PHOTOPRODUCTION OF NEGATIVE Π MESONS ON DEUTERIUM

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(presented by M. I. Adamovich)

Introduction

Studies of the photoproduction of charged π mesons from deuterium enable one to obtain data on the dependence of the process upon the charge, nucleon spin, and the nucleon binding in a deuteron. A number of experiments [1,2,3] were devoted to an investigation of the ratio π^-/π^+.

In order to be able to interpret the experimental results and to compare them with existing meson theories it must be known to what extent the deuteron ratio π^-/π^+ approaches the ratio for free neutrons and protons. Hence, it must be established experimentally whether the hypothesis that the electromagnetic interaction causing the production of photomesons from deuterium is the same as the interaction with individual nucleons in a nucleus is valid. The effect of the Pauli principle, of the Coulomb and nuclear interaction between nucleons must also be studied.

Experimental investigations [3,5] of the cross section ratio of positive hydrogen and deuterium mesons were made in connection with the above questions. But the results of these investigations did not allow an examination of the correctness of the impulse approximation to be made or to establish to what extent the Pauli principle influences photoproduction of π mesons from deuterium. As a result of the experiment [6] contradictory data were obtained; on the one hand the angular distribution showed an agreement with the impulse approximation, while on the other hand an evident divergence in the energy distribution of the recoil protons was observed.

Experiment

Proceeding from the above, it was decided to determine the peculiarities of the negative photomesons production on deuterium, to establish the influence of the nucleon blinding and of the Pauli principle, and to check the validity of impulse approximation. For this purpose the reaction $\gamma + d \rightarrow p + p + \pi^-$ was studied in detail using the method of nuclear photoplates. Type P plates, 400μ thick, produced by the Research Institute for Cinematography and Photography (NIKFI), sensitive to tracks of relativistic particles were used for this study. Previous to exposure, a set of plates was loaded with heavy water at a temperature of 18° to 19° C. The amount of heavy water in the emulsion was determined by checking the weight of every plate on analytical balances previous to and after loading. A plate of $3{,}0 \times 6{,}0$ cm^2 absorbs, on the average, 0,770 gm. of heavy water. In the case of such loading, the thickness of the emulsion layer equals 800 μ during exposures, and 1 cm^3 of emulsion contains $3{,}2 \times 10^{22}$ deuterium nuclei.

The plates were exposed to a collimated Bremsstrahlung beam with a maximum energy of 250 Mev (fig. 1) produced by means of the Lebedev Physical Institute Synchrotron. The angle between the direction of photons and the

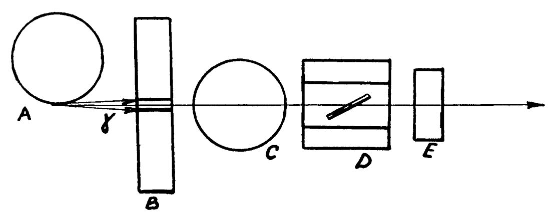

Fig. 1. Geometry of the experiment.
A. Synchrotron target.
B. Lead collimator.
C. Magnet.
D. Photoplate, screened by carbon blocks.
E. Graphite ionisation chamber.
γ. Photon beam.

emulsion surface of the plates was 30°. A magnetic field intensity of 7000 oersteds removed the electrons accompanying the photon beam. To protect the plates from scattered radiation they were surrounded by carbon blocks. The photon flux passing the emulsion, was determined by means of a graphite ionisation chamber mounted directly behind the plate. A mean flux of energy of 6.10^8 Mev per cm^2 passed through each plate during exposures. To avoid latent image regression the plates were developed immediately after exposures, using amidol developer according to NIKFI method. The uniformity of development was found to be quite satisfactory.

The scanning of photoplates was carried out by means of a MBI-2 microscope, with magnification $20 \times 10 \times 1{,}5$.

