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PHOTOPRODUCTION OF CHARGED MESONS FROM DEUTERIUM AND THE π^-/π^+ RATIO

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We have used a 4-in. diameter deuterium bubble chamber at the Lawrence Radiation Laboratory electron synchrotron to observe the reactions

$$\gamma + d \to \pi^- + 2p, \tag{1}$$

and

$$\gamma + d \to \pi^+ + 2n \text{ (followed by } \pi^+ \to \mu^+ + \nu), \tag{2}$$

in the interval between threshold and 194-Mev photon energy (lab).[1] In Reaction (1), sufficient final-state information was obtained to determine the kinematical parameters required to calculate the final-state Coulomb effects. By correcting the observed ratio $R_d = (\sigma_{\gamma d \to \pi^-})/(\sigma_{\gamma d \to \pi^+})$ to account for the final-state Coulomb interactions, we obtained values of the ratio $R = (\sigma_{\gamma n \to \pi^-})/(\sigma_{\gamma p \to \pi^+})$ (see Table I), which involves the reaction of

Table I. σ^-/σ^+ as a function of photon energy and meson angle.

Bins	Spectator photon energy (Mev)[a]	θ^* pion c.m. angle, (deg)	σ^-/σ^+ Before (R_d) Coulomb correction	σ^-/σ^+ After (R) Coulomb correction
I	152 - 158	0 - 90	1.22 ± 0.16	1.08 ± 0.14
II	158 - 165	90 - 140	1.36 ± 0.19	1.27 ± 0.18
III	165 - 175	135 - 180	1.54 ± 0.21	1.44 ± 0.20

[a]The spectator photon energy (lab) and pion angle θ^* (lab) are from $(\gamma + p \to \pi^+ + n)$ two-body kinematics.

principal interest:

$$\gamma + n \to \pi^- + p. \qquad (3)$$

Very basic theoretical assumptions[2] lead to the conclusion that R is 1.28 at threshold, independent of the details of the meson-nucleon interaction, if nucleon recoil is included and final-state Coulomb effects are excluded. Ball[3] has recently estimated $R = 1.28(1 - 0.14\Lambda)$, where Λ is a parameter, measured in units of $e = 1/(137)^{1/2}$, arising from the photon three-pion interaction. Low-energy positive and neutral photopion production and neutral pion decay data are not inconsistent with a value of Λ as large as unity, but small values for Λ are not excluded. Our data are consistent with a value $\Lambda = +1.1$.

The question of general agreement among several measured threshold pion parameters[4-6] requires knowledge of R, and a value near that predicted is required for agreement. Several groups[7-9] have investigated Reactions (1) and (2) near threshold, and have determined that the ratio R_d lies in the range 1.3 to 2.1, before Coulomb corrections are made. However, their knowledge of the final-state parameters was generally insufficient to allow a detailed correction.

Baldin[4] has employed the impulse approximation to calculate the corrections needed to account for the Coulomb interactions between all final-state particles in Reaction (1); no correction is necessary in Reaction (2). We have uniquely determined the kinematical parameters required for the Baldin corrections in the energy range $152 \leq k \leq 175$ Mev.

The experimental arrangement is shown in Fig. 1.[10] In an auxiliary experiment, a pair spectrometer was used to determine both the peak energy and the spectrum of the hardened bremsstrahlung beam incident on the bubble chamber. All together, 1300 analyzable π^- events and 450 $\pi^+ \to \mu^+$ events were found. After the multipronged events were located, each was measured and the angles and lengths of the tracks were calculated. By means of energy-momentum conservation laws we were able to determine completely any π^- event in which three prongs were visible and those events in which only two prongs were visible but both prongs stopped in the chamber. The background of single-prong heavy-particle events was about one per picture. The occasional scattering of a photoproton by a deuteron was distinguished from Reaction (1) on the basis of kinematics, ionization, or location of the vertex.

