Charged-π Photoproduction at 180° in the Energy Range between 300 and 1200 MeV

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The differential cross sections at 180° for the reactions $\gamma+p\rightarrow\pi^++n$ and $\gamma+n\rightarrow\pi^-+p$ were measured using a magnetic spectrometer to detect $\pi^\pm$ mesons. In order to reduce the spread of energy resolution due to the nucleon motion inside the deuteron, a photon difference method was employed with a 50-MeV step for the reaction $\gamma+n\rightarrow\pi^-+p$. The data show structures at the second- and the third-resonance regions for both reactions. A simple phenomenological analysis was made for fitting the data, and the results are compared with those of previous analyses.

For studying the electromagnetic character of nucleon resonances, the measurement of $(d\sigma/d\Omega)_{180°}$ in the energy range below 1200 MeV is of special interest for the following reasons: (a) The dominant resonances such as $D_{13}(1518)$ and $F_{15}(1688)$ are known to be photoexcited mainly by the helicity-$\frac{3}{2}$ amplitudes.[1] The direct measurement of the energy dependence of $(d\sigma/d\Omega)_{180°}$ provides a sensitive test of their smallness in the helicity-$\frac{1}{2}$ amplitude. (b) The effect of the third resonance has been scarcely observed in any previous measurement of the reaction $\gamma+n\rightarrow\pi^-+p$,[2] while it does exist in $\gamma+p\rightarrow\pi^++n$. The eventual cancelation between the isovector and isoscalar parts for the B_3 amplitude is related to the quark-model prediction.[3] It is interesting to see the situation for the pure helicity-$\frac{1}{2}$ amplitude, even if it may be small. (c) The Stanford measurement[4] of $\gamma+p\rightarrow\pi^++n$ at 180° has revealed a sharp structure around $k=700$ MeV, suggesting a cusplike effect at the threshold of η^0 production. This measurement extends the π^+ data to a wider energy region and supplies new information on $\gamma+n\rightarrow\pi^-+p$ to examine the rapidly varying electric dipole amplitude in both reactions.

The experiment was performed using the bremsstrahlung beam of the 1.3-GeV electron synchrotron at the Institute for Nuclear Study, University of Tokyo. The π mesons produced from the hydrogen or deuterium target in the backward direction were momentum analyzed by a C-type wedge-shaped magnet and detected by a counter hodoscope system. The momentum acceptance of one of the hodoscope counters ranged from 1.6 to 1.30%. The brass slit at the entrance of the magnet accepted the particles with a solid angle of 6.2 msr. The field of the analyzing magnet was continuously monitored by a simple precision fluxmeter.[5] The end-point energy of the photon beam was measured with a relative accuracy of 0.2% by the synchrotron energy indicator.[6] The contribution of pions and protons produced in the target material, together with that of the upstream background, were measured with an empty cup, totaled 10-15% of the real event rate, and directly subtracted from the yield with full target.

To ensure that the net yield came from the desired process, the following procedures were taken: (a) The contribution from the double-pion production was made negligible by keeping the end-point energy of the photon beam well below the threshold of that process for the given kinematical setting. (b) To estimate the contribution of positrons and electrons from the target-produced π^0's ($\pi^0 \to 2\gamma$, $\gamma \to e^+, e^-$), check runs were performed with the magnetic field reversed. The net counts were less than 2% of the total. (c) The excitation curves were measured for $\gamma + p \to \pi^+ + n$ by varying the end-point energy of the bremsstrahlung with a constant momentum setting. They confirmed that the spectrometer was correctly set for detecting pions from the desired process.

In the measurement of $\gamma + n \to \pi^- + p$, as the spectrometer only determines the momentum vector of the pions and disregards the recoil nucleons, the effect of the Fermi motion is to broaden the resolution of the experiment. In order to reduce the energy spread, the photon difference method was employed with a 50-MeV step. By effectively selecting the reactions from neutrons of small internal momenta, the energy resolution is improved to 40 MeV in the neutron rest system at 800 MeV; it would have been 120 MeV or worse otherwise. A photon difference efficiency, which is a measure of how much of the Fermi motion is allowed to be counted by our spectrometer, was calculated by a Monte Carlo method assuming a Hulthén wave function for the neutron motion inside the deuteron.[7] The validity of the photon difference method was experimentally tested by measuring the cross sections of $\gamma + (p) \to \pi^+ + n$ with the deuterium target (D^+) and comparing with those obtained with the hydrogen target (H^+) at several energies. The ratio D^+/H^+ was found to be consistent with unity over the whole energy range, the average value being 0.99 ± 0.04.