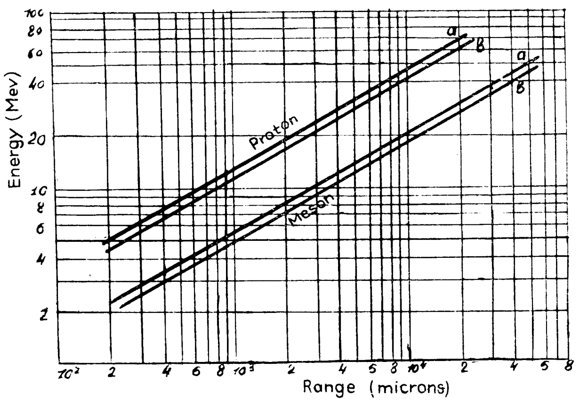

Fig. 2. Range-energy curves for loaded type-P emulsion.
(a) 35 per cent loading.
(b) 60 per cent loading.

The scanning efficiency of every plate was examined twice by different observers and was found to be not less than 95 per cent.

Three-prong stars found in emulsion were analysed in order to select cases, related to reaction $\gamma + d \rightarrow p + p + \pi^-$. This analysis is based on the application of conservation laws. For this purpose the energy and the angle of emission of all particles of a star were determined in relation to the direction of the photons. The energy of the particles remaining in the emulsion was determined according to the residual range. The calculated curves of the range-energy relation for two different percentages of loading are given in fig. 2. The energies in Mev and particle ranges in microns are marked along the axes. The energy of particles leaving the emulsion was determined by measuring the grain density of a track in a cell of 500 μ. Calibration curves of the dependence of the grain density upon the residual range of protons and mesons were obtained for every set of plates. A typical curve obtained for one of the treated sets of plates is given in fig. 3.

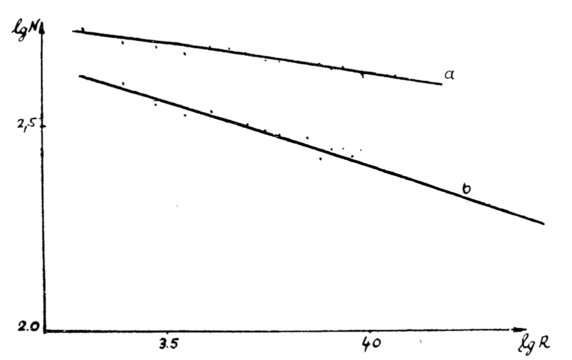

Fig. 3. Experimental range-grain density curve of protons and mesons for one of the treated sets.
(a) Proton.
(b) Meson.

Along the Y-axis are plotted the logarithms of grain density, along the X-axis—the logarithms of the residual range. The sensitivity of the plates is reduced according to the loading. This allows one to count the grains in order to determine particle energies in a wide interval. But only π mesons with energies not exceeding 45 Mev could be registered by means of the above plates. Therefore only an interval of photon energies not exceeding 200 Mev is discussed in the present paper. The precision of the particle energies measurements according to their grain density was 10 to 15 per cent.

Identification of tracks stopping in the emulsion offered no difficulties. Identification of tracks escaping the emulsion was carried out, when possible, according to the grain density in a track and measurements of the multiple scattering. A special microscope MB1-8 was used to measure the multiple scattering by means of the coordinate method. Fig. 4 shows the separation of proton and meson

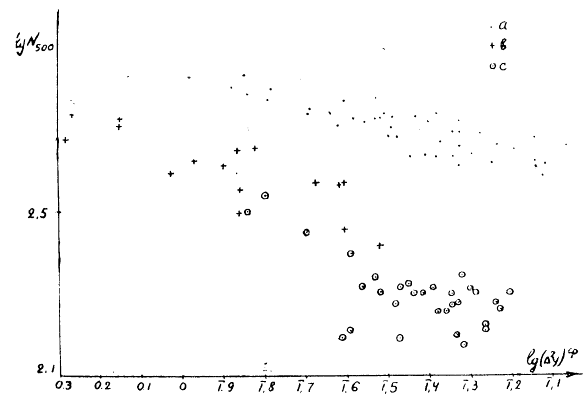

Fig. 4. Grain density-scattering dependence for protons and mesons of one of the treated sets.
(a) Protons.
(b) π mesons.
(c) π mesons of reaction $\gamma + d \rightarrow p + p + \pi^-$.

tracks according to the grain density and the multiple scattering. The logarithm of grain density is given along the Y-axis, logarithm of the 2nd difference—along the X-axis. The primary cell was equal to 50 μ, the secondary to 500 μ. π mesons of the reaction $\gamma + d \rightarrow p + p + \pi^-$ leaving the emulsion are marked with circles. In cases when multiple scattering could not be measured, tracks were identified according to the grain density, using one of the three equations of the law of energy and momentum conservation. A vector diagram of momenta was drawn from the measured particle energies in a star and the total momentum $\overline{P}_{st}$ of a star was determined. The photon momentum $\overline{P}_\gamma$ equal to the sum of the kinetic energies of the particles, rest energy of meson and the binding energy were plotted on the same diagram in the direction of the beam.