Reaction (2) was identified by the characteristic range of the muon (1.004 ± 0.053 cm in the bubble chamber), and in 27% of the cases by the electron decay of the muon as well. Because of the requirement for identification of the π^+, the π^+ and π^- energies accepted for the calculation of R were limited to energies (lab) of 3 to 9 Mev. A total of 299 π^+ (out of 450 observed) and 369 π^- events satisfying all criteria was found within these energy limits. Corrections were made for the efficiency of observing the events by means of a Monte Carlo calculation on an IBM 704. An additional 9.5% correction was applied to the π^- data to account for scanning efficiency and for events missed because both recoil protons were invisibly short or too short to be measured satisfactorily. For consistency in the evaluation of the ratio R_d, two-body kinematics were used to

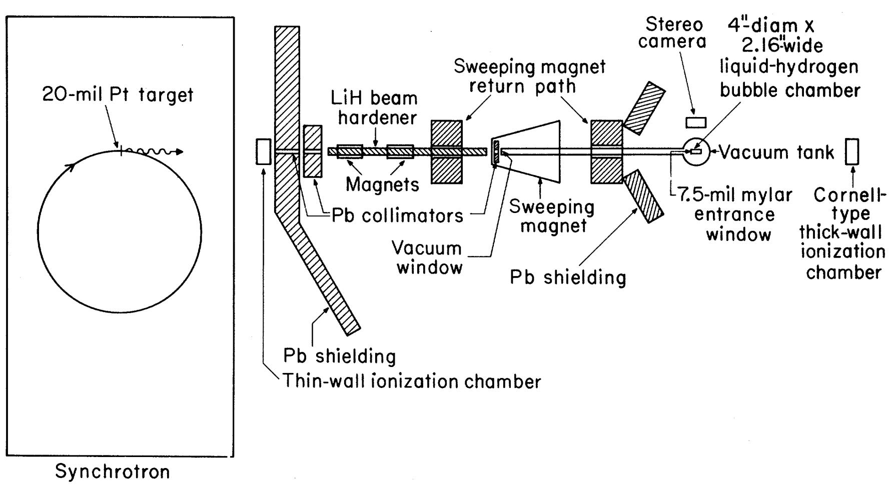

FIG. 1. Schematic diagram of setup.

determine k in both reactions, because they were necessary in Reaction (2).

Using the impulse approximation, Baldin[4] has calculated the spin-flip part of the cross section for π^- production from deuterium as

$$\partial^2\sigma/\partial p\partial q = A(p, q)\,|K^{(-)}|^2,$$

where the final-state Coulomb interactions are ignored in obtaining the values for $A(p, q)$. Near threshold, the no-spin-flip term is negligible. The quantities p and q are, respectively, half the vector difference and the vector mean of the momenta (lab) of the recoiling nucleons, and $|K^{(-)}|^2$ is the square of the matrix element for Reaction (3). By using exact Coulomb wave functions, values of $A^c(p, q)$ are also obtained to replace $A(p, q)$ when p-p final-state Coulomb effects are included. From Baldin's tabulated values we have applied a correction by weighting each event by the ratio $A(p, q)/A^c(p, q)$. The average value of the correction is +5.49 %.

The π-p final-state Coulomb correction (average value = -14.6 %) was estimated for each pion momentum (lab) $\vec{p}_\pi$ by dividing the number of events of pion momentum $\vec{p}_\pi$ by Baldin's expression

$$1+\frac{2\pi e^2}{|\vec{p}_\pi - \vec{q}/M|}.$$

This correction is roughly independent of photon energy, for a given pion momentum and direction. After both the p-p and π-p corrections were made, the combined average Coulomb correction was -8.6 %.

Before Coulomb correction, the average ratio was $R_d = 1.38 \pm 0.12$; after Coulomb corrections, the average ratio was $R = 1.27 \pm 0.11$.

The pions included had an average kinetic energy (lab) of 6.15 Mev and angle 90 deg, corresponding to the photon energy (lab) of 162 Mev and c.m. pion angle 120 deg, in the two-body ($\gamma + p \rightarrow \pi^+ + n$) center-of-mass system. However, these spectator photon energies range from 152 Mev at forward pion angles to 175 Mev in the backward direction.

The data, broken down into three bins roughly according to spectator photon energy, are presented in Table I. The points show the expected increasing trend with photon lab energy and pion c.m. angle. After Coulomb correction, the two points at higher energy are in agreement, within statistics, with the dispersion relations and with previous experiments in this range corrected for

