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3

SOVIET PHYSICS JETP VOLUME 35(8), NUMBER 1 JANUARY, 1959

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

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Submitted to JETP editor February 10, 1958

J. Exptl. Theoret. Phys. (U.S.S.R.) **35**, 39-44 (July, 1958)

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.

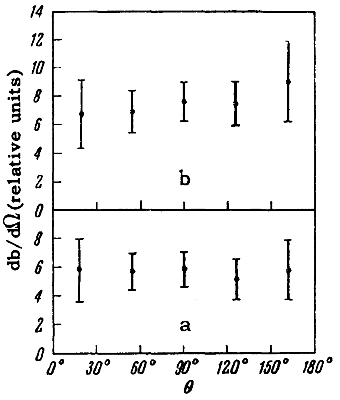

FIG. 1. Angular distribution of π mesons in the c.m. system for photon energies (a) 153 to 167 Mev, and (b) 167 to 174 Mev.

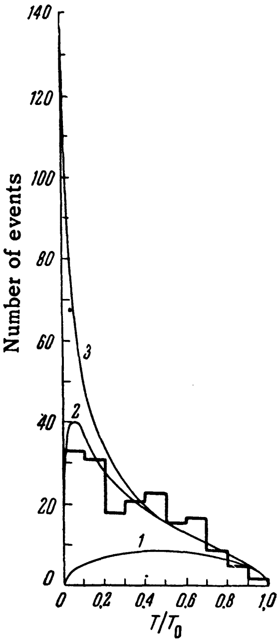

FIG. 2. The energy spectrum of relative motion of the two protons.

FIG. 3. The energy spectrum of the π mesons in the c.m. system.

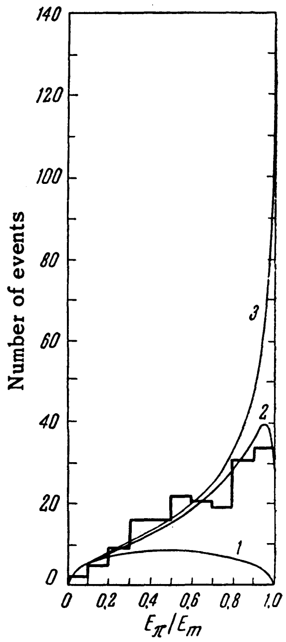

Figure 2 shows a histogram of the kinetic energy of relative motion of the two protons in the 153 to 174 Mev interval. The abscissa is measured in units of T/T_0, where T_0 is the maximum possible energy of relative motion and is equal to the sum of the energies of all three particles in the c.m. system.

Figure 3 shows a histogram of the π-meson energy spectrum in the same photon-energy interval, in the c.m. system. The abscissa is measured in units of E_π/E_m, where E_m is the maximum possible kinetic energy of the π meson, which, in the nonrelativistic approximation, is $E_m = 2MT_0/(2M + \mu)$, where μ and M are the meson and proton masses, respectively.

2. ANALYSIS OF THE MESON ANGULAR DISTRIBUTIONS

For photon energies up to 174 Mev, the energy of relative motion of the two protons in the final state is always less than 25 Mev and tends to be small because the mesons carry away most of the momentum. Since the nucleons in deuterium are located far from each other, the protons emitted as a result of π-meson photoproduction can have large orbital angular momenta in spite of their relatively low energy. The protons may therefore be in final S, P, D, F, or higher angular-momentum states. In the photon energy range studied, the π-meson momentum in the c.m. system is always less than 0.62 (we express the momentum η in units of μc). If we assume the meson-nucleon interaction radius to be finite and of order of magnitude $\hbar/\mu c$, then in the c.m. system the π mesons will be in S and P states.

The table gives all the dipole transitions as a result of which the π mesons are produced in the S state, and some dipole transitions which lead to π mesons in the P state. The same table gives the total angular momentum and parity of the system in the intermediate state. The relative intensities to different final states for the transitions indicated in the tables depend both on the electromagnetic structure of the system and on the type of interaction which leads to meson production. For instance, one of the factors giving rise to the E1 ($^1S_0$, S) transition is the nucleon-spin dependence of the interaction leading to meson photoproduction (the first symbol in the brackets denotes the state of the protons, and the second the meson state). This transition

