PHOTOPRODUCTION OF NEGATIVE PIONS FROM DEUTERIUM NEAR THE THRESHOLD

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This investigation was performed with the Lebedev Physics Institute's 265-Mev synchrotron using photographic emulsions containing D_2O. Detailed information concerning the reaction $\gamma + d \rightarrow p + p + \pi^-$ was obtained for photon energies up to 200 Mev. Various experimental characteristics of the reaction are compared with the predictions of the impulse approximation theory. The experimental results are consistent with the theory which takes into account the interaction between nucleons in the final state. It is shown that the square of the matrix element for photoproduction of pions from neutrons near the meson threshold is constant and equals $(0.785 \pm 0.072) \times 10^{-27}\,cm^2$. This value corresponds to $\sigma^-/\sigma^+ = 1.34$.

1. INTRODUCTION

A number of investigators[1-3] have measured the ratio between the cross sections for the reactions $\gamma + d \rightarrow p + p + \pi^-$ and $\gamma + d \rightarrow n + n + \pi^+$. This ratio is used to represent the ratio for the photoproduction of negative and positive pions from free nucleons. Watson[4] has indicated the following conditions under which the observed ratio σ^-/σ^+ for deuterium will be the same as for free nucleons:
(1) correctness of the impulse approximation,
(2) production of photomesons in the S state, and
(3) negligibly small Coulomb interactions between mesons and nucleons. Fulfillment of the first two conditions has not been verified experimentally, although σ^-/σ^+ has been measured many times. Fulfillment of the third condition has been secured experimentally by the recording of high-energy mesons. The following fact must be taken into account in connection with the first condition. For photons up to 200 Mev (to insure fulfillment of the second condition) the relative kinetic energy of the two protons is small and, as we have shown experimentally,[5,6] an essential part is played by interaction of the nucleons in the final state. The nucleon interaction rules out the application of single-nucleon kinematics to the photoproduction of pions from deuterium.

In the experiments reported in references 1 and 2, the single-nucleon kinematics was used to determine σ^-/σ^+. The energy dependence obtained in this way and the value of σ^-/σ^+ at the meson threshold are in disagreement with theoretical predictions. This discrepancy may possibly be accounted for by the difference between the $\pi^- - p - p$ and $\pi^+ - n - n$ systems and the contribution of photons from the entire bremsstrahlung spectrum above threshold to the yield of pions with a definite energy. A certain arbitrariness in extrapolating σ^-/σ^+ to the pion photoproduction threshold is also involved.[2]

It was the purpose of the present work to obtain information concerning the reaction $\gamma + d \rightarrow p + p + \pi^-$ near the threshold of pion photoproduction, with principal attention being devoted to verification of the correctness of the impulse approximation. Furthermore, by using the impulse approximation and taking into account the Coulomb and nuclear interactions of the particles in the final state, conclusions are reached regarding pion photoproduction from free neutrons.

2. EXPERIMENTAL METHOD

We studied the photoproduction of negative mesons from deuterium by means of emulsions containing deuterium which were exposed directly to the photon beam. Emulsions loaded with deuterium served as targets and detectors at the same time. This method provides a detailed picture of the interaction which leads to the production of negative pions from deuterium.

We used type-P 400 μ NIKFI emulsions, which are sensitive to relativistic particles. An amidol developer was used as recommended by the NIKFI (Motion Picture and Photography Scientific Research Institute). The uniformity of development as to depth was entirely satisfactory.

Before irradiation a batch of plates was impregnated with heavy water at 18 to 19°C. A plate measuring 3.0×6.0 cm^2 absorbs an average of 0.770 g of heavy water in one hour. Such a loaded emulsion is 800 μ thick during irradiation, and 1 cm^3 of the loaded emulsion contains 3.2×10^{22} deuterium nuclei.

The plates were bombarded by photon beams, with a maximum energy of 250 and 200 Mev at a distance of 5 m from the target, produced by the Lebedev Physics Institute synchrotron. The photon beam traversed the shielding and primary lead collimators, passed through the gap of the electromagnet, and reached a plate whose emulsion faced the beam. The 7000-oersted field of the electromagnet swept electrons from the photon beam. Carbon blocks shielded the plates from scattered radiation. Irradiation occurred at a glancing angle of 30°. A graphite ionization chamber was placed directly behind the plate to determine the photon beam through the emulsion.

The plates were scanned by MBI-2 microscopes with $20 \times 10 \times 1.5$ magnification. As a check of efficiency, some batches of plates were scanned twice by different persons. Stars were recorded with an efficiency not lower than 96% under the worst conditions. $60 \times 15 \times 1.5$ magnification was used in the measurements.

The energies of particles stopping in the emulsion were determined from the residual ranges. The dependence of the residual range on particle energy was calculated for different degrees of impregnation occurring experimentally. The energies of particles whose tracks did not terminate in the emulsion but were inclined at a small angle were determined from grain density by comparison with calibration curves of grain density versus residual range. The calibration was performed for each set of plates, using a few long-range mesons and protons stopping in the emulsion. The sensitivity of the plates was considerably reduced by impregnation; this made it possible to use grain counts to determine particle energies in a broad interval. However the reduced sensitivity of the plates permitted registration of pions only with energies not above 40 Mev.

