PHOTOPRODUCTION OF CHARGED PIONS NEAR THRESHOLD

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We have measured the differential cross section for the photoproduction of positively-charged π mesons on hydrogen at photon energies 153 — 175 Mev. We also give the total cross section for the photoproduction of negative π mesons on deuterium. A comparison is made between the experimental and theoretical values for the squares of the matrix elements $|K_p|^2$ and $|K_n|^2$ for the photoproduction of π^+ and π^- mesons on free nucleons. The quantity $|K_n|^2$ is compared with the Panofsky ratio and with the meson-nucleon interaction S-phase shifts. The value of the ratio σ^-/σ^+ has been obtained in the photon-energy range from 153 to 175 Mev.

INTRODUCTION

A large number of experiments have been done on the photoproduction of charged π mesons on nucleons. In most of these the quantity measured was the cross section for meson production at large photon energies. Up to the present time, no measurements have been made on the differential cross section for the photoproduction of π mesons for photon energies in the range 150 to 170 Mev. At these energies, only the total cross section for the photoproduction of positively charged π mesons on hydrogen has been measured.[1] The photoproduction of negative π mesons on deuterium has been studied with nuclear emulsions doped with heavy hydrogen.[2]

A comparison of the experimental data with the results of theoretical calculations[3] has yielded the squares of the matrix elements for the photoproduction of π^- mesons on free neutrons for photon energies in the 153 — 188 Mev range. Extrapolation of these data to lower energies leads to a value for the square of the matrix element at threshold. The method used was that employed by Beneventano et al.[4] to find the threshold value for the square of the matrix element for the photoproduction of π^+ mesons on protons. It is based on an empirical rule valid in the 170 — 250 Mev energy range, and also on the experimental data on photoproduction near threshold obtained by Leiss et al.[1] In a succeeding paper these authors have noted that their earlier results were wrong.[5]

In principle, the threshold value for the square of the matrix element for photoproduction of π^- mesons can be obtained from an investigation of the radiative capture of slow negative π mesons by protons, $\pi^- + p \rightarrow n + \gamma$. However, it would be very difficult to study this reaction directly, because there are two neutral particles in the final state. For this reason it is customary to measure the Panofsky ratio, i.e., the ratio of the probability of scattering with charge exchange to that of radiative capture of negative π mesons. It is uniquely connected with the threshold value of the square of the matrix element for photoproduction of π^- mesons on neutrons, $|K_n|^2$, through the limit of the quantity $|\alpha_3 - \alpha_1|/\eta$ as $\eta \rightarrow 0$. Here α_1 and α_3 are the S-phase shifts for the scattering of mesons in the states with isotopic spin $1/2$ and $3/2$, respectively, and η is the meson momentum in the center-of-mass system.

As is well known,[3] the threshold value of $|K_n|^2$, obtained by extrapolation or from the difference between the S-phase shifts $|\alpha_3 - \alpha_1| = 0.28\,\eta$,[6] disagrees with the directly-measured Panofsky ratio.[7,8] Baldin[3] attempted to explain this discrepancy by assuming the existence of a neutral π_0^0 meson, an isotopic spin singlet. However, it was later shown experimentally that an isotopic scalar meson does not exist. Cini et al.[9] then pointed out that in the extrapolation of Beneventano et al.[4] no account was taken of the direct interaction between the electromagnetic field and the meson current. This contribution to the amplitude for meson photoproduction is described by the so-called "retarded term" and it has a significant effect in the analysis of the experimental data on the photoproduction of charged mesons near threshold. In particular, this "retarded term" contradicts the extrapolation employed and can improve the agreement between data on the photoproduction of π mesons and the Panofsky ratio. To check these aspects of meson theory, it is necessary to measure the cross section for the photoproduction of π^+ mesons near threshold and to improve the statistical accuracy of measurements on the cross section for photoproduction of π^- mesons on deuterium. Good measurements of these quantities would also lead to a value for the ratio of probabilities for production of π^- and π^+ mesons on free nucleons near threshold.