Our results of the differential cross sections for $\gamma + p \to \pi^+ + n$ and $\gamma + n \to \pi^- + p$ are plotted in Figs. 1(a) and 1(b), respectively. The data were corrected for decay in flight and nuclear absorptions of pions. While only the statistical error was attached to each value, the systematic uncertainties were estimated to be 6% for the π^+ data and 7% for the π^- data. The behavior of the $\gamma + p \to \pi^+ + n$ cross sections is characterized by the following features: (a) The prominent peak at 300 MeV is apparently due to $P_{33}(1236)$, and its position and magnitude agree remarkably well with the recent data of Bonn.[8] (b) A sharp, small peak appears at 710 MeV riding on a broad resonance-like structure. Its shape is similar to the one found in the Stanford data, while the magnitude of our data is larger than theirs by a factor 1.5.[9] (c) A broad bump is observed between 850 and 1050 MeV, followed by a rapid decrease toward higher energy.[10]

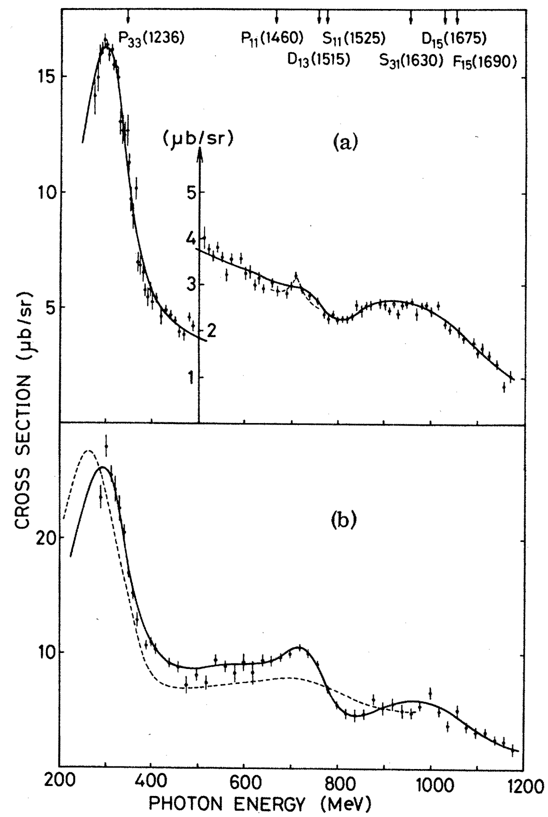

FIG. 1. Differential cross sections at 180° as functions of photon energy (a) for $\gamma + p \to \pi^+ + n$, and (b) for $\gamma + n \to \pi^- + p$. The solid curves are the resonance-model fits. The dashed line in (a) is a result of the multichannel analysis for a cusp effect. The dashed line in (b) is calculated with the amplitudes of Walker's analysis.

The cross sections for $\gamma + n \to \pi^- + p$ are approximately twice as large as those for the π^+ data, suggesting a large contribution from a proton exchange term in the Born amplitude. A conspicuous structure observed in the 700- to 800-MeV region seems to indicate a fairly large interference between a resonance wave and the background amplitude. This is in contrast to the smooth feature predicted by Walker's analysis[1] [dashed line in Fig. 1(b)]. A broad bump, similar in shape to the one in the π^+ data, also appears in the third-resonance region.

To emphasize the difference between two reactions, the ratio $\sigma_-(180°)/\sigma_+(180°)$ is plotted in

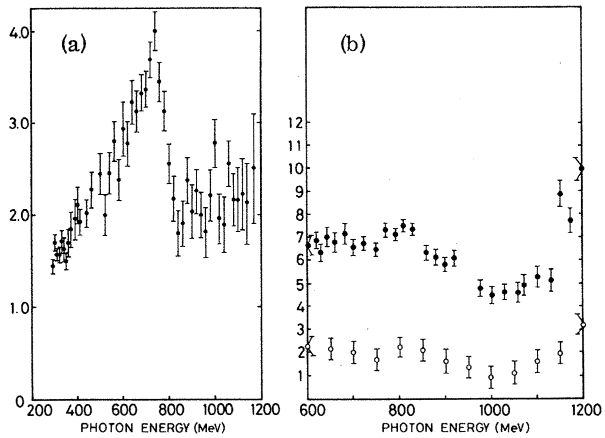

FIG. 2. Energy dependence of the ratios of cross sections. (a) $\sigma_{\pi^-}(180°)/\sigma_{\pi^+}(180°)$; (b) closed circles for $\sigma_{\pi^+}(0°)/\sigma_{\pi^+}(180°)$ and open circles for $\sigma_{\pi^-}(0°)/\sigma_{\pi^-}\times(180°)$.