The identification of particle tracks stopping in the emulsions presented no difficulty. Tracks which left the emulsion at a small dip angle were identified from grain density and multiple scattering. Multiple scattering was measured with a MBI-8 microscope using the coordinate method. Figure 1 shows the distribution of proton and pion tracks according to grain density and multiple scattering. The axes of the figure are the logarithms of the grain density in 500-micron cells and the coordinate second difference. Identification by means of grain density and multiple scattering can be used only within certain limits and is laborious; we therefore used it relatively infrequently.

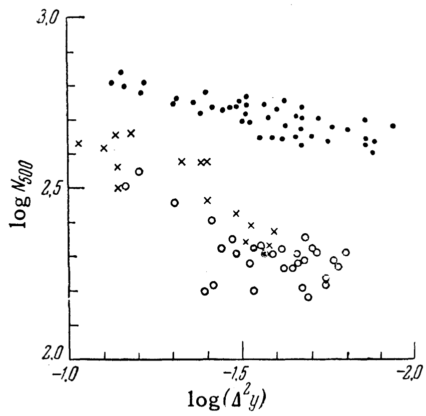

FIG. 1. Grain density vs multiple scattering for protons and mesons of one of the processed sets of plates. The dots represent protons; the crosses represent pions; the circles represent pions from the reaction $\gamma + d \to p + p + \pi^-$.

Three-prong stars found in the plates were analyzed in order to distinguish those associated with the reaction $\gamma + d \to p + p + \pi^-$. For this purpose we determined the energies and angles of emission of all particles in a star with respect to the photon beam direction, which was ascertained in each plate from the tracks of secondary electrons, the majority of which were parallel to the photon beam. Analysis of each star was based on conservation of photon energy and momentum in $\gamma + d \to p + p + \pi^-$. For brevity the following notation was used. The vector sum of the momenta of all three particles is called the star momentum **P**. The sum of the particle energies, the meson rest mass, and the difference between the rest masses of the deuteron and the two protons is called the photon energy E_γ. The photon energy expressed in momentum units and directed along the photon beam is called the photon momentum $\mathbf{P}_\gamma$. When **P** agreed with $\mathbf{P}_\gamma$ the star was assigned to the reaction $\gamma + d \to p + p + \pi^-$. A natural measure of the deviation of the star momentum from the photon momentum is $\Delta P = |\mathbf{P} - \mathbf{P}_\gamma|$. This parameter includes the errors in measurements of both angles and energies. If the spread of ΔP results only from errors of measurement, its distribution must obey the Maxwellian law $\Phi(\Delta P) \sim (\Delta P)^2 \exp\{-h^2(\Delta P)^2\}$, where h is a measure of accuracy equal to $2/\pi(\Delta P)_{av}$. Figure 2 shows the distribution of stars with respect to ΔP. In the momentum measurements the proton rest mass is taken as unity. The same figure shows the Maxwellian distribution with the parameter h obtained experimentally. The distribution

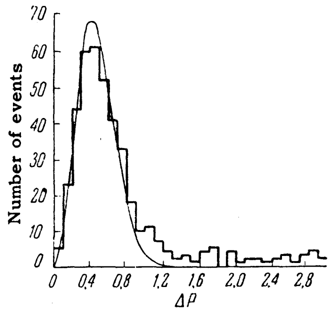

FIG. 2. Histogram of star distribution with respect to ΔP. The solid curve is the Maxwellian distribution.

has a maximum at $\Delta P = 0.45$ and drops sharply in the interval from 0.5 to 1.0. The experimental distribution also shows a "tail" for large values of ΔP. All stars with ΔP smaller than 1.1 are assigned to the reaction $\gamma + d \rightarrow p + p + \pi^-$.

It is necessary to determine the validity of ΔP as a criterion. The investigated reaction $\gamma + d \rightarrow p + p + \pi^-$ could contain an admixture of photoreactions in emulsion nuclei such as the following photoreactions for oxygen:

$$\gamma + O_8^{16} \rightarrow p + \pi^- + O_8^{15};\quad O_8^{15} \rightarrow N_7^{15} + \beta^+;$$

$$\gamma + O_8^{16} \rightarrow p + p + \pi^- + N_7^{14};$$

$$\gamma + O_8^{16} \rightarrow p + p + n + \pi^- + N_7^{13},\quad N_7^{13} \rightarrow C_6^{13} + \beta^+.$$