The value ($\overline{P}_{st} - \overline{P}_\gamma$) was determined from this diagram for each star. The distribution according to this para-

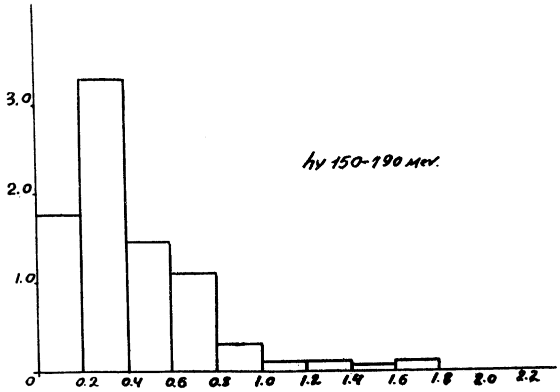

Fig. 5. Distribution of $(\bar{P}_{st} - \bar{P}_{\beta})$ for plates loaded with D_2O. For momenta are used units in which proton mass is $M_p = 1$.

meter of stars developed on plates treated with heavy water is given in fig. 5. The distribution is maximum for values $(\bar{P}_{st} - \bar{P}_{\gamma})$ about 0.4 and decreases sharply in the interval from 0.4 to 1.0.

An experiment with ordinary water was undertaken for control purposes. All three-prong stars were treated on these plates in the same way. Their distribution according to the parameter $(\bar{P}_{st} - \bar{P}_{\gamma})$ is given in fig. 6. It differs sharply from the distribution given in fig. 5. The total area examined on plates loaded with H_2O constituted 64 cm². No stars for which the parameter $(\bar{P}_{st} - \bar{P}_{\gamma})$ was less than 1.0 were discovered over the above area. Therefore, we refer cases in which the values of $(\bar{P}_{st} - \bar{P}_{\gamma})$ are less than 1.0 to the reaction $\gamma + d \rightarrow p + p + \pi^-$.

406 stars, which can be identified with the investigated reaction, were discovered over an area of 1.224 cm² of emulsion loaded with heavy water.

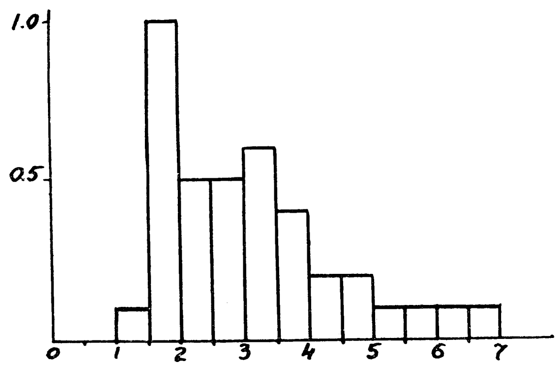

Fig. 6. Distribution of $(\bar{P}_{st} - \bar{P}_{\beta})$ for plates loaded with H_2O. Units same as in Fig. 5.

Results of the experiment

259 cases related to the interval of photon energies of 150 to 200 Mev were discovered over an area of 1,224 cm².

The dependence of the total cross-section of the photoproduction of negative π mesons upon photon energies is given in Table I. The spectrum of the bremsstrahlung is taken according to Schiff [4]. Only the statistical errors were shown. Data [7] of the π^+ mesons photoproduction from a free photon are also given for comparison.

