Measurement of π^-/π^+ Ratios in Photoproduction from Deuterium: The Dip Test of an Isotensor Current

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The angular distributions of π^-/π^+ ratios in photoproduction from deuterium were measured for fourteen photon energies between 260 and 800 MeV. The energy dependence of $\sigma^- - \sigma^+$ near the $\Delta_{33}(1236)$ resonance region shows no dip structure, consistent with an absence of the isotensor term. The differential cross sections of $\gamma n \to \pi^- p$ at $k = 350$ MeV are considerably larger than the ones obtained from the inverse reaction $\pi^- p \to \gamma n$, but the two are in fair agreement at $k = 500$ MeV.

Recent theoretical conjectures on an existence of an $I=2$ term in the electromagnetic current[1-4] have revived a new interest in low-energy pion photoproduction. If an isotensor amplitude T exists in addition to the ordinary isovector term V for the isospin-$\frac{3}{2}$ πN state, the radiative width of charged states of the first resonance $\Delta_{33}(1236)$ can be compared as

$$\Gamma(\Delta^0 \to n\gamma)/\Gamma(\Delta^+ \to p\gamma) = (1+x)^2,$$

where $x = (\frac{3}{5})^{1/2} T/V$. One of the experimental tests proposed by Sanda and Shaw[4] was to investigate an energy variation of the quantity

$$\Delta'(k) = (k^*/q^*)[\sigma_{\gamma n \to \pi^- p}(k) - \sigma_{\gamma p \to \pi^+ n}(k)],$$

where $\sigma(k)$ denotes a total cross section at the laboratory photon energy k, and q^* and k^* are c.m. pion momentum and photon energy, respectively. If a substantial amount of the isotensor term exists ($x \neq 0$), a dip (or peak) of approximately the width of Δ_{33} will show up in the first resonance region. On the other hand, only a slow variation due to the background is expected for $x = 0$.

The existing experimental data have so far presented an interesting but somewhat confusing aspect for this test.[5-8] A main uncertainty comes from the data on the reaction $\gamma n \to \pi^- p$, while the reaction $\gamma p \to \pi^+ n$ has been thoroughly investigated. In order to provide precise $\gamma n \to \pi^- p$ data, a part of which would serve for this test, we have made a systematic investigation of π^-/π^+ ratios from deuterium. The data were taken in 15° steps in the c.m. angular range $\theta^* = 30°-150°$ and at fourteen photon energies between 260 and 800 MeV. As is well known, the ratio method has the following advantages for obtaining the cross section for free neutrons: (1) Most of the uncertainties due to deuteron effects, such as the Pauli exclusion principle and final-state interactions, are eliminated to first order. (2) Since the energy variation of the ratio has turned out to be not so rapid, the energy resolution is not much impaired by the internal motion of nucleons inside the deuteron. (3) The Coulomb correction due to the difference in the final charge states was estimated to be negligibly small except at forward angles.[9] (4) Subtle experimental corrections due to π-μ decays and nuclear absorptions are irrelevant to the ratio measurement.

The experiment was performed using the bremsstrahlung beam of the 1.3-GeV electron synchrotron at the Institute for Nuclear Study (INS), The University of Tokyo. The π mesons produced from the liquid deuterium target were detected by a 700-MeV/c spectrometer, which consists of a momentum-analyzing magnet, three sets of scintillation hodoscopes, three trigger counters, and a threshold-type gas Cherenkov counter, all being mounted on a rotatable platform. The solid angle was defined to be 2.1 msr by the trigger counter in front of the magnet. The momentum acceptance of the whole system was about 15%, which was subdivided into bins of a few percent by selecting a combination of hodoscope elements. All digital signals from the hodoscopes and the Cherenkov counter, analog-to-digital converter signals of the time of flight (TOF) and the energy loss (dE/dx), are transferred to the on-line computer TOSBAC 3400-41. The on-line analysis included hodoscope distributions, the momentum distribution, the TOF distribution, the event distribution at the target, and event classifications, all of which served to monitor functioning of the spectrometer system. The incident beam flux was measured by a thick-wall ionization chamber which had been calibrated with a Faraday cup. In addition, a thin-wall ionization chamber placed in the beam path and a counter telescope aimed at the target were used as relative monitors to check the internal consistency among the different runs.