Similar reactions can be written for carbon, nitrogen and other nuclei. A control experiment was performed for the purpose of estimating the contribution of these secondary reactions to the number of recorded instances of the reaction under investigation. The control emulsions were loaded with light water and irradiated by a photon beam. Three-prong stars were analyzed by the previous method. The scanned area on plates loaded with light water was 64 cm^2. This same area on plates loaded with heavy water contains on the average 20 instances of the reaction $\gamma + d \rightarrow p + p + \pi^-$, represented by stars with the parameter $\Delta P < 1.1$. In the plates containing light water not a single three-prong star was found with ΔP smaller than 1.1. It might be assumed that all stars with $\Delta P < 1.1$ represent reactions with emulsion nuclei rather than with deuterium. Then the probability that an area of 64 cm^2 would contain not a single star with ΔP between 0 and 1.1 is of the order of 10^{-9}. The assumption is thus shown to be unfounded. We can thus consider that, within the limits of accuracy of the control experiment, no secondary reactions appear among assigned instances of $\gamma + d \rightarrow p + p + \pi^-$. The "tail" of the star distribution with respect to the parameter is, however, caused by secondary reactions with emulsion nuclei. Thus the analysis using the ΔP criterion unambiguously selects instances of negative-pion photoproduction from deuterium.

The following different cases were encountered during the analysis: (1) All three particles stopped in the emulsion. (2) One or two particles emerged from the emulsion but could be identified either visually or by grain density and multiple scattering. These were the two simplest cases where the ΔP criterion of $\gamma + d \rightarrow p + p + \pi^-$ could be applied. (3) A particle left the emulsion and could not be identified by multiple scattering. In this case we were able to arrive at an unambiguous conclusion regarding the nature of the particle. We had two unknown quantities (the energy of the particle and the energy of the photon) and four equations which described the conservation laws. Two equations were used to determine the energy of the particle and the total momentum of the star. The satisfying of the other two equations showed the correctness of the hypothesis that the star represented $\gamma + d \rightarrow p + p + \pi^-$. (4) Two particles left the emulsion, neither of which could be identified by the usual methods. As in the preceding cases, we knew the directions of all three particles and thus had three unknown quantities (the energies of the particles and of the photon) and four conservation equations. Three equations served to determine the unknowns, while the fourth equation verified fulfillment of the conservation laws. Different masses were successively assumed for the two particles, after which the ΔP criterion for conservation was checked. If the criterion was satisfied, then, as in the preceding case, the hypothesis concerning the nature of the particles was correct and the star represented $\gamma + d \rightarrow p + p + \pi^-$. If $\Delta P > 1$, so that the ΔP criterion was not satisfied, nothing could be said regarding the nature of the particles. It could only be affirmed that the star did not result from the reaction under investigation. The number of $\gamma + d \rightarrow p + p + \pi^-$ stars that were identified only by means of the conservation laws, comprised 8% of the instances of this reaction.

As an additional check of the correctness of pion identification in the $\gamma + d \rightarrow p + p + \pi^-$ reaction by the third and fourth methods described above, stars which included pion tracks with small dip angles were subjected to identification by these same methods. The same mesons were then identified by grain density and multiple scattering. Figure 1 shows to what extent these different methods were identical. Here the crosses denote the calibration pions and the circles denote pions in the reaction $\gamma + d \rightarrow p + p + \pi^-$ that were identified through the conservation laws.

For the investigated photon energy range, there were no cases in which all three particles left the emulsion. This fact, as well as the small percentage of stars with two escaping and unidentified tracks, was favored by the following factors: the irradiation of the plates at a small glancing angle (30°) and the discarding of the lowest 100 μ and uppermost 20 μ of the impregnated emulsion.

3. EXPERIMENTAL RESULTS

Emulsions loaded with heavy water enabled us to register pions with energies up to 40 Mev. However, in view of the density fluctuations of the grain background, 30 Mev must be regarded as the effective limit. We were thus able to measure the total cross sections in all plates for photons up to 174 Mev. In an area of 2050 cm^2 of scanned emulsion containing deuterium nuclei, we found, in the entire photon spectrum, 720 stars belonging to the photoproduction of negative pions from deuterium. The method described in the preceding section enables us to determine for each instance of $\gamma + d \rightarrow p + p + \pi^-$ the photon energy, the particle energy, the energy of relative motion of the two protons, the direction of emission of the particles with respect to the photon beam, and other characteristics.

The complete results for photons from the threshold to 174 Mev are represented in Fig. 3. Each $\gamma + d \rightarrow p + p + \pi^-$ event is characterized in this diagram by the momentum of relative motion of the two protons $p = \frac{1}{2}|\mathbf{p}_1 - \mathbf{p}_2|$ on the vertical axis and the half-sum of the momenta $q = \frac{1}{2}|\mathbf{p}_1 + \mathbf{p}_2|$ on the horizontal axis. The proton momenta $\mathbf{p}_1$ and $\mathbf{p}_2$ are expressed in units of μc, where μ is the pion rest mass. The curve represents the limiting values of p and q determined by the conservation laws for 174-Mev photons. From similar diagrams for each photon energy interval we obtain all the characteristics of the $\gamma + d \rightarrow p + p + \pi^-$ reaction, which are discussed below. A few sets of more sensitive plates made it possible to obtain total cross sections for photon energies from 174 to 202 Mev. All of these plates were used to determine the cross sections for the production of pions of less than 30 Mev for the photon range from 174 to 202 Mev. In order to obtain total cross sections for photons from the threshold to 202 Mev, we used 320 instances of pion photoproduction from deuterium.

