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PHOTOPRODUCTION OF NEUTRAL π MESONS ON HYDROGEN BY γ QUANTA WITH ENERGY BETWEEN THE THRESHOLD AND 240 Mev

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The angular distribution of neutral π mesons produced on hydrogen by γ quanta with energy between the threshold and 240 Mev have been investigated. The energy dependence of photoproduction was studied employing the method of a multichannel analysis of the data of the monitor and of the counters recording single decay γ quanta during an expanded synchrotron pulse. The angular distribution of the π^0 mesons in the c.m.s. has the form given by Eq. (2), which signifies that the photoproduction of neutral π mesons occurs not only in the P but also in the S state. The experimental data on the contribution of the S state are in agreement with the results of the calculations based on Watson's[16] and Feld's[22] theories and makes it possible to estimate the contribution of the direct π^0 meson photoproduction processes and the "intranucleon charge exchange" of π^+ mesons in the S state.

1. INTRODUCTION

THE photoproduction of π^0 mesons on protons has recently been subject to a series of investigations[1-6] because of its importance for the theory of the meson-nucleon interaction. However, the majority of sufficiently accurate measurements[4-6] were carried out for an energy of primary γ quanta higher than 260 Mev, far from the threshold of π^0-meson photoproduction (145 Mev). In the cited experiments, it was found that the main contribution to the total cross section σ_p of the reaction

$$\gamma + p \rightarrow \pi^0 + p \tag{1}$$

is due to the process associated with the production of an intermediate isobaric (excited) nucleonic state $^3/_3$, $^3/_2{}^+$ with total and isotopic spins $^3/_2$ and positive parity. The isobaric state $^3/_2$, $^3/_2$ corresponds to the production of the meson in the form of a P wave and principally to M1 absorption of γ quanta in the photoproduction. The angular distribution of π^0 mesons should then be described by the two-term formula $d\sigma/d\Omega = 2 + 3\sin^2\theta$, as has been found in reference 4.

In the energy range close to the meson photoproduction threshold, relatively accurate measurements were carried out essentially in one experiment only, that of Koester and Mills.[2] In this experiment, the total cross sections σ_p of process (1) were measured, and it was found that, near the threshold (up to the energy of $\sim$ 180 Mev), σ_p varies as $\tilde{q}^3$, where $\tilde{q}$ is the c.m.s. momentum of the π^0 meson. An analysis of the obtained data based on the theory of Chew and Low[7] confirmed the important role of the ($^3/_2$, $^3/_2{}^+$) state in reaction (1) also in this energy range. Koester and Mills also obtained information regarding the asymmetry in the S state of the angular distribution of π mesons with respect to the direction of 90° due to the photoproduction of π^0 mesons at energies close to the threshold.

A rather strong production of mesons in the S state takes place in the photoproduction of charged π mesons, owing to a straight E1 interaction of γ quanta with the meson cloud. Although an electromagnetic interaction of γ quanta with the $\pi^0 p$ system should also take place (as was indicated by Fermi[8]), it is still markedly weaker than for $\pi^+ n$ and $\pi^- p$ systems, since, in the first case, the classical radius of the charge carrier, the proton, amounts to $\mu/M \sim 0.15$ of the corresponding value for $\pi^\pm$ mesons. The contribution of photoproduction in the S state for π^0 mesons is therefore much weaker than for $\pi^\pm$ mesons. In the case of the π^0 meson, the bulk of photoproduction in the S state is due not to the straight process of π^0 production but to the production of $\pi^\pm$ mesons with subsequent internal charge exchange.

The effect of π^0 production in the S state should be especially clearly observed in angular distributions near the production threshold. The presence of a small S wave in the production of π^0 mesons should lead to an asymmetry of angular distributions due to the interference between the S wave and the predominating P wave, so that the angular distribution for energies close to the threshold should be described by a three-term formula

$$d\sigma/d\Omega = A + B\cos\theta + C\cos^2\theta, \quad (2)$$

in which the coefficients A, B, and C are determined by the contribution of the different variants (E1, M1, and E2) of the absorption of γ quanta. It is the purpose of the present work to establish the energy dependence of the coefficient A, B, and C near the photoproduction threshold of π^0 mesons, which will make possible to draw a series of conclusions about the mechanism of photoproduction in this energy range.

2. METHOD OF OBSERVATION OF π^0 MESONS

In principle, five methods of observation of the process (1) are possible:

1) Detection of single γ quanta from π^0 meson decay.

2) Detection of single recoil protons.

3) Detection of coincidences of one of the decay γ quanta and the recoil proton.

4) Detection of coincidences of the two decay γ quanta.

5) Detection of coincidences of the two decay γ quanta and the recoil proton.