Fig. 2(a). A large deviation in the second-resonance region suggests a considerable amount of an isoscalar amplitude. The rapid variation of the π^-/π^+ ratio between 600 and 900 MeV is consistent with the recent result of the Cornell group at 0°.[11] While they found a pronounced dip at 1100 MeV in their measurement between 600 and 1700 MeV, our data show a rather flat feature between 900 and 1200 MeV.

In Fig. 2(b) are presented also the ratios of cross sections at 180° to those at 0° for both reactions above 600 MeV.[12] There is a marked variation of these ratios between the second- and the third-resonance regions. Assuming that $S_{11}(1525)$ and/or $D_{13}(1515)$ are dominant in the former region, the most likely candidate for the latter region is $F_{15}(1690)$ with the opposite parity rather than $D_{15}(1675)$.

For further quantitative understanding, a simple phenomenological analysis[13] was performed based on a resonance model, following the works of Chau, Moorhouse, and Dombey[14] and Walker.[1] In this model, six resonances are taken into account: $P_{33}(1236)$, $P_{11}(1460)$, $D_{13}(1515)$, $S_{11}(1525)$, $S_{31}(1630)$, and $F_{15}(1690)$.[15] The fit was made independently for each reaction, and the best fits are shown by the solid curves in Figs. 1(a) and 1(b).

The results of the analysis are summarized as follows: (a) Small but finite amounts of the resonance amplitudes of $D_{13}(1515)$ and $F_{15}(1690)$ are seen in the helicity-$\frac{1}{2}$ state. (b) A fairly large amount of $S_{11}(1525)$ is required to explain the conspicuous structure in the second-resonance region. The difference between two reactions implies a mixture of isoscalar and isovector amplitudes. On the other hand, the same sign and nearly equal amplitudes obtained for D_{13} and F_{15} suggest the isovector dominance in these waves.[16] (c) The broad-bump structures observed for both reactions around 900 MeV were best fitted by introducing a small amount of $S_{31}(1630)$. (d) The contribution of $P_{11}(1460)$ is relatively small for both reactions. No indication was found that the excitation of P_{11} is more favorable for $\gamma+n\to\pi^-+p$ than for $\gamma+p\to\pi^++n$.[17]

In Table I are listed the resonance amplitudes obtained from our analysis together with those of Walker,[1] Moorhouse and Rankin,[18] and a quark-model prediction of Copley, Karl, and Obryk.[3] The overall agreement with the quark-model prediction is fairly good except for S_{11} and F_{15}. It should be remarked that the model essentially

Table I. Best-fit parameters. All amplitudes are normalized to Walker's amplitudes and absolute values are given for the quark-model amplitudes.

Resonance with mass and width	$\gamma+p\to\pi^++n$ This solution	Walker	Moorhouse and Rankin	Quark model	$\gamma+n\to\pi^-+p$ This solution	Walker	Quark model
$P_{33}(1236, 120)$	1.06 [a]	1.00		0.84	1.06 [a]	1.00	0.84
$P_{11}(1460, 260)$	−0.15	−0.25	−0.07	0.20	−0.20	0	0.13
$D_{13}(1515, 120)$	−0.25	−0.20	−0.14	0.15	−0.25	0	0.33
$S_{11}(1525, 80)$	−0.66	−0.65	−0.42	1.81	−1.51	−0.80	1.35
$S_{31}(1630, 160)$	−0.45	0		0.28	−0.32	0	0.28
$F_{15}(1690, 120)$	−0.20	0		$<10^{-2}$	−0.22		0.25
Background amplitude of this solution[b]		$-(2.9+0.94i)s^{-0.81}$				$-(3.4+0.81i)s^{-0.78}$	

[a]The amplitude of P_{33} was fixed to the value obtained from Noelle *et al.*, Ref. 19.
[b]s is the total energy squared in GeV^2.

determined two parameters so as to make the contributions of D_{13} and F_{15} in the helicity-$\frac{1}{2}$ state as small as possible for the reaction $\gamma+p \rightarrow \pi^+ + n$.[3] As for $S_{11}(1525)$, the model predicted large and nearly equal amplitudes for two reactions, while we found a large difference, $A(S_{11}(\pi^-)) \sim 1.5A(S_{11}(\pi^+))$.

We made an attempt to interpret a sharp peak found at 710 MeV for $\gamma+p \rightarrow \pi^+ + n$ as a cusp effect at the η^0 threshold. The dashed curve in Fig. 1(a) shows the shape obtained from our multichannel analysis with a K-matrix formalism.[20] A similar effect for the reaction $\gamma+n \rightarrow \pi^- + p$ was estimated to be about half of the one for $\gamma+p \rightarrow \pi^+ + n$, which was too small to be observed with the present energy resolution.