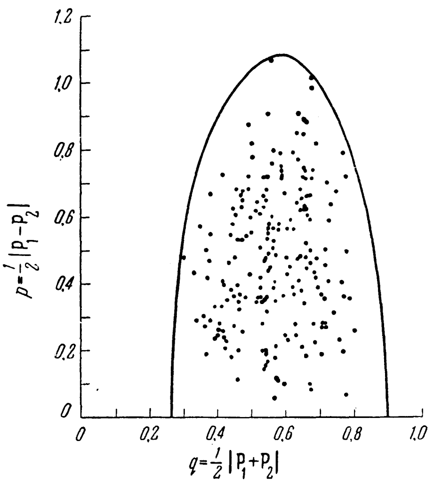

FIG. 3. Distribution of $\gamma + d \rightarrow p + p + \pi^-$ events with respect to p and q.

Figure 4 shows the dependence of the total cross section for pion photoproduction on the photon energy. Schiff's spectrum[7] was used as

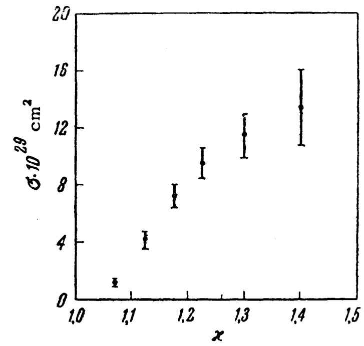

FIG. 4. Dependence of the total cross section for $\gamma + d \rightarrow p + p + \pi^-$ on the photon energy $\varkappa$.

the bremsstrahlung spectrum. The vertical lines represent statistical errors. The photon energy κ is expressed in units of μc^2. Errors in the determination of photon energies result from errors in measurement of the energies of particles that leave the emulsion. The error in the photon energy varies from event to event but is always smaller than the selected photon energy interval.

Figure 5 gives the experimental ratio of the cross section $\sigma_{2.5}$ for $\gamma + d \rightarrow p + p + \pi^-$ with $q/p \geq 2.5$ to the total cross section σ as a function of photon energy. Instances of the reaction with $q/p \geq 2.5$ are in the lower part of the $p - q$ diagram (Fig. 3).

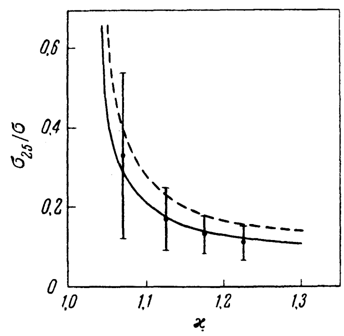

FIG. 5. Dependence of the ratio $\sigma_{2.5}/\sigma$ on the photon energy $\varkappa$.

The relative motion of two protons is characterized by the kinetic energy $T = p^2/M$, where

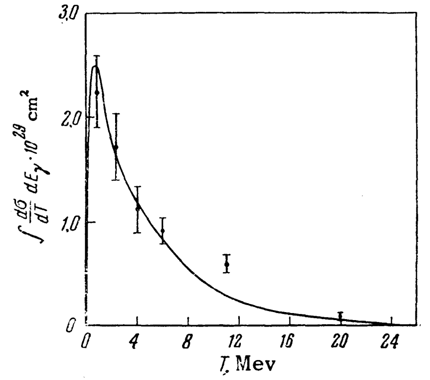

FIG. 6. Energy spectrum of the relative motion of the two protons.

M is the proton mass. Figure 6 shows the energy spectrum of this relative motion. T is plotted on the horizontal axis while the vertical axis gives the integral of $d\sigma/dT$ over the photon spectrum from the threshold to 174 Mev, i.e., $\int (d\sigma/dT)\, dE_\gamma$. The error ΔT in the kinetic energy of relative proton motion is determined by the errors in measuring the energy of each proton and the angle between their directions of motion. The errors are smallest for low values of T. The intervals of T were selected to make ΔT smaller than the intervals themselves.

Figure 7 shows the experimental distribution of $\gamma + d \rightarrow p + p + \pi^-$ with respect to the parameter $\epsilon = p - q$ for photons up to 174 Mev. ϵ in-

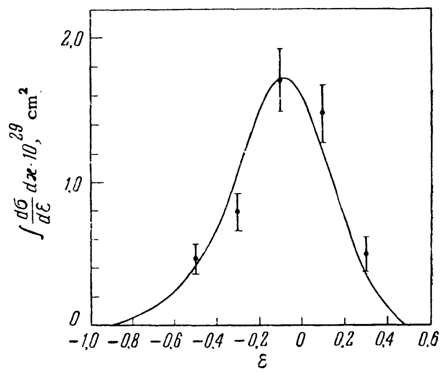

FIG. 7. Spectrum of ε.

directly describes the angle between the two proton directions The parameter ϵ is zero when the angle between the proton tracks is close to 90°; it becomes negative for angles smaller than 90° and positive for angles larger than 90°. The peak of the experimental distribution is on the side of negative values of ϵ, which is evidence that angles smaller than 90° predominate.

