and Nambu, Phys. Rev. **106**, 1345 (1957).

[4] Logunov, Tavkhelidze, and Solov'ev, Nucl. Phys. **4**, 427 (1957); A. A. Logunov and B. M. Stepanov, DAN SSSR **110**, 368 (1957), Soviet Phys. Doklady **1**, 552 (1957).

[5] A. M. Baldin and A. I. Lebedev, Reports Presented to the All-Union Conference on Elementary Particle Theory, October 61, Uzhgorod, pp. 28 and 94; A. M. Baldin and A. I. Lebedev, Nucl. Phys. (in press).

[6] J. S. Ball, Phys. Rev. **124**, 2014 (1961).

[7] Gourdin, Lurie, and Martin, Nuovo cimento **18**, 198 (1960).

[8] Govorkov, Denisov, and Minarik, JETP **42**, 1010 (1962), Soviet Phys. JETP **15**, 699 (1962).

[9] Agafonov, Govorkov, Denisov, and Minarik, PTÉ **5**, 47 (1962).

[10] S. P. Denisov, Preprint FIAN, A-154, 1962.

[11] L. J. Koester and F. E. Mills, Phys. Rev. **105**, 1900 (1957).

[12] Vasil'kov, Govorkov, and Gol'danskiĭ, JETP **37**, 11 (1959), Soviet Phys. JETP **10**, 7 (1960).

[13] Robinson, Baum, Crigee, and McKinley, Preprint, Illinois, 1962.

[14] D. C. Oakley and R. L. Walker, Phys. Rev. **97**, 1283 (1955); McDonald, Peterson, and Corson, Phys. Rev. **105**, 577 (1957).

[15] K. Berkelman and J. A. Waggoner, Phys. Rev. **117**, 1364 (1959).

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