The small cross section for process (1) for energies close to the π^0 photoproduction threshold, and also the small magnitude of the energy of recoil protons, have determined the choice of the first of the methods listed above for this work. If the cross section for the photoproduction of π^0 mesons in the c.m.s. for a given energy of the primary quantum is given by formula (2) (see Appendix), then the counting rate of γ quanta at an angle θ_γ in the laboratory system (l.s.) per single proton and unit intensity of the incident flux of primary photons is given by the equation

$$N(\theta_\gamma) = \int_{E_{min}}^{E_{max}} N(\theta_\gamma, E_\gamma)\,\eta(E_\gamma)\,dE_\gamma = a(\theta_\gamma)A + b(\theta_\gamma)B + c(\theta_\gamma)C, \quad (3)$$

where E_γ is the energy of the decay γ quantum in the l.s.;

$$E_{min} = (1 - \tilde{\beta})\frac{\tilde{\varepsilon}}{2\gamma_c(1 - \beta_c\cos\theta_\gamma)},$$

$$E_{max} = (1 + \tilde{\beta})\frac{\tilde{\varepsilon}}{2\gamma_c(1 - \beta_c\cos\theta_\gamma)};$$

$\eta(E_\gamma)$ is the efficiency of detection of γ quanta with energy E_γ:

$$N(\theta_\gamma, E_\gamma) = \frac{2}{\tilde{q}\gamma_c(1-\beta_c\cos\theta_\gamma)}\Big\{A + B\left(\frac{\cos\theta_\gamma - \beta_c}{1-\beta_c\cos\theta_\gamma}\right) \times\left[\frac{1}{\tilde{\beta}} - \frac{\mu^2}{2\tilde{q}\gamma_c(1-\beta_c\cos\theta_\gamma)E_\gamma}\right] + C\Big\{\frac{\sin^2\theta_\gamma}{2\gamma_c^2(1-\beta_c\cos\theta_\gamma)} + \frac{3}{2}\left[\frac{1}{\tilde{\beta}} - \frac{\mu^2}{2\tilde{q}\gamma_c(1-\beta_c\cos\theta_\gamma)E_\gamma}\right]^2 \times\left[\left(\frac{\cos\theta_\gamma-\beta_c}{1-\beta_c\cos\theta_\gamma}\right)^2 - \frac{1}{3}\right]\Big\}\Big\}; \quad (4)$$

$\beta_c = h\nu/(h\nu + M)$ is the velocity of the c.m.s. in the l.s., and

$$\tilde{\varepsilon} = (2Mh\nu + \mu^2)/2(2Mh\nu + M^2)^{1/2},$$
$$\tilde{q} = (\tilde{\varepsilon}^2 - \mu^2)^{1/2}, \quad \tilde{\beta} = \tilde{\varepsilon}/\tilde{q}$$

are the energy, momentum, and velocity of the π^0 meson in the c.m.s. respectively.

Thus, the measured counting rate of single photons from π^0 decay can be correlated with the angular coefficients of Eq. (3).

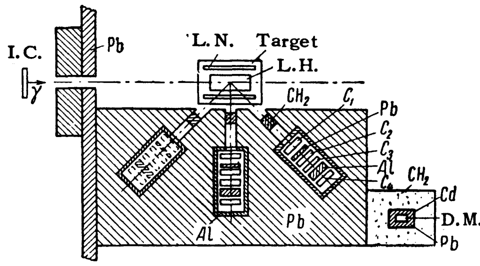

FIG. 1. Schematic diagram of the array. L. H. – Liquid hydrogen, L. N. – liquid nitrogen, I. C. – ionization chamber, D. M. – differential monitor, C_1, C_2, C_3, C_4 – scintillation counters.

3. METHOD OF MEASUREMENT

The experiments were carried out using the 265-Mev synchrotron of the Physics Institute of the U.S.S.R. Academy of Sciences, using the array shown in Fig. 1. Single γ quanta from the decay of π^0 mesons were detected by two telescopes consisting of four scintillation counters (of the type described earlier[9]). The telescopes were set up simultaneously at the angles 90° and 135° or 45° and 90° in the l.s. The length of the synchrotron pulses was stretched to 3000 μsec by a gradual lowering of the amplitude of the accelerating high-frequency voltage, and, during that time, the value of the magnetic field around the position of the synchrotron target was considerably varied, correspondingly changing the maximum energy of the bremsstrahlung spectrum. During each such stretched synchrotron pulse, detector pulses due to the decay γ quanta were fed, as described by us in reference 10, to five channels of a time analyzer, set and checked according to the intensity of the magnetic field through the use of this method. We determined in each measurement the yield of the decay γ quanta for five maximum bremsstrahlung energies simultaneously at both angles.

Apart from the counts of the telescopes that detected the decay γ quanta, the counts of the differential monitor (a single scintillation counter placed in the field of the scattered γ quanta) were fed to a multichannel analyzer. The measurements were carried out for seven maximum bremsstrahlung energy values in various channels, 130, 150, 170, 190, 210, 230, and 250 Mev.