Electromagnetic transition	Intermediate state	Dependence of cross section on maximum meson momentum	Meson angular distribution
$E1\,(^1S_0, S)$	0^-	η_m^2	const
$E1\,(^3D_2, S)$	2^-	η_m^4	const
$M1\,(^3P_0, S)$	0^+	η_m^4	const
$M1\,(^3P_1, S)$	1^+	η_m^4	const
$M1\,(^3P_2, S)$	2^+	η_m^4	const
$M1\,(^3F_2, S)$	2^+	η_m^4	const
$E1\,(^3P_0, P)$	1^-	η_m^6	$1 + \cos^2\theta$
$E1\,(^3P_1, P)$	1^-	η_m^6	$3 - \cos^2\theta$
$M1\,(^1S_0, P)$	1^+	η_m^4	$1 + \cos^2\theta$
$M1\,(^3D_2, P)$	1^+	η_m^6	$13 + \cos^2\theta$

must involve a spin change in the nucleon system, which is possible only if the interaction Hamiltonian contains a term depending on the nucleon spin.

An attempt was made to discover which transitions actually take place by analyzing the angular distributions of the mesons. To do this, we calculated the angular distributions of the electromagnetic dipole transitions shown in the table, using the formula obtained by Morita and others[2] for the differential cross section of photonuclear reactions; this formula is found from quite general premises concerning the addition of angular momenta and parity conservation. Schematically, our reaction can be represented in the form

$$\text{photon} + \text{deuteron} \rightarrow \text{intermediate state} \rightarrow \text{nucleon system} + \text{meson}$$

We treat the nucleon system as the final nucleus, which contains the angular momentum of the system. The theoretical meson angular distributions for the dipole transitions are shown in the table. Mesons produced in the S state have isotropic angular distributions for all dipole transitions. From these calculations it follows also that transitions with the same proton states will interfere. For instance, the angular distribution of π mesons for the E1 ($^1S_0$, S) and M1 ($^1S_0$, P) transitions and their interference is of the form

$$d\sigma/d\Omega \sim |a|^2 - (3\sqrt{2}/2)(a^*b + ab^*)\cos\theta + {}^9/_4|b|^2(1+\cos^2\theta),$$

where a and b are the amplitudes of these two transitions.

The fact that the experimental π-meson angular distributions are isotropic in the c.m. system indicates that in the photon energy interval between 153 and 174 Mev the transitions involve mostly meson production in the S state. Our analysis of the angular distributions of the π mesons cannot be used to choose any particular one of the transitions shown in the table.

3. ANALYSIS OF THE ENERGY SPECTRA

A finite meson-nucleon interaction radius implies[3] that at low meson energies the transition amplitude depends on the meson momentum as η^l, where l is the orbital angular momentum of the meson. The energy dependence of the cross section of the $\gamma + d \rightarrow p + p + \pi^-$ reaction is determined not only by that of the matrix element and the density of final meson states, but also by the density of the final states for the pair of nucleons, as well as by their interaction.

Let the total kinetic energy of the particles in the c.m. system after the reaction be T_0. This energy is divided between the π meson and both protons in such a way that the vector sum of the three momenta vanishes. The π mesons therefore have a continuous energy spectrum extending from zero to the maximum energy E_m, corresponding to a continuous kinetic energy spectrum for the relative motion of the two protons from T_0 to zero. When the π meson is produced in the S state and the particles do not interact, the shapes of these spectra are uniquely determined by the density of final states, and can be written

$$\frac{d\sigma}{dT} = A\sqrt{\frac{T}{T_0}}\sqrt{1-\frac{T}{T_0}}; \qquad \frac{d\sigma}{dE_\pi} = B\sqrt{1-\frac{E_\pi}{E_m}}\sqrt{\frac{E_\pi}{E_m}} \tag{1}$$

for the relative motion of the protons and for the mesons, respectively. In this equation A and B are normalizing constants. In Figs. 2 and 3 these spectra are indicated by the curves labeled 1. It is seen that the experimental spectrum is heavier in the region of low kinetic energy of relative motion of the two protons. One might expect that as a result of the attraction of the nucleons the energy spectra would have maxima in the neighborhood of E_m for the mesons and $T = 0$ for the protons.