TABLE I

The dependence of the total cross-section of the π meson photoproduction upon photon energies.

cm² E_{mev}	150-160	160-170	170-180
σ_d^- 10^{29}	2.8 ± 0.6	7.1 ± 0.9	8.8 ± 1.1
σ_p^+ 10^{29}	—	7.0 ± 0.48	9.2 ± 0.7

All stars of the studied reaction were divided into three classes. Stars in which one proton has an energy more than 10 Mev and exceeds by at least 9 times the energy of the second proton are referred to the class 1. This condition will become clear from the following discussion of the results. This type of star is distinguished by the fact that a proton possessing a greater energy carries away almost the whole momentum of the photon. The angular distribution of the rapid protons is represented in fig. 7. Stars in which the two protons are of about the same energy and possess a large relative kinetic energy were referred to the second class.

The difference and the sum of the momenta of the two protons had also been measured for each star referred to the above two classes. The distribution of the reaction

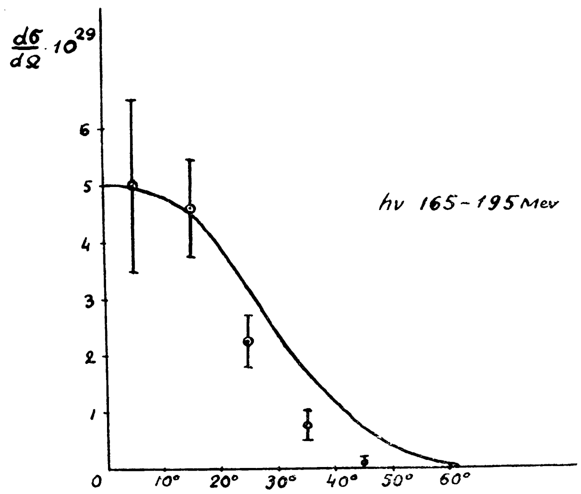

Fig. 7. Angular distribution of high energy protons for stars referred to as class 1.

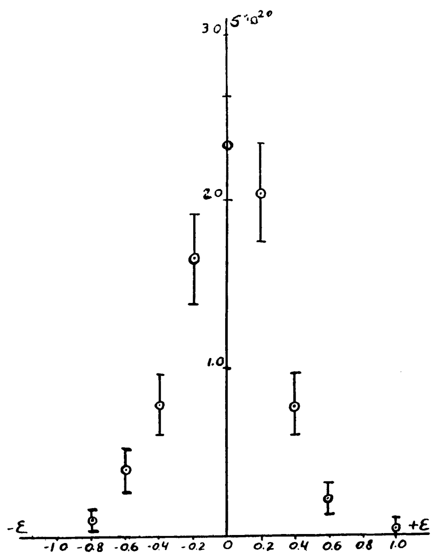

Fig. 8. ε distribution.

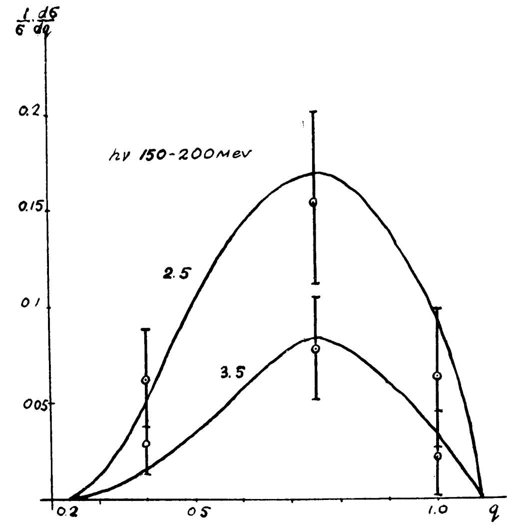

Fig. 10. Distribution according to q of class III stars. Curves — theoretical calculations for two values of q/p.

$\gamma + d \rightarrow p + p + \pi^-$ according to a parameter $\varepsilon = \frac{|\overline{P}_1 - \overline{P}_2| - |\overline{P}_1 + \overline{P}_2|}{2}$ describing indirectly the angle between the protons, is given in fig. 8. P_1 and P_2 are the momenta of the first and second protons, respectively ($\mu c = 1$, where μ is the mass of a π meson).

The protons of stars referred to the third class are of about the same energies and of a low relative kinetic energy. When comparing with the theoretical data, cases were considered in which the half-sum ratio of two protons momenta (q) and their half-difference (p) exceeded 2,5 and 3,5, respectively, (see "Discussion of the results"). The relative kinetic energies of the protons was for these values of Q/p of the order 1 Mev.