The table gives experimental cross sections for $\gamma + d \rightarrow p + p + \pi^-$ with the pion energy lying in the range $5 < E_\pi < 30$ Mev and the relative proton momentum $p < 0.7$. The cross sections, which were determined for all of the plates, are given for the photon energies $\kappa = 1.125, 1.175, 1.225$, and 1.30 in units of μc^2. The statistical errors are also indicated.

4. DISCUSSION OF RESULTS AND COMPARISON WITH THEORY

The $p - q$ diagram of Fig. 3 shows that, for photon energies from the threshold to 174 Mev, reactions with a relative proton momentum below 0.3 comprise 21% of the total. This relative momentum corresponds to 2.0 Mev energy of relative proton motion. From this experimental fact we can derive qualitative information concerning a change of the spin of the nucleon system during the photoproduction of negative pions from deuterium. If the deuteron radius 4.3×10^{-13} cm represents the size of the nucleon system, then, roughly speaking, when the energy of relative proton motion is below 2.5 Mev, a triplet proton spin state is forbidden by the Pauli principle. Our large count of reactions with small relative kinetic energy of the two protons indicates that the spin of the nucleon system is changed during the photoproduction of negative pions. This means that an E1 transition occurs and leads to the production of S-state pions and of protons in the singlet spin state $^1S_0$. A detailed investigation of the final states of the $\gamma + d \rightarrow p + p + \pi^-$ reaction has been performed by one of the present authors and is presented in reference 8.

Let us now consider the influence of the initial nucleon state on the photoproduction of pions. The average distance between the nucleons in the deuteron is large. We can therefore assume that the

Dependence of cross section for meson production ($5 < E_\pi < 30$ Mev, $p < 0.7$) on photon energy κ

κ	1.125	1.175	1.225	1.30
$\sigma \cdot 10^{29}$, cm² (experimental)	2.98 ± 0.50	5.90 ± 0.70	5.91 ± 0.91	3.66 ± 0.52
$\sigma \cdot 10^{29}$, cm² (theoretical)	$4.09\,\lvert K_n\rvert^2 \cdot 10^{-2}$	$7.15\,\lvert K_n\rvert^2 \cdot 10^{-2}$	$7.44\,\lvert K_n\rvert^2 \cdot 10^{-2}$	$4.62\,\lvert K_n\rvert^2 \cdot 10^{-}$

photon interacts with one nucleon while the other nucleon remains in the state of motion which it possessed in the deuteron. This picture of the photon-deuteron interaction in pion production corresponds to the impulse approximation, which employs an initial-state wave function that takes into account the motion of the nucleons in the deuteron. This is usuallly the Hulthen wave function

$$\varphi(r) = \sqrt{7/9\pi}\,[e^{-\alpha r} - e^{-7\alpha r}]/r,$$

where $\alpha = \sqrt{M\epsilon_0/\hbar}$ and ϵ_0 is the deuteron binding energy. The nucleon states following the reaction appear in the final-state wave function.

A quantitative comparison of theory and experiment requires consideration of the particle interaction in the final state of the $\gamma + d \rightarrow p + p + \pi^-$ reaction. An exact calculation of the Coulomb and nuclear interactions of the nucleons in the impulse approximation has been performed by A. M. Baldin,* whose final expression for the photoproduction cross section of pions from deuterium is

$$d\sigma = \{A(p, q)\,|K_n|^2 + B(p, q)\,|L_n|^2\}\,dp\,dq,$$

where $A(p, q)$ and $B(p, q)$ are complicated functions of the absolute values of the relative proton momentum p and the half-sum q and depend only slightly on the photon energy; $|K_n|^2$ and $|L_n|^2$ are squared matrix elements of the operators in the interaction Hamiltonian $H = K_n\sigma + L_n$ usually used in the impulse approximation. Here σ is the Pauli spin matrix. Baldin kindly placed at our disposal his tables of values of $A(p,q)$ and $B(p,q)$. Integration of $d\sigma$ over p and q gives the total cross section for negative pion photoproduction from deuterium. The integration region for each photon energy is determined by energy and momentum conservation. For example, the integration region for 174-Mev photons is the portion of the plane bounded by the curve and the axis $p = 0$ in the $p - q$ diagram of Fig. 3. To perform the integration it is necessary to know the dependence of the operators K_n and L_n on q and on the pion momentum. In deriving his expression for $d\sigma$, Baldin neglected the dependence of K_n and L_n on the nucleon momentum. For $q < 1$ this is an accurate approximation, but for $q \sim 1$ it can cause an error on the order of 10%.[5] From experimental findings we can reach some conclusion regarding the magnitudes of $|K_n|^2$ and $|L_n|^2$ and their dependence on pion momentum. The analysis in reference 8 of the pion angular distributions and the energy dependence of the total cross section for $\gamma + d \rightarrow p + p + \pi^-$ showed that, close to threshold, the pions are produced in the S state as a result of electric dipole absorption of photons. This indicates that the matrix element of pion photoproduction is independent of pion momentum. It is known[4] that, from spin and parity conservation and from the hypothesis that S-state pions are produced near threshold, the transition matrix has the form $A\sigma\mathbf{e}$, which is of the type $K\sigma$. It thus follows from experiment that, first, $|K_n|^2 \gg |L_n|^2$ (if, of course, the impulse approximation is valid) and second, the matrix element can be regarded as independent of pion momentum within the limits of statistical accuracy.