Watson[4] has given a consistent theory of the effect of interaction between the particles in the final state. He showed that independent of the type of primary process, the forces of nuclear attraction not only increase the cross section, but also change the shape of the spectrum. The new expressions for the spectra given in Eq. (1) then become

$$\frac{d\sigma}{dT} = A\,\frac{\left[\frac{T}{T_0}\left(1-\frac{T}{T_0}\right)\right]^{1/2}}{[(\alpha^2/MT_0)+(T/T_0)]}; \qquad \frac{d\sigma}{dE_\pi} = B\,\frac{\left[\left(1-\frac{E_\pi}{E_m}\right)\frac{E_\pi}{E_m}\right]^{1/2}}{\{[2\alpha^2/(2M+\mu)E_m]+1-(E_\pi/E_m)\}}, \tag{2}$$

where α is the reciprocal of a, the nucleon-nucleon scattering length. The numerators of these expressions are proportional to the final-state densities of the three particles. The final-state interaction between the nucleons determines the denominators. Strictly speaking, the shape of the spectra given by (2) is correct only for relative proton momenta p for which $\hbar/p > r_0$, where r_0 is the range of the primary interaction. Since we have assumed from the start that $r_0 \sim \hbar/\mu c$, Eqs. (2) are valid for small T/T_0 up to about 0.3 or 0.4. For large values of T/T_0 (greater, say, than 0.7), however, the interaction does not contribute strongly and Eqs. (2) automatically become (1). Since it is not particularly important in what follows to know the shape of the spectra for T/T_0 values lying between 0.4 and 0.7, we shall assume that Eqs. (2) are valid over the whole range of this variable. Curves 2 on Figs. 2 and 3 give the spectra according to this equation, where we have set $a = 7.7 \times 10^{-13}$ cm, as obtained by Jackson and Blatt from experiments on proton-proton scattering in the singlet $^1S_0$ state. The value of T_0 was obtained by averaging experimental results in our photon energy range. Curves 2 are normalized to the experimental spectra. The normalizing coefficients A and B found in this way are also used in normalizing other spectra (curves 1 and 3). Curves 3 on the figures are the spectra given by Eq. (2) if the scattering length of the singlet state is taken as $a = -2.43 \times 10^{-12}$ cm, obtained from experiments on neutron scattering by protons.

It is seen from the graphs that curves 2 are in good agreement with experiment. This means that the nuclear interaction between the protons in the $^1S_0$ state plays an important role in the $\gamma + d \rightarrow p + p + \pi^-$ reaction. The only transition which leads to the S state for the meson and the $^1S_0$ state for the protons is E1 ($^1S_0$, S). Therefore among the different possible transitions with photon energies up to 174 Mev, the controlling one is electric dipole absorption of the photons with formation of an S state meson and with a spin change in the nucleon system.

In addition to the nuclear interaction, there is a Coulomb interaction between the protons in the final state of this reaction. Comparison of curves 2 and 3 on Figs. 2 and 3 can be used to estimate the effect due to this Coulomb interaction. Estimating this effect on the principle of charge independence of nuclear forces, we see that the maximum in the $\gamma + d \rightarrow p + p + \pi^-$ reaction is much lower than that in the $\gamma + d \rightarrow n + n + \pi^+$ reaction.

4. ANALYSIS OF THE ENERGY DEPENDENCE OF THE TOTAL CROSS SECTION

How the total cross section depends on the maximum possible π-meson energy can be found by integrating the meson energy spectra. It is more convenient to express this dependence in terms of the square of the maximum π-meson momentum in the c.m. system. The maximum possible momentum η_m is uniquely related to the photon energy κ in the laboratory coordinate system. Integration of the spectra given by (1) indicates a relation of the form $\sigma \sim \eta_m^4$. According to Eq. (2) the total cross section is proportional to η_m^2. Thus the total cross section for the photoproduction of π mesons in the S state is proportional to η_m^2 for the E1 ($^1S_0$, S) transition, and proportional to η_m^4 for all the other dipole transitions. It can be shown similarly that the total cross section is proportional to η_m^4 for the M1 ($^1S_0$, P) transition, and to η_m^6 for all the other dipole transitions into the meson P state. The dependence of the total cross section on the maximum possible π-meson momentum for each transition is given in the third column of the table.