We are grateful to the operating crew of the Institute of Nuclear Study synchrotron for the stable operation of the machine.

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[1] R. L. Walker, Phys. Rev. 182, 1729 (1969).

[2] P. E. Scheffler and P. L. Walden, Phys. Rev. Lett. 24, 952 (1970).

[3] L. A. Copley, G. Karl, and E. Obryk, Nucl. Phys. B13, 303 (1969).

[4] L. Hand and C. Schaerf, Phys. Rev. Lett. 6, 229 (1961); C. Schaerf, Nuovo Cimento 44A, 504 (1966).

[5] H. Sasaki, Nucl. Instrum. Methods 76, 100 (1969).

[6] T. Fujii *et al.*, to be published.

[7] D. H. White *et al.*, Phys. Rev. 120, 614 (1960).

[8] G. Fisher *et al.*, Bonn University Report No. PI-1-101, 1970 (unpublished).

[9] J. T. Beale, S. D. Ecklund, and R. L. Walker, California Institute of Technology Report No. CALT-68-108, 1968 (unpublished).

[10] The recent preliminary data of the Orsay-Daresbury group on $\gamma+p \rightarrow \pi^+ + n$ at 180° seem to indicate a steeper decrease toward high energy than ours. E. F. Erickson, private communication.

[11] A. Ito *et al.*, Phys. Rev. Lett. 24, 687 (1970).

[12] Cross sections at 0° were taken from S. D. Ecklund and R. L. Walker, Phys. Rev. 159, 1195 (1967), for $\gamma+p \rightarrow \pi^+ + n$ and from Refs. 3 and 11.

[13] The details of the analysis will be published elsewhere.

[14] Y. C. Chau, R. G. Moorhouse, and N. Dombey, Phys. Rev. 163, 1632 (1967).

[15] N. Barash-Schmidt *et al.*, Rev. Mod. Phys. 41, 109 (1969).

[16] The convention for isospin decomposition used in our analysis is as follows: $\gamma+p \rightarrow \pi^+ + n$, $(\frac{1}{3})^{1/2}A_{3/2}{}^v - (\frac{2}{3})^{1/2}(A_{1/2}{}^v - A_{1/2}{}^s)$; $\gamma+n \rightarrow \pi^- + p$, $(\frac{1}{3})^{1/2}A_{3/2}{}^v - (\frac{2}{3})^{1/2} \times (A_{1/2}{}^v + A_{1/2}{}^s)$.

[17] T. Nishikawa *et al.*, Phys. Rev. Lett. 21, 1288 (1968).

[18] R. G. Moorhouse and W. A. Rankin, Nucl. Phys. B23, 181 (1970).

[19] P. Noelle, W. Pfeil, and D. Schwela, Bonn University Report No. PI-2-79, 1970 (unpublished).

[20] S. F. Tuan, Phys. Rev. 139, B1393 (1965).

Coherent Production of High-Mass Meson States in $\pi^+ d$ Collisions at 13 GeV/c*

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Evidence is found for the coherent production of high-mass meson states in the 1.6- and 1.9-GeV mass regions. These states are observed, respectively, in the 3π and 5π systems produced in the reactions $\pi^+d \rightarrow d\pi^+\pi^+\pi^-$ and $\pi^+d \rightarrow d\pi^+\pi^+\pi^+\pi^-\pi^-$ at 13 GeV/c. The spin and parity of the 3π state, identified as the A_3 meson, is determined to be in the series $2^-, 3^+, \cdots$ with a dominant $f\pi$ decay.

At present[1] evidence for the coherent production of the A_3 meson[2] has come from an experiment with 16-GeV/c negative pions on Freon.[3] The results from this experiment needed confirmation since a clear peak in the 1.6-GeV region was only observed in the $f^0\pi^-$ effective-mass spectrum and then with small statistics. Evidence from the same experiment for a coherently produced 5π state at about 1.9 GeV was presented by Huson *et al.* and Allard *et al.*[4]

The events considered in this Letter come from a completely analyzed 260 000 picture exposure of the Stanford Linear Accelerator Center 82-in. bubble chamber, filled with deuterium, to a beam of positive pions of 13-GeV/c momentum. Four- and six-prong events have been fitted[5] by the reactions

$$\pi^+d \rightarrow np\pi^+\pi^+\pi^-, \qquad (1)$$

$$\pi^+d \rightarrow np\pi^+\pi^+\pi^+\pi^-\pi^-, \qquad (2)$$

respectively. A clear deuteron signal was observed in the proton-neutron effective-mass spectra of both reactions, and events for which this effective mass was less than 1.884 GeV in