We shall now make a direct comparison of the impulse approximation and experiment. Let us consider the reaction $\gamma + d \rightarrow p + p + \pi^-$ when $q/p \gg 2.5$. In this region $B(p, q) \ll A(p, q)$, which is associated with the fact that $B(p, q)$ does not take into account the interaction of the nucleons in the final state. We shall assume $L_n \neq 0$ and $K_n = 0$. This leads to the following value for the ratio of the integral cross section over the photon spectrum with $q/p \geq 2.5$ to the total pion photoproduction cross section:

$$\int \sigma_{q/p \geqslant 2.5}\, d\varkappa \Big/ \int \sigma d\varkappa$$

$$= \iiint\limits_{q/p \geqslant 2.5} B(p, q)\, dp\, dq\, d\varkappa \Big/ \iiint B(p, q)\, dp dq d\varkappa = 0.003.$$

As could be expected, this value disagrees strongly with the experimental result $\int \sigma_{2.5} d\kappa / \int \sigma d\kappa = 0.146 \pm 0.036$. Thus the assumptions that the nucleons do not interact in the final state and that $K_n = 0$ are invalid. If $|L_n|^2/|K_n|^2$ is small, the ratio of the integral cross sections is 0.145, which is in very good agreement with the experimental result 0.146 ± 0.036. Figure 5 shows the dependence of $\sigma_{2.5}/\sigma$ on the photon energy κ. The solid curve represents the theoretical dependence of this ratio on photon energy. The dashed curve represents the theoretical ratio $\sigma_{2.5}/\sigma$, neglecting the Coulomb interaction of protons in the final state. Both curves were calculated for $L_n = 0$. The figure shows that the experimental points are close to the solid curve but all lie below the dashed curve. It follows that the Coulomb interaction of the protons plays an important part in addition to the nuclear interaction.

For a more detailed comparison of theory and experiment we must know the magnitude of the squared matrix element $|K_n|^2$. In our calcula-

*Presented at the 1957 Conference on Elementary Particle Physics in Venice and Padua.

tions we used $|K_n|^2 = 0.76 \times 10^{-27}$ cm^2, which corresponds to a theoretical value of 1.30[9] for σ^-/σ^+ near the pion photoproduction threshold. Figure 6 compares the theoretical distribution $f(T) = \int \frac{d\sigma}{dT} dE_\gamma$ with the experimental distribution with respect to the kinetic energy T of relative proton motion. Good agreement is shown both in absolute magnitude and in shape up to values of T of the order of 8 to 10 Mev. For higher energies the experimental points are above the theoretical curve; this will be accounted for hereinafter. Figure 7 compares the experimental distribution of $\gamma + d \rightarrow p + p + \pi^-$ with respect to ϵ and the theoretical distribution $\varphi(\epsilon) = \int \frac{d\sigma}{d\epsilon} d\kappa$, where $\epsilon = p - q$. The figure shows that the experimental values are in satisfactory agreement with theory regarding the absolute value and location of the maximum as well as the shape of the distribution, although for positive values of ϵ (large values of p) the experimental points lie somewhat above the theoretical curve. Distributions with respect to T and ϵ were chosen for the comparison with theory because the cross sections show sharpest dependence on these parameters. The lack of a large amount of data makes this very important. The differential cross sections $d\sigma/dT$ and $d\sigma/d\epsilon$ were obtained by numerical integration.

The agreement between experiment and the theoretical curves in Figs. 5 to 7 is evidence of the correctness of the impulse approximation, which takes account of nucleon interaction in the final state. We note that for p and q ~ 1 much significance must not be attached to the theoretical results because in this range of values the behavior of the wave function within the range of the nuclear forces is important and corrections that have been neglected in the theory are highly significant. Examples of such corrections are the dependence of K_n on nucleon momentum and the correction for the Coulomb interaction between the pion and protons. This may explain the discrepancy between experiment and theory for large T and positive ϵ, corresponding to $p > 0.7$. For other values of p the experimental distributions are in good agreement with theory. It must be especially emphasized that the impulse approximation furnishes a good description of the experimental results by using the theoretical value $\sigma^-/\sigma^+ = 1.3$ for the negative-to-positive ratio of pion photoproduction.