The quantity measured in the experiments was the ratio of the observed numbers of decay γ quanta and the number of counts of the differential monitor for three angles of 45°, 90°, and 135° at the energies given above. To obtain from these data the energy dependence of the decay γ quanta yield at any of the angles, the dependence of the counting rate of the differential monitors per unit photon flux on the maximum bremsstrahlung energy was taken into account. The dependence of the monitor counting rate on the maximum bremsstrahlung energy and on the pulse intensity was determined with a good ($\sim 1\%$) statistical accuracy in special experiments discussed in reference 10, which is specially devoted to the present experimental method. The corrections for this dependence are the same for measurements at any angle, and in practice do not influence the measured angular distribution of the decay γ quanta.

To obtain the angular distributions of decay γ quanta from the experimental ratios of their counting rates at various angles, a correction was introduced for these angles for the difference of the product of the effective target volume by the acceptance solid angle of the telescope. This difference was assessed by comparing the counting rate of decay γ quanta during the irradiation of a polysterene "point" source and of a continuous foamed polystyrene target having the dimensions of the hydrogen target. To obtain absolute values of the volume, a correction was applied for the difference of the mean flux of the γ quanta on the surface of the target and on the "point" source. The correction for the not 100%-efficient detection of the anticoincidences by the γ telescope amounted to a fraction of one percent. Also of the same order magnitude were the corrections due to the delayed detection by the differential monitor of the slow neutrons. Both these corrections were neglected in view of their small magnitude.

The liquid hydrogen used in the experiments was contained in a hydrogen target of foamed polystyrene PS-4 (cooled by nitrogen) of cylindrical shape, 12 cm in diameter and 30 cm long. The γ quanta beam from the cyclotron, 6 cm in diameter, was incident upon the base of the cylinder. The background counting rate (from an empty target) amounted, on the average, to 30% (at 45°), 8% (at 90°), and 4% (at 135°) of the counting rate in the main experiments.

The absolute flux of γ quanta incident on the target was determined from the activation of specially calibrated graphite detectors in the $C^{12}(\gamma n)C^{11}$ reaction.

4. RESULTS OF THE EXPERIMENTS

The curves of the energy dependence of the relative yield of decay γ quanta at the angles of 45°, 90°, and 135°, with all the above-mentioned corrections made, are shown in Fig. 2.

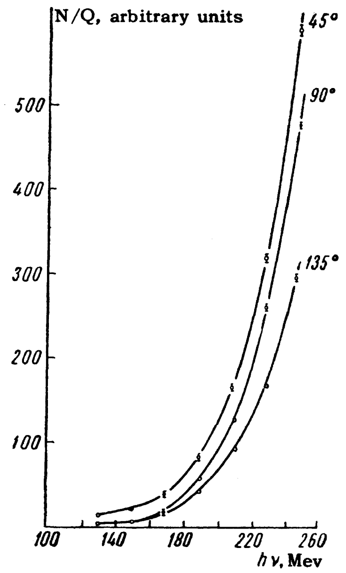

FIG. 2. Energy dependence of gamma yield of π^0-meson decay for 45°, 90°, and 135° in the l.s.

The cross sections for emission of decay γ quanta in the l.s. were obtained from these curves by means of the photon difference method, and were then compared with the values of $N(\theta_\gamma)$ calculated according to Eq. (4), for the determination of the coefficients A, B, and C in Eq. (2). As has been shown by a special analysis, even a rather strong variation of the form of the energy dependence of the detection efficiency of the telescope, $\eta(E_\gamma)$ influences $N(\theta_\gamma)$ very little at various angles for a given energy of the primary γ quanta. In the calculations, we used an efficiency curve for a telescope similar to the one used in the present experiment, as given in reference 1.

$$\eta(E_\gamma) = \alpha\left[1 - \exp\left\{-\left(\frac{E_\gamma - E_{\mathrm{thr}}}{43}\right)\right\}\right],$$

where, in our experiment, E_{thr} = 35 Mev.

The absolute value of α (α = 0.13) was obtained by comparing the yield of γ quanta from the elastic γp scattering for $h\nu$ = 130 Mev, observed at 90°, with a calculated value based on the formula of Powell,[11] which was confirmed by a series of experiments. At present, additional experiments are being carried out to determine the absolute efficiency of detection of γ quanta of various energies by our telescope. The preliminary results of these experiments are in agreement with the calculations. The values of the coefficients $a(\theta_\gamma)$, $b(\theta_\gamma)$, and $c(\theta_\gamma)$ in Eq. (3), calculated for the form of $\eta(E_\gamma)$ given above for various photon energies, are shown in Fig. 3.