EXPERIMENT

The purpose of the experiment was to find the cross sections for the photoproduction of charged π mesons near threshold:

$$\gamma + p \rightarrow \pi^+ + n, \qquad (1)$$

$$\gamma + n \rightarrow \pi^- + p. \qquad (2)$$

These reactions were investigated on the synchrotron of the Academy of Sciences Physis Institute. The methods used to study the reaction (1) depended on the energy range. To measure the differential cross section of this reaction for photon energies in the 153 — 161 Mev range, a polyethylene film of thickness 0.00905 g/cm^2 was used as a target. Data for hydrogen were obtained by subtracting the background due to photoproduction of π^+ mesons on carbon. To do this, we irradiated a carbon target of thickness 0.0129 g/cm^2 simultaneously with the polyethylene film. This technique was feasible because the Coulomb field inside the carbon nucleus sharply inhibits the production of low energy π^+ mesons. Since we were interested in slow π^+ mesons, thin films had to be used, which eliminated the necessity for making corrections for scattering and energy loss of mesons in the target.

The photon beam was obtained by bremsstrahlung of 263-Mev electrons. The mesons from the target were detected by NIKFI K-400μ nuclear emulsions. Both the emulsions and the targets were in vacuum. The entrance window (100μ Al) was 1 m from the targets and the plates. A magnetic field inside the vacuum chamber was used to filter out electrons from the beam. Lead and carbon blocks shielded the chamber from externally scattered γ rays.

The plates were scanned twice. The average efficiency for detecting mesons was 90%. The total number of π^+ mesons was found by counting the number of the $\pi \rightarrow \mu$ decays for which the μ-meson track ended in the emulsion. The energy of each π^+ meson was found by measuring its residual range; the other quantity measured was the angle between its direction of motion and the photon beam.

The geometry of the experiment was such that the plates would register mesons in the energy range 0.5 to 6 Mev and at angles to the photon beam ranging from 60° to 120° in the laboratory frame of reference. To find the cross section in the center-of-mass system, all the events were sorted out into energy and angle intervals. The values of the cross section were obtained from mean values taken in these intervals.

The table shows the cross section for photon energies in the ranges 152.9 — 158.3 Mev and 158.3 — 161 Mev, and for a c.m.s. mean angle θ = 120°.

To measure the differential cross section of reaction (1) at higher photon energies, the target used was liquid hydrogen in a foamed polystyrol vessel. The π^+-meson detectors were layers of unbacked type NIKFI P-400μ emulsion. The placing of the emulsions depended on the π meson energy.

To detect mesons produced by photons of energy 160 — 165 Mev, the emulsion stack was placed in a small vacuum chamber in the vessel with the hydrogen. The entrance window of the chamber was a brass foil 30μ thick, 6 mm from the axis of the beam. The average angle between the mesons detected and the beam was 78° in the laboratory frame of reference. The target was irradiated by a photon

Eγ, Mev	$10^{30}\,\frac{d\sigma^+}{d\Omega}$ (120°), cm^2/sr (c.m.s.)	$10^{29}\,\sigma_d^-$, cm^2 (l.s.)	$f^2_{\pi^+}$	$f^2_{\pi^-}$
150		1.07±0.25		
156.5	3.4±0.6	4.01±0.57	0.078±0.013	0.077±0.011
159.5	4.2±1.7			
162.5	6.7±1.5		0.089±0.011	
163.5		6.97±0.79		0.082±0.009
167.5	5.94±0.97 (θ = 103°)		0.081±0.009	
170.5		8.98±1.09		0.087±0.01
172.5	7.50±0.58		0.090±0.007	
181		6.68±0.69 ($E_\pi \leqslant$ 30 Mev)		0.085±0.009

beam obtained by stopping 180-Mev electrons.