5. PHOTOPRODUCTION OF NEGATIVE PIONS FROM NEUTRONS

The analysis of experimental results which was given in the preceding section shows that the S matrix of negative pion photoproduction from neutrons is of the form $K\sigma$. The differential cross section for pion photoproduction from free neutrons in the center-of-mass system can, like that for protons,[2] be written as

$$\frac{d\sigma^-}{d\Omega} = \frac{1}{(2\pi)^2} |K_n|^2 \frac{\eta\omega}{(1 + (\nu/M))^2},$$

where η and ω are the momentum and total energy of the pion in the center-of-mass system, ν is the photon energy in the same system, and $\mu = \hbar = c = 1$. The magnitude of $|K_n|^2$ could be determined from the differential cross section $d\sigma = A(p, q) |K_n|^2 dp\,dq$ of negative pion photoproduction in deuterium. Unfortunately, we have insufficient data for the purpose. The squared matrix element $|K_n|^2$ must therefore be determined from the integral cross sections.

The weighted average $|K_n|^2_{av}$ obtained from five values of $|K_n|^2$ for different photon energies κ in the interval from 1.04 to 1.35 is $(0.84 \pm 0.04) \times 10^{-27}$ cm^2. However the integration of the differential cross section $\int d\sigma = |K_n|^2 \iint A(p, q)\, dp\, dq$ over the entire range of variation of p and q that is determined by the conservation laws artificially introduces some uncertainties into the value of $|K_n|^2$, which are ignored in the impulse approximation.

To obtain the most accurate value of $|K_n|^2$, the experimental and calculated cross sections must be compared in the region where the theory has greatest validity, i.e., for values of p and q which permit us to neglect effects that are not taken into account in the theory. The best region of applicability of the impulse approximation, when the Coulomb interaction between the pion and protons is neglected, is given by the conditions p, q < 1. The condition $q < 1$ is satisfied by photon energies from threshold ($\kappa_0 = 1.04$) to $\kappa = 1.30$. On the other hand, as we have seen from comparison of the experimental and theoretical distributions with respect to T, experiment and theory are in good agreement for $p < 0.7$. For the photon energies $\kappa = 1.07$ and 1.125, p and q are always smaller than 0.7, while for $\kappa = 1.175$ they are always smaller than 0.8. Therefore the total cross sections for $\gamma + d \rightarrow p + p + \pi^-$ at these energies does not depend essentially on the behavior of the wave function within the range of nuclear forces. Multiple scattering is also unimportant, since the pion energy does not exceed 30 Mev. But in the photon energy range $\kappa = 1.04$ to 1.35 the total cross section can be affected by a Coulomb interaction between the pion and one of the protons. The Coulomb force between a pion and a proton can be neglected when the pion has energy of at least a few Mev.[4] We have chosen 5 Mev as a reasonable criterion. Then the cross sections for pion photoproduction with $E_\pi > 5$ Mev by photons with $\kappa = 1.125$ and 1.175, together with the cross sections for $p < 0.7$ and $5 < E_\pi < 30$ Mev at $\kappa = 1.225$ and 1.30, will provide a correct value for negative pion photoproduction from free neutrons near threshold. The table contains experimental values of $\gamma + d \rightarrow p + p + \pi^-$ cross sections for $5 < E_\pi < 30$ Mev and relative proton momentum $p < 0.7$.

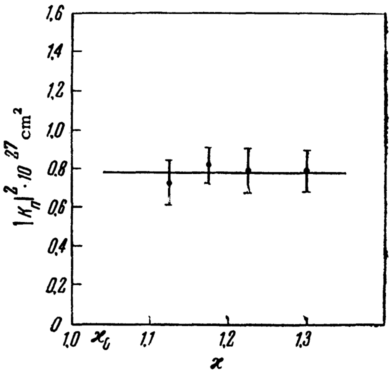

FIG. 8. The squared matrix element of pion photoproduction from neutrons as a function of photon energy.

The second line of the table gives the theoretical values of the same cross sections. Figure 8 represents the squared matrix element $|K_n|^2$ as a function of photon energy κ, the values being taken from the table. The vertical lines denote statistical errors. We see from the figure that within the limits of statistical error the squared matrix element of S-state pion photoproduction from neutrons is constant in the photon energy range from 1.125 to 1.30. The horizontal line represents the average value $|K_n|^2_{av} = (0.785 \pm 0.072) \times 10^{-27}\,\text{cm}^2$. The integral cross section with respect to photon energy κ for $p < 0.5$ gives $|K_n|^2 = (0.755 \pm 0.081) \times 10^{-27}\,\text{cm}^2$. The insensitivity of $|K_n|^2$ to p proves that $|K_n|^2$ has been determined accurately.

Thus a detailed investigation of the reaction $\gamma + d \rightarrow p + p + \pi^-$ shows that the squared matrix element of pion photoproduction from neutrons near threshold has the constant value $|K_n|^2 = (0.785 \pm 0.072) \times 10^{-27}\,\text{cm}^2$. The data given in reference 2, unlike ours, indicate that this squared matrix increases as the threshold is approached. In our experiments $\gamma + d \rightarrow p + p + \pi^-$ was investigated by registering all three particles, whereas the authors of reference 2 registered only a single photon of definite energy out of the entire photon spectrum with a 300-Mev maximum. Since the single-nucleon kinematics, which serves as a basis for interpretation of the data in reference 2, is invalid for the $\gamma + d \rightarrow p + p + \pi^-$ reaction, we question the conclusion reached in that paper that $|K_n|^2$ increases as the threshold is approached.