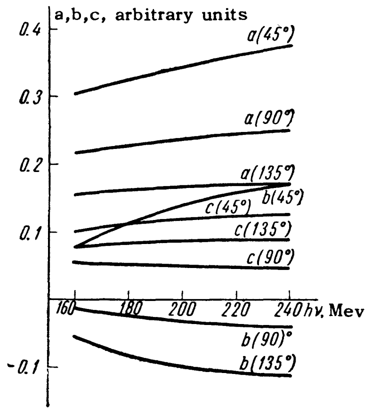

FIG. 3. Dependence of the coefficients $a(\theta_\gamma)$, $b(\theta_\gamma)$, and $c(\theta_\gamma)$ in Eq. (3) on the photon energy.

The obtained values of the coefficients A, B, and C, of the angular distribution, and also the values of the total cross section σ_p of process (1), are given in Table I.

The dependence of the coefficients on the energy of the quanta is shown in Fig. 4. Values of the coefficients obtained in other experiments[3-4] are also given for comparison.

The energy dependence of the total cross section of the photoproduction of π^0 mesons on protons, as

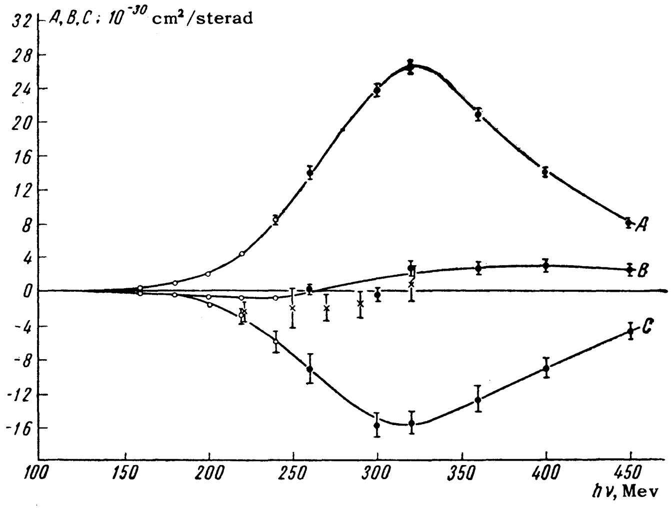

FIG. 4. Coefficients of the angular distribution of π^0 mesons (A, B, and C). o – our data, • – data of reference 4, x – data of reference 3.

obtained from the data of our experiments and from those given in the literature,[2-4] is shown in Fig. 5. It can be seen that the total cross sections obtained in this experiment are in a good agreement with earlier published data. With respect to the data on angular distribution, there is no point in comparing them with the results of previous articles, since the only previously available data on the an-

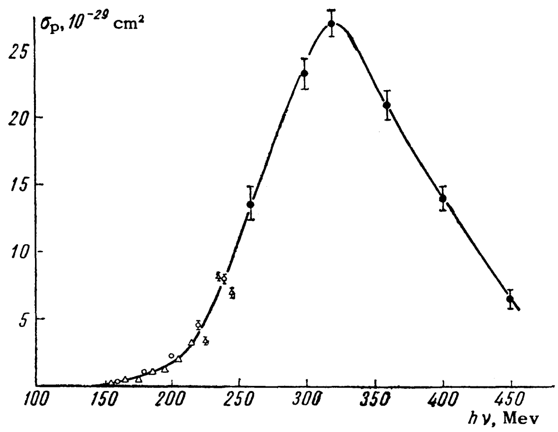

FIG. 5. Energy dependence of total cross sections for the photoproduction of π^0 mesons on protons: o – our data, • – data of reference 4, Δ – data of reference 2.

TABLE I. The measured coefficients A, B, and C (in units of 10^{-30} cm²/sterad) and σ_p (in units of 10^{-29} cm²)

$h\nu$, Mev	A	B	C	σ_p
160	0.28±0.03	0.13±0.03	0.09±0.12	0.31±0.06
180	0.95±0.02	0.39±0.06	0.5 ±0.1	0.98±0.04
200	2.10±0.05	0.56±0.07	1.3 ±0.2	2.08±0.08
220	4.5 ±0.1	0.7 ±0.1	2.9 ±0.4	4.5 ±0.2
240	8.4 ±0.2	0.9 ±0.2	6.0 ±0.6	8.1 ±0.3

gular distribution of π^0 mesons in this energy range were obtained with a much lower accuracy.

The data of the present experiment for higher energies, as well as those of McDonald, Peterson, and Corson,[4] are represented in Fig. 6.

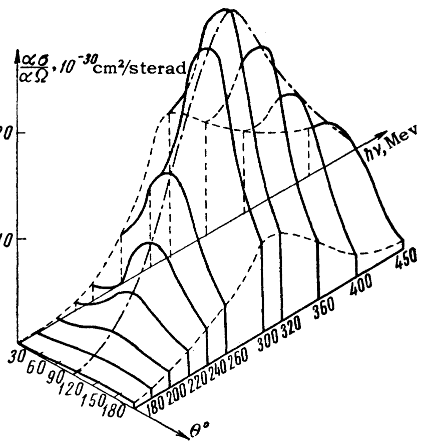

FIG. 6. The form of the angular distribution of π^0 mesons for the reaction $\gamma + p \to \pi^0 + p$ for γ-quanta energy from 160 to 450 Mev.