The distribution according to p of values q/p, larger than 2,5 and 3,5, respectively, is shown in fig. 9. The ratio of the differential cross section with respect to p, to the total cross section of the reaction is plotted on the Y-axis. The distribution according to q of values q/p exceeding 2,5 and 3,5 respectively, is given in fig. 10. The statistical errors are shown in figs. 9 and 10. For the values of momenta units were taken, in which $\mu c = 1$, where μ — is the mass of a π meson.

The yield of the reaction $\gamma + d \rightarrow p + p + \pi^-$ depending upon the relative kinetic energy of two protons is shown in fig. 11.

The angular distribution corresponding to the reaction of photoproduction of π^- mesons on deuterium in the

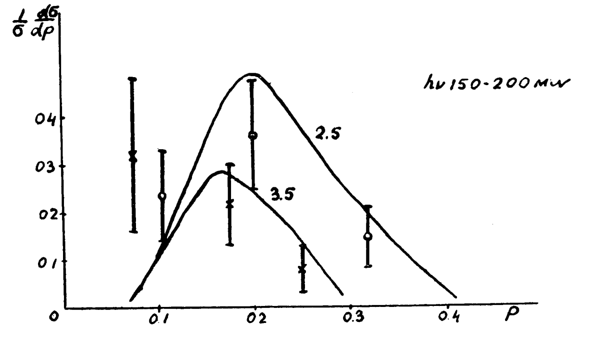

Fig 9. Distribution according to p of class III stars. Solid curves — theoretical calculation for two values of q/p.

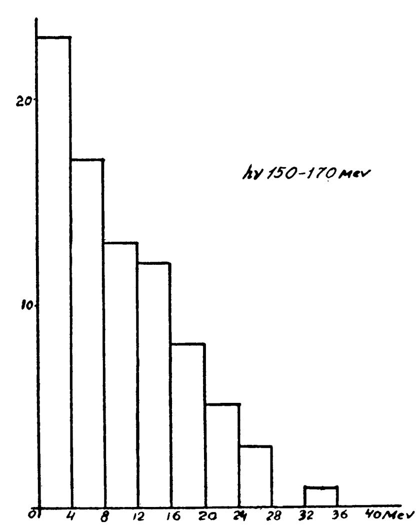

Fig. 11. Reaction yield depending upon the relative kinetic energy of two protons.

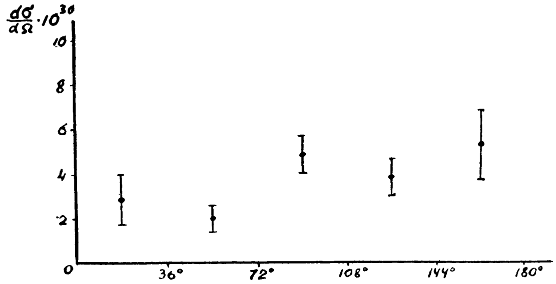

Fig. 12. Angular distribution of π mesons in c.m.s. for photon energy interval from 170 to 185 Mev.

c.m. system in the photon energy intervals from 150 to 170 and 170 to 185 Mev, respectively, is given in fig. 12 and 13. Statistical errors are also indicated.

Values of $\frac{d\sigma}{dp_\pi}$, $\frac{d\sigma}{dp_\pi/p_\pi}$ and $\frac{d\sigma}{dp_\pi/p_\pi^3}$ where p_π is the momentum of a π meson in the c.m. system are shown in Table II. The statistical errors are given in the table, the momenta being expressed in Mev/c.

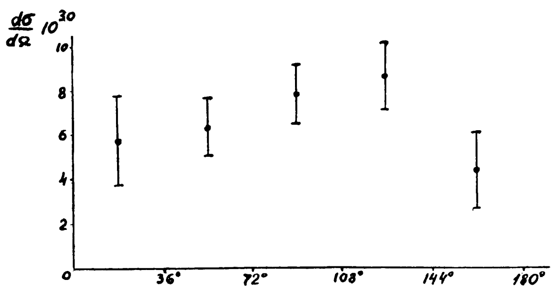

Fig. 13. Angular distribution of π mesons in c.m.s. for photon energy interval from 170 to 185 Mev.