Our value $|K_n|^2_{av} = (0.785 \pm 0.072) \times 10^{-27}\,\text{cm}^2$ corresponds to the following value for the cross section ratio for photoproduction of S-state negative and positive pions from free nucleons near threshold:

$$\sigma^-/\sigma^+ = |K_n|^2/|K_p|^2 = 1.34 \pm 0.14.$$

The indicated errors include only the statistical errors of σ^- and σ^+; the value of σ^-/σ^+ depends strongly, of course, on the calibration of the photon beam. We have used the data of reference 2 on positive photomesons from hydrogen, which were obtained with the University of Illinois betatron. A number of effects (photodisintegration of deuterons, proton Compton effect etc), which were measured at both the Illinois betatron and the Lebedev Physics Institute synchrotron, given identical cross sections with 10% statistical accuracy. We can thus assume that the ratio $\sigma^-/\sigma^+ = 1.34 \pm 0.14$ does not contradict field theory.[9] We arrived at this conclusion in the preceding section in comparing the experimental and the theoretical distributions calculated by using the theoretical value $\sigma^-/\sigma^+ = 1.3$.

We are now engaged in measuring the cross section for positive pion photoproduction from hydrogen in order to obtain a more certain value of σ^-/σ^+.

In conclusion we wish to thank Professor V. I. Veksler for valuable suggestions and his continued interest, and A. M. Baldin for the use of his tables of functions and for a discussion of the results.

[1] Beneventano, Carlson-Lee, Stoppini, Bernardini, and Goldwasser, Nuovo cimento **12**, 156 (1954).

[2] Beneventano, Bernardini, Carlson-Lee, Stoppini, and Tau, Nuovo cimento **4**, 323 (1956).

[3] Sands, Teasdale, and Walker, Phys. Rev. **95**, 592 (1954).

[4] K. M. Watson, Phys. Rev. **95**, 228 (1954).

[5] A. M. Baldin, Proc. CERN Symposium, Geneva, **2**, 272 (1956).

[6] Adamovich, Veksler, Kuz'micheva, Larionova,

and Kharlamov, Proc. CERN Symposium, Geneva, **2**, 265 (1956).

[7] L. I. Schiff, Phys. Rev. **83**, 252 (1951).

[8] M. I. Adamovich, J. Exptl. Theoret. Phys. (U.S.S.R.) **35**, 39 (1958), JETP **8**, 29 (1959).

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

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AN INVESTIGATION OF THE FINAL STATES IN THE PHOTOPRODUCTION OF NEGATIVE π MESONS ON DEUTERIUM

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Photographic emulsions were used to study the $\gamma + d \rightarrow p + p + \pi^-$ reaction, giving the angular distributions and energy spectra of the mesons and the relative motion of the two protons close to the meson photoproduction threshold. Analysis shows that there is an electric dipole transition taking place, causing the spin of the nucleon system to change and the meson to be produced in the S state. The shape of the spectra and the energy dependence of the cross section are explained by the interaction of the nucleons in the final state.

1. INTRODUCTION

A detailed investigation of the photoproduction of negative π mesons on deuterium can be used to obtain information both on the elementary process of meson photoproduction on neutrons,[1] and on the process of meson production on the simplest nucleon system. In this two-nucleon system it is easy to study the effects of nuclear binding, the Pauli exclusion principle, and the Coulomb and nuclear interactions of the particles in the final state on the photoproduction of mesons. Such an investigation should be performed at photon energies up to 200 Mev, since at these energies the influence of multiple scattering of the meson is negligible. In this way we can investigate how the final state of the particles influences the properties of the meson production process and establish some of the properties of negative π-meson production on deuterium. A detailed investigation of this process gives information on the role of the spin interaction in photoproduction close to threshold.

The $\gamma + d \rightarrow p + p + \pi^-$ reaction was studied in nuclear emulsions containing deuterium. The emulsions were placed in the photon beam (maximum energy 250 Mev) of the synchrotron of the Academy of Sciences Physics Institute. The experimental procedure is described elsewhere.[1] The data were obtained for the photon energy range between threshold and 174 Mev. Figure 1 shows the angular distributions of the π mesons in the center-of-mass (c.m.) coordinate system for photons with energies of 153 to 167 and 167 to 174 Mev. The vertical line segments indicate the statistical uncertainties. Within the limits of statistical uncertainty, the angular distributions are isotropic.

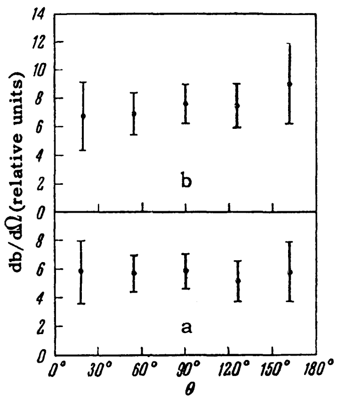

FIG. 1. Angular distribution of π mesons in the c.m. system for photon energies (a) 153 to 167 Mev, and (b) 167 to 174 Mev.