5. DISCUSSION OF RESULTS

By way of comparison of the obtained data on the energy dependence and the absolute values of coefficients A, B, and C with the corresponding data for π^+ mesons,[12-15] and to take into account the data available in the literature on the photoproduction of π^0 mesons at higher energies,[4-6] a certain phenomenological analysis was carried out by the method of Watson.[16] The basis of such an analysis is the expression of the cross section of the meson-photon production through the matrix elements of electric and magnetic multipole transitions obtained from general angular momentum and parity conservation considerations. In addition, in such an analysis one uses the assumption of the presence of an "amplified" contribution of the isobaric state $(3/3, 3/2^+)$ in the photoproduction of mesons.

In the compilation of the photoproduction of π^+ and π^- mesons near the threshold, we compared the values of the coefficients of angular distributions for various energies of primary γ quanta, corresponding to identical momenta $\tilde{q}$ of produced mesons in the c.m.s. We thus introduced a correction for the difference of the masses of the π^+ and π^0 mesons (based on the fact that the photoproduction cross section is much less dependent on $\tilde{q}$ than on the energy of the primary γ quanta. The results of such a phenomenological analysis are given in Table II.

The parameters in Table II have the following meanings[16]: A_S is the contribution of the S wave to the cross section of photoproduction of π^+ mesons, A_{X_0} is the contribution of the "amplified" P wave that does not interfere with the S wave, A_{K_0} is the contribution of the "amplified" P wave interfering with the S wave, A_{Δ_1} is the contribution of the "non-amplified" P wave not interfering with the S wave, and A_{P^+} is the contribution of the P state to the isotropic part (A^+) of the angular distribution of the photoproduction of π^+ mesons. The values of these parameters were then used for the calculation of the ratio of the coefficients B/A of the angular distribution of π^0 mesons.

According to reference 16, the coefficient B can be expressed by the formula

$$B = -\tfrac{4}{3}(A_S A_{K_0})^{1/2}\{[\cos(\alpha_{33}-\alpha_3)-\cos(\alpha_{33}-\alpha_1)] + (r+\sqrt{2}\,r_0)[\cos(\alpha_{33}-\alpha_3)+\tfrac{1}{2}\cos(\alpha_{33}-\alpha_1)] - (r+\sqrt{2}\,r_0)(3/8A_{K_0})[A_{K_1}+4A_{\Delta_3}]\}. \quad (5)$$

The quantities A_{K_1} and A_{Δ_3} are small, and we can therefore neglect the last term in Eq. (5). In that energy range where α_1 and α_3 are also small, Eq. (5) reduces to

TABLE II. Results of a phenomenological analysis of the photoproduction of π^0 and π^+ mesons (parameters A given in units of 10^{-30} cm²/sterad)

$h\nu$, Mev	A_S	A_{K_0}	A_{P+}	A_{X_0}	A_{Δ_1} with α_{33}
160	4.6 ±2.4	0.09±0.10	0.4±2.3	0.3±2.5	0.3±0.8
180	5.8 ±0.8	0.22±0.06	1.5±0.6	0.8±0.8	0.7±0.4
200	7.4 ±1.2	0.39±0.07	2.3±1.1	1.6±1.3	1.2±0.7
220	8.0 ±1.1	0.8 ±0.2	5.0±1.0	3.0±1.2	1.8±0.7
240	8.9 ±1.1	1.2 ±0.3	7.2±1.0	4.9±1.1	2.0±0.6
260	7.1 ±1.4	2.4 ±0.9	9.9±1.3	7.3±1.4	1.9±0.8
300	7.25±1.3	4.0 ±0.8	11.7±1.2	10.8±1.3	—0.2±0.8
320	5.8 ±1.3	5.5 ±0.7	12.6±1.2	11.7±1.3	—0.5±0.7
360	5.4 ±1.2	4.1 ±0.8	8.6±1.1	8.8±1.2	—1.3±0.7
400	4.9 ±1.1	2.5 ±0.6	3.8±1.0	5.4±1.1	—2.2±0.6
450	4.5 ±1.0	1.7 ±0.4	1.1±0.9	3.8±1.0	—2 ±0.6

$$B = -{}^4/_3 (A_S A_{K_0})^{1/2} [(\alpha_3 - \alpha_1) \sin \alpha_{33} + {}^3/_2 (r + \sqrt{2} r_0) \cos \alpha_{33}]. \quad (6)$$

The first term in the square brackets in Eq. (6), which contains the scattering phases, can be interpreted as being connected with the production of π^0 mesons in the S state due to "charge exchange" scattering of π^+ mesons in the nucleon field, and the second term is connected with the direct production of π^+ mesons in the S state, due to the photoelectric effect caused by the presence of an electrical dipole moment in the final state.