To measure the differential cross section in the 165 — 175 Mev energy range, the mesons were detected by emulsions placed right in the liquid hydrogen, 2 cm from the axis of the photon beam. The mean angle between the π mesons and the beam was 90°. In this case the energy spectrum of the photons had a maximum at 200 Mev. The plates were scanned and measured as described above.

The table gives the measured values of the differential cross section for the photoproduction of π^+ mesons on hydrogen in the center-of-mass system for mean photon energies 162.5, 167.5, and 172.5 Mev.

In all experiments on reaction (1), the photon energy was measured with an ionization chamber calibrated against the thick-walled graphite chamber used to measure photon intensities.[2]

Data on reaction (2) were obtained by studying the reaction

$$\gamma + d \rightarrow \pi^- + p + p \tag{3}$$

using nuclear emulsions doped with deuterium and irradiated in the photon beam of the synchrotron of the Academy of Sciences Physics Institute. The experiment has been described in detail previously.[2] For the present investigation, the statistical accuracy was increased and several non-essential improvements were made. In particular, the following were taken into account: 1) the detection efficiency (96%)[2]; 2) the increase in the concentration of ordinary water in the heavy water after each doping of the emulsion (this increased the calculated cross sections by 5%); 3) the low efficiency with which the upper 20 and bottom 100μ of the doped emulsion registered the reaction studied.[2]

The table shows the total cross section for reaction (3) for photons in the energy intervals 153 — 160, 160 — 167, 167 — 174 and 174 — 188 Mev. The statistical accuracy here is significantly higher for the more energetic photons, than that previously quoted.[4]

DISCUSSION OF THE RESULTS

Figure 1 shows the experimentally derived values for the squares of the matrix element for photoproduction of π^+ mesons:

$$|K_p|^2 = (\pi/W)\, d\sigma^+/d\Omega.$$

As usual,

$$W = \eta\omega/(1+\omega/M)(1+\nu/M),$$

where η and ω are the c.m.s. momentum and

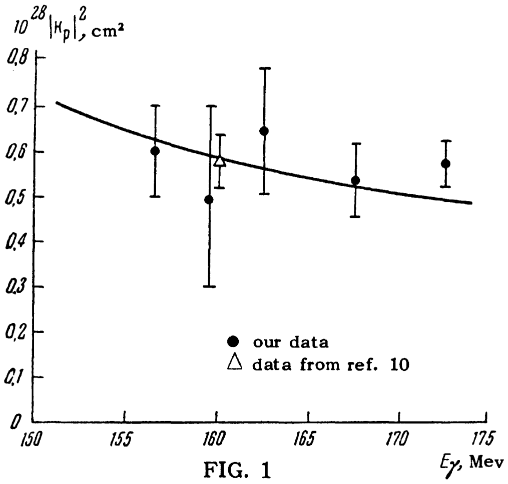

FIG. 1

total energy of the meson, ν is the photon energy, and M is the nucleon mass. The same figure shows the experimental data obtained by Barbaro et al.[10] with the Illinois betatron.

The solid curve on the figure is the theoretical curve $|K_p|^2 = (\pi/W)\, d\sigma^+/d\Omega$ for photoproduction of π^+ mesons near threshold (taking into account S states and the direct π-meson photo effect:

$$\frac{d\sigma^+}{d\Omega}\frac{\pi}{W} = \frac{2\pi e^2 f^2}{\mu^2}\frac{1}{\nu\omega}\left[1 - \frac{\eta^2}{2\nu^2}\frac{\sin^2\theta}{(1-\eta\cos\theta)^2} - \frac{g_n+g}{M}\,\omega\left(1-\frac{\eta^2}{2}\right)\right], \tag{4}$$

where μ is the meson mass, and the meson-nucleon coupling constant f^2 is taken to be 0.08.