Discussion of the results

From the dependence of the reaction cross section upon the relative kinetic energy, represented in fig. 11, it follows that cases, where the relative energies of two protons are up to 12 Mev, constitute about 65 per cent of the cross section values in an energy interval from 150 to 170 Mev.* On the other hand, as is seen from Table I, the cross-section in the production of photomesons on deuterium is of the same order of magnitude as that for hydrogen.[7] This experimental fact allows us to arrive at a qualitative conclusion concerning spin flips of nucleon systems, when photoproduction of π mesons is taking place. If the radius of nuclear forces is taken for the dimension of the nucleon system, triplet spin state for energies, roughly speaking, less than 12 Mev, is forbidden by the Pauli principle.

The value of the π^- meson photoproduction cross-section on deuterium, for relatively small proton energies, comparable to the π^+ mesons cross section on hydrogen, suggests a spin flip of a nucleon system. This means that the interaction hamiltonian has a term, depending upon the spin of the nucleon system.

In the report by A. M. Baldin, a theoretical calculation of the respective number of reactions is given, in which the value of q/p exceeded 2.5 and 3.5. It was assumed that a photomeson is produced in a nucleon. Furthermore, the Coulomb and nuclear interaction of protons in final states were taken into account. Two cases were examined : 1. Assuming the absence in the hamiltonian of a term, depending upon nucleon spin. 2. Assuming the hamiltonian to consist of only one term, depending upon the nucleon spin and responsible for the spin flip. The data and results of these two cases of calculations are summarized in Table III.

TABLE II

The dependence of the π meson photoproduction cross-section upon the meson momentum in c.m.s.

$P_\pi \left(\frac{\text{Mev}}{c}\right)$ cm²	10-20	20-30	30-40	40-50
$\frac{d\sigma}{dp_\pi} \cdot 10^{-30}$	0,14 ± 0,07	0,35 ± 0,11	0,62 ± 0,15	0,83 ± 0,17
$\frac{d\sigma}{dp_\pi/p_\pi} \cdot 10^{-31}$	0,093 ± 0,048	0,140 ± 0,043	0,177 ± 0,043	0,185 ± 0,038
$\frac{d\sigma}{dp_\pi/p_\pi^3} \cdot 10^{-34}$	0,403 ± 0,202	0,225 ± 0,071	0,145 ± 0,035	0,091 ± 0,019

* For smaller values of this parameter the statistical accuracy of the experiment must increase, but the theory is valid only under these conditions.

TABLE III

Percentage of cases			
q/p >	Experiment	Spin flip not accounted for in the theory	Spin flip accounted for in the theory
2.5	8.5 ± 1.8	0.010	8.4
3.5	3.9 ± 1.2	0.002	3.2

Experimental results are incompatible with calculations based on the case 1, and are fairly consistent with the results of calculations for case 2.

The agreement of our results with theoretical calculations, if interaction depending upon nucleon spin is taken into account, is also confirmed when comparing the experimental p and q distributions with the theoretical ones (see figs. 9 and 10). It must be pointed out that a divergence in the p distribution with the theoretical results is observed when $q/p \geqslant 3.5$. This divergence may, possibly, be caused by insufficient statistical accuracy. The experimental and theoretical data are compatible in the case of a greater statistical accuracy ($q/p \geqslant 2.5$).

Thus, a study of the reaction $\gamma + d \rightarrow p + p + \pi^-$ in cases of relatively low kinetic energies of two protons confirms the validity of the theoretical assumptions, concerning photoproduction from a nucleon and the nuclear interaction of protons in final states. A considerable percentage of cases, when the angle between two emitted protons is small, may lead to an increase of the amount of protons with high energies, when recording them by means of a scintillation counter, as it was observed in the experiment by Keck and Littauer [6]. This effect may, probably, explain the contradictions of this experiment.