On the basis of Eq. (6) we can first determine the sum $(r + \sqrt{2}\, r_0)$ for that energy of primary γ quanta for which B (or the ratio B/A) vanishes (i.e., the contributions of the "direct" and the "charge-exchange" photoproduction of π^0 mesons in the S state are equal to each other). It is evident that the following equation is satisfied for that energy:

$$\tan \alpha_{33} = -{}^3/_2 (r + \sqrt{2} r_0) / (\alpha_3 - \alpha_1). \quad (7)$$

As can be seen from the data on the ratio B/A obtained in this work as well as in the experiment of McDonald, Peterson, and Corson,[4] (see Fig. 7), B vanishes for a primary γ-quanta energy of 260^{+20}_{-10} Mev, which corresponds to $(r + \sqrt{2}\, r_0) = 0.140^{+0.080}_{-0.020}$, if we assume Orear's values[17] of the phases of α_3 and of α_1 and Bruekner's values[18] of α_{33}. It should be noted that, using the values of B/A obtained in the work of Goldschmidt-Clermont, Osborn, and Scott,[3] for γ quanta of energy close to threshold we obtain, for B/A = 0, an energy of about 300 Mev; hence, $(r + \sqrt{2}\, r_0) = 0.45$.

From the dispersion relations[19] one can conclude that $r_0 = 0$ and $r = \mu/M = 0.144$ near the meson photoproduction threshold. In addition, the values r and r_0 should, as has been shown by Baldin,[20] be constant in a wide energy range. Thus, the value of $(r + \sqrt{2}\, r_0)_{B=0} = 0.14$ obtained above is in good agreement with the prediction of the field theory. It should be noted that the parameter r is directly related to the threshold ratio of the cross sections of photoproduction of π^- and π^+ mesons on nucleons, $(\sigma_-/\sigma_+)_{thr} = (1 + r)$. Evidently, according to our data $(\sigma_-/\sigma_+)_{thr} = 1.30^{+0.19}_{-0.05}$, while the old data[3] yield $(\sigma_-/\sigma_+)_{thr} \approx 2.1$. The given value of $(\sigma_-/\sigma_+)_{thr}$ is in agreement with the value obtained in the experiments of the Adamovich group.[21] Assuming that $(r + \sqrt{2}\, r_0) = \mu/M =$ const, we calculated the curve of the dependence of the ratio B/A on the energy of γ quanta up to 450 Mev, shown in Fig. 7. It is evident that all the collected experimental data are well described by this curve.

In Fig. 7 are also shown two curves of B/A calculated by Feld[22] on the basis of the semi-phenomenological "atomic" nucleon model. Feld calculated the photoproduction of π^0 mesons in the S state by perturbation theory, but applied a small correction to take into account the final mass of the nucleon and the possibility of a "charge exchange" scattering of π^+ mesons in the nucleon field. In the final expressions for the cross section only the contributions of transition amplitudes leading to the excited isobaric state and to the photoproduction of π^0 mesons in S state were taken into account. The angular distribution of π^0 mesons in the c.m.s. is then obtained in the following form

$$\frac{1}{\sigma_0} \frac{d\sigma}{d\Omega}(\theta) = A_0 + B_0 \times \left[1 - \frac{\tilde{\beta}^2 \sin^2\theta}{2(1 - \tilde{\beta}\cos\theta)}\right] \cos\theta + C_0 \cos^2\theta, \quad (8)$$

where $\sigma_0 \approx 25\tilde{q}$ microbarn/sterad. The value in Eq. (8) is proportional to the sum $(\xi_r \cos \alpha_{33} + \xi_i \sin \alpha_{33})$, where ξ_r and ξ_i are respectively the real and imaginary parts of the electrical dipole amplitude of π-meson photoproduction. The factor in the square brackets of the second term in Eq. (8) is due to the role of the higher multipoles in the photoproduction of $\pi^\pm$ mesons (retarded effects).

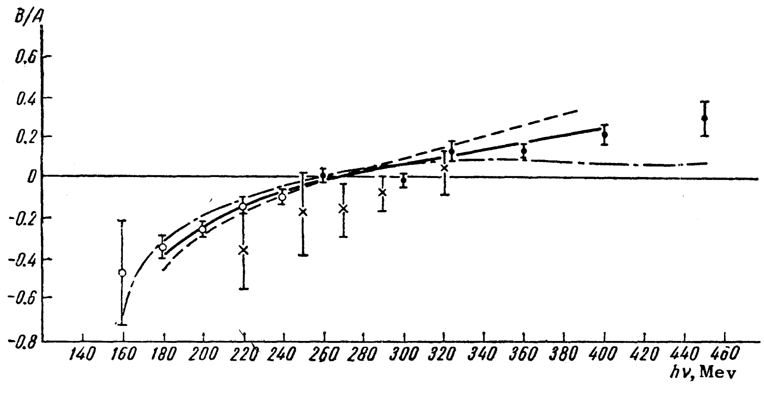

FIG. 7. Ratio of the coefficients B/A. Experimental data: o – our data, ● – data according to reference 4, × – data of reference 3; dash-dot line – calculated according to the method of Watson,[16] solid and dotted lines – according to the theory of Feld,[22] taking into account and neglecting the "retardation" effects respectively.