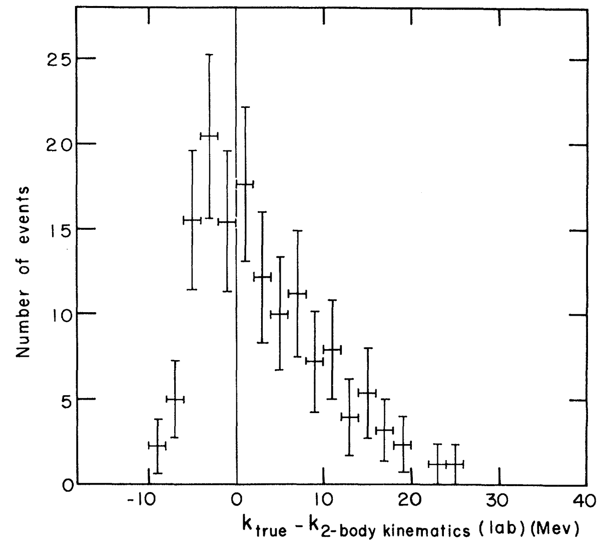

FIG. 2. Laboratory-system photon energy distribution for the negative photopion events of Bin II, Table I. The abscissa is obtained by subtracting the spectator photon energy (obtained from two-body kinematics) from the true photon energy for each event. The two-body kinematics gave a lab photon energy in the range 158 to 165 Mev and a c.m. pion angle $\theta^* = 90$ to 140 deg for events in this bin.

final-state Coulomb interactions. The point at lowest energy is below the theoretical value by two standard deviations. This may reflect the influence of the parameter Λ. If so, this value of R corresponds to a value $\Lambda = +1.1$.

A typical distribution of photon energies contributing to the bins of Table I is presented in Fig. 2. As may be seen, the distribution is peaked at its spectator energy, but also has a high-energy tail which makes an important contribution. The distribution is in qualitative agreement with calculations made by Beneventano et al.,[9] and justifies the use of two-body kinematics in determining the photon energy for ratios determined in this manner.

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TOTAL CROSS SECTION FOR $\gamma+n\rightarrow\pi^-+p$ NEAR THRESHOLD BY CHEW-LOW EXTRAPOLATION

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The basic reaction

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

has previously been studied[1] near threshold by measuring the ratio

$$R_d=\sigma(\gamma+d\rightarrow\pi^-+2p)/\sigma(\gamma+d\rightarrow\pi^++2n),$$

and inferring the parameters of interest from R_d and the measured cross section for the reaction $\gamma+p\rightarrow\pi^++n$. Two separate experiments are required, and Coulomb corrections to R_d near threshold are large and not well understood.

A new approach to the study of Reaction (1) is now possible through the recently developed Chew-Low technique[2] of extrapolating certain recoil-nucleon momenta into the nonphysical region. The method is both powerful and quite general. When the method is specialized to treat the reaction

$$\gamma+d\rightarrow\pi^-+2p \tag{2}$$

near threshold, the data are extrapolated to a pole in the transition amplitude in the nonphysical region of negative kinetic energy of the recoiling spectator proton [of Reaction (2)]. The residue of this pole is proportional to the T matrix for Reaction (1). At the pole, the "spectator" proton has a negative kinetic energy in the final state just equal to its share of the (negative) deuteron binding energy in the initial state. The recoil proton is really a noninteracting spectator at the pole in the nonphysical region. The total cross section near threshold for Reaction (1) on free stationary neutrons, deduced directly from the extrapolation, involves no uncertainties arising from the presence of the second nucleon in the target deuteron. The Chew-Low method requires somewhat greater numbers of events than usual for a given statistical error in the result, but this difficulty is compensated by the new ability to use unstable particles as free stationary targets.

Reaction (2) was observed in a deuterium bubble chamber,[1] with complete final-state kinematics known for each event. These data were extracted from the observations discussed in the authors' previous Letter.[1]

The free-nucleon cross sections $\sigma(\gamma+n\rightarrow\pi^-+p)$ have been obtained at five effective photon energies by this method, which requires that one carry out the following limiting procedure:

$$\sigma(w^2)=\lim_{p^2\rightarrow-\alpha^2}\frac{4\pi k^2}{\Gamma^2}\,\frac{M_d}{M_p}\,\frac{(p^2+\alpha^2)^2}{(w^2-M_n^{\,2})}\,\frac{\partial^2\sigma}{\partial p^2\partial w^2}.$$

Here k = laboratory-system photon energy, M_d = deuteron mass, M_p = proton mass, M_n = neutron mass, p = momentum (lab) of recoil proton (lower-energy proton), α^2 = (deuteron B. E.)M_p, w = internal total energy of the (π^-+p) system, $\Gamma^2=(4/M_p)\times\alpha/(1-\alpha r_0)$, $r_0=n$-p triplet effective range, and $\hbar=c=\mu=1$.

In compiling the data, plots of the events, such as Fig. 1, were used. The curves in p^2, w^2 designate the boundaries for kinematically possible values of p^2 and w^2 for the photon energies 160 Mev and 165 Mev.

The data were averaged over those real photon energies from 150 to 180 Mev which were capable of contributing to the various w^2 bins.