The angular distribution of protons with energies larger than 10 Mev and exceeding by at least 9 times the energy of the second proton is given in fig. 7. Reactions referred by us to the class 1 satisfy this condition. The theoretical curve calculated by Baldin [8] using impulse approximation, interpreting the interaction between photon and deuteron as the sum of interactions with individual nucleons, is given in the same fig. The Coulomb interaction, which should be essential for proton energies less than 10 Mev, has not been taken into account in calculations. A satisfactory agreement between the experimental and theoretical data (within the limits of the statistical accuracy) confirms the above assumption about the interaction of photons with individual nucleons, causing photoproduction of negative π mesons from deuterium. A sufficiently accurate experimental distribution of the reaction $\gamma + d \rightarrow p + p + \pi^-$ according to the parameter ε may, apparently, also serve as a check for this statement.

Thus, an examination of the characteristics of the protons in reactions $\gamma + d \rightarrow p + p + \pi^-$ enables one to conclude that negative photomesons are produced from individual neutrons of deuterium.

The angular distribution of the photomesons from deuterium in the mass-centre system for photon energy interval from 150 to 170 and 170 to 185 Mev, respectively, are given in figs. 12 and 13. The curves of angular dependences of hydrogen cross-sections are similar [7]. This suggests, obviously, that photoproduction of negative π mesons on neutrons of deuterium are quite similar to that of positive mesons on protons. Thus, the experimental angular dependences for deuterium cross sections may be interpreted as a production of π mesons on individual nucleon in S and P-states. Being isotropic the angular distribution of π mesons (in the limits of statistical accuracy) suggests a prevalence of electric dipole absorption of γ quanta by an individual nucleon near meson threshold. As is seen from Table II this conclusion is confirmed by the fact that the cross section of negative photomesons from deuterium (in the c.m. system) is in agreement with the linear dependence upon the impulse $P\pi$ and shows a disagreement with the dependence $P^3\pi$.

The electric dipole absorption of photons by an individual nucleon of deuterium expressed in terms of phenomenological theory with impulse approximation, means that near the meson threshold an interaction hamiltonialy consists of a single term only, depending upon the nucleon spin.

The latter agrees with our conclusions about the effect of spin flip, when photomesons are produced from deuterium, arrived at when examining protons in the reaction $\gamma + d \rightarrow p + p + \pi^-$.

Conclusions

The present paper allows one to draw the following conclusions :

1. Negative photomesons are produced on individual neutrons of deuterium.

2. Near the threshold the photoproduction of π mesons on deuterium is accompanied by spin flips, i.e. the interaction hamiltonian contains only one term, depending upon nucleon spin.

3. Nuclear interaction of protons in the final state does exist.

4. Production of π mesons in S-states prevails near meson threshold, which means, together with conclusion 1, that there is an electric dipole absorption of photons by neutrons.

LIST OF REFERENCES

1. Sands, M., Teasdale, J. G. and Walker, R. L. Negative to positive ratio of photomesons from deuterium. Phys. Rev., *95*, p. 592-3. 1954.
2. Beneventano, M., Carlson-Lee, D. and Stoppini, G. The π^-/π^+ ratio from deuterium near photo-pion threshold. Nuov. Cim. *12*, p. 156-9, 1954.
3. White, R. S., Jacobson, M. J. and Schulz, A. G. The production of charged photomesons from deuterium and hydrogen. Phys. Rev., *88*, p. 836-50, 1952.
4. Schiff, L. I. Energy-angle distribution of thin target Bremsstrahlung. Phys. Rev., *83*, p. 252-3, 1951.
5. Lebow, I. L., Feld, B. T., Frisch, D. H. and Osborne, L. S. Photomeson production from deuterium. Phys. Rev., *85*, p. 681 1952.
6. Keck, J. and Littauer, R. Production of photomesons in deuterium. Phys. Rev., *88*, p. 139-40, 1952.
7. Rochester Conference on high energy nuclear physics. 5th, Proceedings, 1955.
8. Baldin, A. M. On the theory of photoproduction of mesons on bound nucleons. See p. 272.

DISCUSSION

L. S. Osborne asked whether M. I. Adamovich had any figures for the variation of meson energy for a given photon energy from deuterium as compared with a single proton and whether the meson energy is less than that corresponding to a single nucleon.

M. I. Adamovich replied that they had no data for a mono-energetic γ ray beam. For the spectrum of the beam they used the meson energy is less than that corresponding to a single nucleon for energies ranging between threshold and 170 Mev.