After averaging over the angles of the factor due to "retarding," Feld obtained the relations of the coefficients of the usual three-term development in the form

$$\frac{B}{A}=\frac{B_0}{A_0}\left[1-\frac{\tilde{\beta}^2}{4\,(1-\tilde{\beta}^2/2)}\right], \qquad (9)$$

$$\frac{C}{A}=\frac{C_0}{A_0}-\frac{B_0}{A_0}\frac{\tilde{\beta}^3}{4\,(1-\tilde{\beta}^2/2)}. \qquad (10)$$

As can be seen from Fig. 7, our experimental data are in excellent agreement with the theoretical curves [solid curve corresponds to B/A, dotted line to B_0/A_0 obtained from Eq. (9)], which testifies in favor of the applicability of perturbation theory to calculations of the photoproduction of mesons in the S state near the threshold. The ratio of the real part (direct photoproduction) to the imaginary part (charge-exchange production) of the photoproduction amplitude of π^0 mesons in the S state in the energy range under consideration is close to unity $\xi_r/\xi_i \approx -0.8/\tilde{q}$.

In Fig. 8 we present experimental results, and calculated curves for the ratio C/A according to Feld's theory. For a pure M1 transition, C/A $= -0.6$. However, as has been mentioned in reference 22, the presence of a small electric-quadrupole contribution (E2) leads to a considerable variation of this ratio. The effects of "retardation" affect this ratio very little up to 300 Mev. As can be seen from Fig. 8, the experimental accuracy of all results obtained is still insufficient to reach a conclusion about the contribution of E2 absorption to meson-photon production. At present, a comparison of the obtained data with the predictions of dispersion relations[19] is being carried out. The results of this analysis will be published in the future.

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APPENDIX

KINEMATIC DISCUSSION OF THE REGISTRATION OF PROCESS (1) FROM THE OBSERVATION OF A SINGLE DECAY PHOTON

We shall write the angular distribution of the π^0 mesons in the photoproduction c.m.s. in the form $F(\theta_\pi, E_\pi)\,dE_\pi$. The number of mesons emitted as a result of reaction (1) at the angle θ_π with energy E_π into solid angle $d\Omega_\pi$ is equal to

$$F\,(\theta_\pi,\,E_\pi)dE_\pi \sin\theta_\pi\, d\theta_\pi\, d\varphi_\pi. \qquad (11)$$

If the decay $\pi^0 \rightarrow 2\gamma$ is isotropic in the rest system of the π^0 mesons, the number of decay γ quanta emitted into the solid angle $d\Omega_\gamma$ at the angle θ_γ to the direction of the mesons in the laboratory system is given by

$$F\,(\theta_\pi,E_\pi)dE_\pi \sin\theta_\pi\, d\theta_\pi\, d\varphi_\pi\, \frac{1}{2\pi}\, \frac{1-\tilde{\beta}^2}{1-\tilde{\beta}\cos\theta_\pi} \sin\theta_n\, d\theta_n\, d\varphi. \qquad (12)$$

The angles are identified in Fig. 9.

Taking into account that γ quanta emitted within the solid angle $d\Omega_\gamma$ can be produced by π^0 mesons going on the surface of a cone with opening angle θ_γ, depending on the energy of the π^0 mesons, we should integrate the expression (12) over the angle φ and the meson energy E_π. Since the energy of the π^0 mesons in the c.m.s. of photoproduction for a given energy of the primary γ quantum ($h\nu$) should be expressed by a δ function, therefore we obtain by integrating (12)

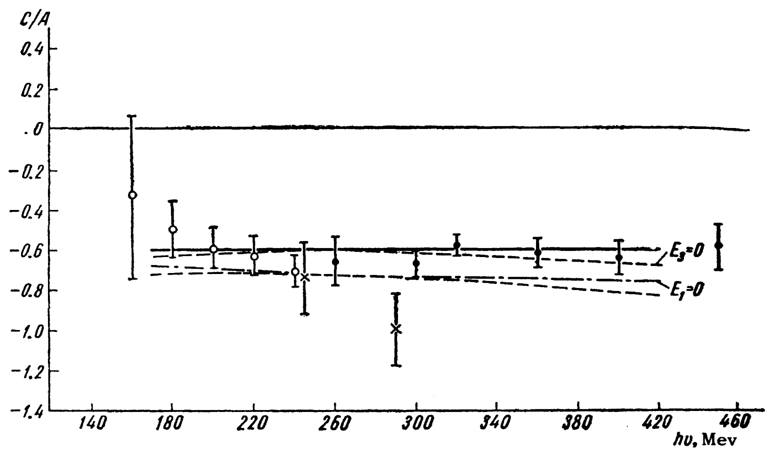

FIG. 8. Ratio of coefficients C/A. o – our data, × – data of reference 3, • – data of reference 4; the upper solid curve corresponds to C/A = – 0.6; lower curves – obtained from the theory of Feld.