As is evident from the figure, in the photon energy range 155.6 — 172.3 Mev the experimental data agree with the supposition that the π^+ meson is formed primarily in an S state. The statistical accuracy of the experimental data is not great enough to distinguish between the solid curve and a constant value for $|K_p|^2$, so it is difficult to conclude whether the experimental data agree with the theory or not. However, if we compare the old Illinois data[4] in the 170 — 250 Mev energy range with Barbaro's data[10] and our own, then it appears that in the 156 — 250 Mev range the experimental values of $|K_p|^2$ increase with decreasing photon energy. This agrees qualitatively with the theoretical prediction, but it is too early to speak of quantitative agreement.

The data on reaction (3) and Baldin's calculations yield the total cross section for photoproduction of π^- mesons on neutrons:

$$\sigma_n = \frac{1}{\pi}|K_n|^2 W,$$

where $|K_n|^2$ is the square of the matrix element. Figure 2 shows the experimental values of $|K_n|^2$. The solid curve on this figure is a theoretical one, calculated from the formula

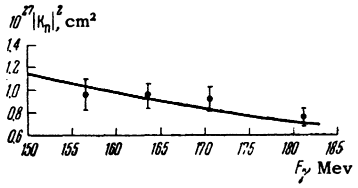

FIG. 2

$$|K_n|^2 = 4\pi^2 \frac{2e^2f^2}{\mu^2}\frac{1}{\nu\omega}\left[1-\left(\frac{1}{2\nu^2\eta}\ln\frac{1+\eta}{1-\eta}-\frac{1}{\nu^2}\right)+\frac{g_n+g_p}{M}\,\omega\left(1-\frac{\eta^2}{2}\right)\right] \quad (5)$$

with $f^2 = 0.08$.

As was the case with photoproduction of π^+ mesons on protons, the inadequate statistical accuracy makes it difficult to discuss agreement between theory and experiment. However, the experimental points do tend to follow the theoretical curve, but do not contradict a constant $|K_n|^2$ in this energy range. At the same time, an extrapolation to the threshold with $|K_n|^2 = \text{const}$ leads to a contradiction between the threshold value of $|K_n|^2$ and the Panofsky ratio. If the experimental data in Fig. 1 were extrapolated to the threshold with formula (5), then the threshold value of $|K_n|^2$ would become 1.16×10^{-27} cm², which agrees with the measured value of the Panofsky ratio.[7,8] The departure from linearity of the S phase as a function of meson momentum is taken into account.[9] It is clear that to really check the theory it is necessary to have experimental data at energies close to threshold and high statistical accuracy. The same applies to the photoproduction of π^+ mesons on protons.

The table shows the meson nucleon coupling constant f^2 obtained from hydrogen (column 4) and deuterium (column 5). As is clear from the table, the values of the constant agree with each other within experimental error. In particular, the mean value of f^2 found from the experiment on the photoproduction of π^+ mesons on protons is 0.085 ± 0.005, while the mean value found from negative mesons is 0.083 ± 0.005. The uncertainties quoted are statistical.

Using the experimental value of the constant for π^+ and π^- mesons, we obtain the following value for the ratio σ^-/σ^+ in the 153 — 175 Mev photon-energy range.

$$\sigma^-/\sigma^+ = 1.3 \pm 0.15.$$

This value of the ratio of the cross sections for formation of negative and positive π mesons on free nucleons agrees well with the theoretical prediction.[11]

In an earlier paper[2] we quoted a value of 1.34 for the ratio σ^-/σ^+ at photon energy very near the threshold for production of π mesons. This was obtained by extrapolating to the threshold the data of Beneventano et al.[4] regarding the photoproduction of π^+ mesons on hydrogen and our data on π^- mesons, the extrapolations being made according to the same law. The value of σ^-/σ^+ quoted in the present paper is free of uncertainties in the calibration of the photon beam. It should be noted that the threshold value of σ^-/σ^+ does not depend on the nature of the extrapolation.

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