The total cross section for production of π-mesons in the S state should be related by an expression of the form $\sigma = (b\eta_m^2 + d\eta_m^4)/\nu$ to the maximum meson momentum, where b and d are constants, and ν is the photon momentum in the c.m. system in units of μc. The intermediate powers of η_m do not appear, since the interference terms do not contribute to the total cross section. The ν-dependence is taken from meson theory.[3] At energies sufficiently close to threshold, the ν-dependence is not important. Figure 4 gives $\sigma\nu/\eta_m^2$ as a function of η_m^2 for the photon energy interval from threshold to 202 Mev. The total cross sections for the $\gamma + d \rightarrow p + p + \pi^-$ reaction are taken from Adamovich et al.[1] The horizontal line through the experimental points on the graph gives $b = (3.25 \pm 0.22) \times 10^{-28}\ \text{cm}^2$, and $d = 0$ within the limits of experimental error. At the meson photoproduction threshold, where the dependence on the photon energy is not important, the total cross section of this reaction is $\sigma = (3.25 \pm 0.22) \times 10^{-28}\, \eta_m^2\ \text{cm}^2$. The proportionality between the cross section and η_m^2 is an indication that the reaction is caused primarily by the electric dipole E1 ($^1S_0$, S) transition. This, in turn, means that the interaction Hamiltonian describing the photoproduction of negative π mesons close to threshold depends on the spin variable of the nucleon. It follows from this that, in terms of the phenomenological impulse approxi-

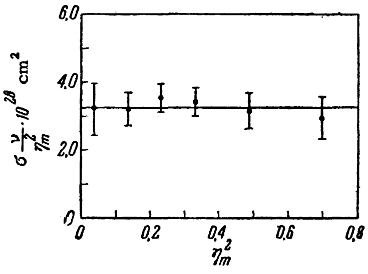

FIG. 4. The dependence of $\sigma\nu/\eta_m^2$ on the square of the maximum π-meson momentum.

mation theory, the interaction Hamiltonian is of the form $H = K\sigma$, where K is the transition operator, and σ is the Pauli spin matrix. In addition, the results presented in the last two sections show that the matrix element for the photoproduction of negative mesons on deuterium neutrons close to threshold is independent of the meson momentum. This last conclusion is in agreement with our previous results[1] obtained by a detailed comparison of experiment and the theory of the impulse approximation.

In conclusion, the author expresses his gratitude to Professor V. I. Veksler for his interest and for valuable advice, as well as to A. M. Baldin and V. N. Maikov for participating in discussions of the results.

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4

SOVIET PHYSICS JETP VOLUME 35 (8), NUMBER 1 JANUARY, 1959

OBSERVATIONS OF THE PINCH EFFECT AT DECREASING CURRENTS

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Submitted to JETP editor February 12, 1958

J. Exptl. Theoret. Phys. (U.S.S.R.) **35**, 45-49 (July, 1958)

Image-converter photographs have been taken of transient states of pulsed discharges in H_2 and Hg at pressures of 10^{-2} to 10^{-3} mm Hg. The peak pulse currents were 1.3 to 5.5 kiloamperes and the pulses were $300\,\mu$sec long. Electrodynamic deformations (contraction and kinking) are observed at negative values of di/dt. It is found that these deformation effects first disappear (as manifested by the straightening and expansion of the column) at points of high local gas density (anode or cathode, depending on the experimental conditions).

THE contraction of a high-current discharge due to its own magnetic field (pinch effect) has been observed by a number of investigators.[1-5] In some of these investigations, contraction of the column has been observed only at increasing currents.[4]

1. We have carried out a systematic investigation of pinches at increasing and decreasing currents in cylindrical tubes (internal diameter 10 and 32 mm) filled with hydrogen or mercury vapor at pressures of 10^{-2} to 10^{-3} mm Hg. The current pulses were approximately $300\,\mu$sec long with peak values $i_p = 1.3$ to 5.5 kiloamperes; these currents were obtained by discharging a 300-μf capacitor charged at 1 to 3 kv. Before the experiments the tubes and the electrodes were conditioned by operation at high pulsed currents (5 to 6 kiloamperes) for several hours, either with frequent replacement of the filler gas or with continuous pumping (if Hg vapor was used).

Pictures of the discharge were obtained with an image converter (IC)* operating as a high-speed one-shot shutter. Because of the low intensity, the exposure time could not be reduced below $1.5\,\mu$sec, although special film and exposure procedures were used. Simultaneous oscillograms were taken of the tube current i and the shutter gating pulse V_g, using a two-beam high-voltage oscilloscope. The particular stage of the discharge at which the photograph was taken was determined by the position of the gating pulse with respect to the initiation of current flow in the discharge.

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*The tube used in the present work was the PIM-3 image converter developed by M. M. Butslov.