$$W(E_\gamma, \theta_\gamma) = \frac{1}{\pi}\int_0^{2\pi} F(\theta_\pi)\frac{d\varphi}{\sqrt{E_\pi^2 - \mu^2}}. \tag{13}$$

The formulae for the transformation from the π^0 meson rest system to the c.m.s. of photoproduction readily relate the angle θ_γ with the energy of the π^0 mesons and the decay γ quantum:

$$\cos\theta_\gamma = (E_\pi - \mu^2/2E_\gamma)/\sqrt{E_\pi^2 - \mu^2}. \tag{14}$$

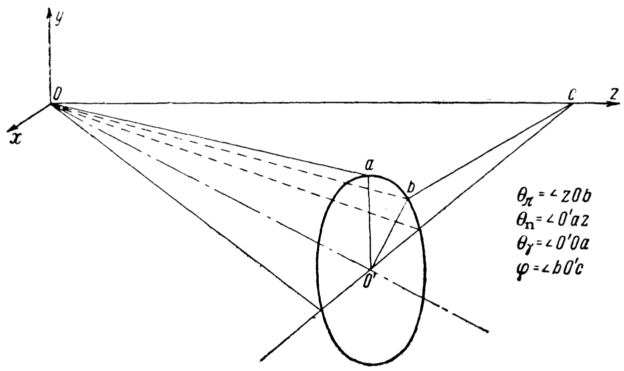

FIG. 9

On the other hand, it is easy to obtain from Fig. 9 the following relation between the angles

$$\cos\theta_\pi = \cos\theta_\gamma\cos\theta_n + \sin\theta_\gamma\sin\theta_n\cos\varphi. \tag{15}$$

Going now over to the laboratory system of coordinates, we obtain Eq. (4).

[1] G. Cocconi and A. Silverman, Phys. Rev. **88**, 1230 (1952).

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

[3] Goldschmidt-Clermont, Osborn, and Scott, Phys. Rev. **97**, 188 (1955).

[4] McDonald, Peterson, and Corson, Phys. Rev. **107**, 577 (1957).

[5] D. Oakley and R. Walker, Phys. Rev. **97**, 1283 (1955).

[6] Walker, Oakley, and Tollestrup, Phys. Rev. **97**, 1279 (1955).

[7] G. Chew and F. Low, Phys. Rev. **101**, 1570 (1956).

[8] E. Fermi, Elementary Particles, Yale University Press, New Haven, 1951.

[9] Govorkov, Gol'danskiĭ, Karpukhin, Kutsenko, and Pavlovskaya, Dokl. Akad. Nauk SSSR **111**, 988 (1956), Soviet Phys. "Doklady" **1**, 735 (1957).

[10] Vasil'kov, Govorkov, and Kutsenko, Приборы и техника эксперимента (Instruments and Measurement Engg.), in press.

[11] J. Powell, Phys. Rev. **75**, 32 (1949).

[12] Beneventano, Stoppini, Tau, and Bernardini, CERN Symposium on High-Energy Accelerators and Pion Physics, Geneva, 1956, page 259.

[13] Walker, Teasdale, Peterson, and Vette, Phys. Rev. **99**, 210 (1955).

[14] Tollestrup, Keck, and Worlock, Phys. Rev. **99**, 220 (1955).

[15] Jenkins, Luck, Palfrey, and Wilson, Phys. Rev. **95**, 179 (1945).

[16] Watson, Keck, Tollestrup, and Walker, Phys. Rev. **101**, 1159 (1956).

[17] J. Orear, Phys. Rev. **96**, 176 (1954); **100**, 288 (1955).

[18] K. Brueckner, Phys. Rev. **87**, 1026 (1952).

[19] Chew, Goldberger, Low, and Nambu, Phys. Rev. **106**, 1344 (1957).

[20] A. M. Baldin, Nuovo cimento **8**, 569 (1958).

[21] Adamovich, Kuz'micheva, Larionova, and Kharlamov, J. Exptl. Theoret. Phys. (U.S.S.R.) **35**, 27 (1958), Soviet Phys. JETP **8**, 21 (1959).

[22] B. Feld, Annals of Phys. **4**, 189 (1958).

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