The electron (or positron) background, which was identified by the gas Cherenkov counter, amounted to 1–10% of the pion yield at the forward angles but decreased to less than 1% in the backward direction. The protons were separated from pions by measuring TOF and the dE/dx in one of the trigger counters. The target-empty background was measured to be 1–3% of the net yield. To ensure that the net yield came from the desired process, as well as to see the effect of the internal nucleon momentum on the energy resolution, excitation curves were taken for π^+'s at a few kinematical settings with both hydrogen and deuterium targets. The end-point energy of bremsstrahlung was selected so as to optimize the yield with little contamination from the 2π process.

The energy resolution in the neutron rest system varied from ± 16 MeV at $k = 260$ MeV and $\theta^* = 30°$ to ± 65 MeV at $k = 800$ MeV and $\theta^* = 90°$. For the measurements at $k \geq 500$ MeV and $\theta^* \geq 105°$, the photon difference method was employed to improve the energy resolution as in the case of our previous 180° measurement.[10] The resultant energy resolution was reduced to ± 20– ± 30 MeV with this method. A check run was made to compare the π^-/π^+ ratios with and without photon difference at $k = 550$ MeV and $\theta^* = 120°$, where the energy dependence was expected to be smooth. They agreed with each other within the statistical accuracy.

The results of our measurements are summarized in Fig. 1. Coulomb corrections were made at all angles based on the calculation of Pine and Bazin.[9] They were 6.8% at $k = 260$ MeV and $\theta^* = 30°$ but decreased to less than 1% at higher ener-

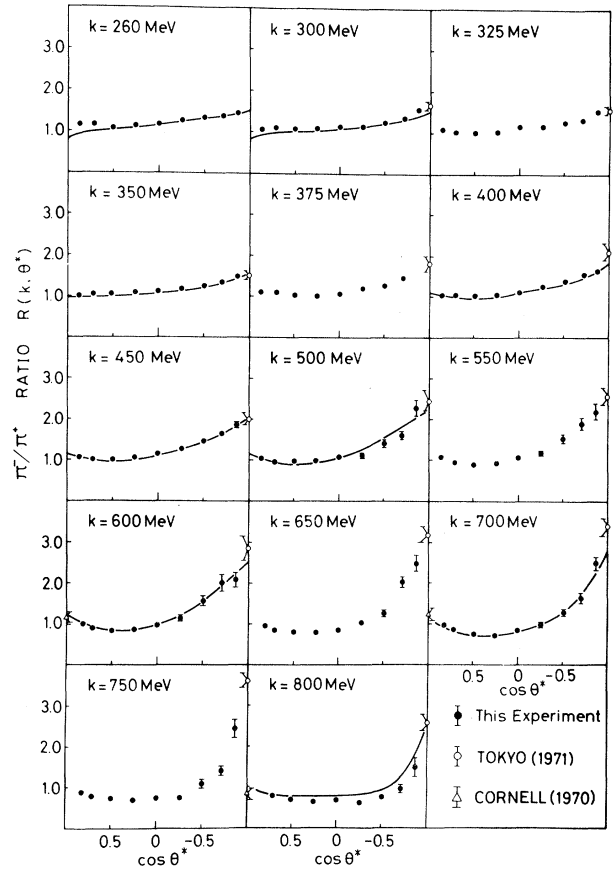

FIG. 1. π^-/π^+ ratio from deuterium as a function of $\cos\theta^*$ at fourteen photon energies from 260 to 800 MeV. Solid curves, calculated with the amplitudes of Walker's analysis (Ref. 14).

gies and/or backward angles. Also in Fig. 1 are shown the 180° points from our previous measurement[10] and the 0° data of Ito *et al.* at 600, 700, and 800 MeV.[11] In the energy region above 600 MeV, our data are also in good agreement with those of other groups.[12,13] The solid lines of Fig. 1 are the results of Walker's analysis.[14]

The angular distributions of π^-/π^+ ratio exhibit a simple and smooth variation throughout the measured range. At the extreme forward direction, the pion-exchange Born term dominates to make the ratio tend to 1. The steep rise toward 180° can be mainly explained by the difference in the electric Born term for nucleon exchange.

For the π^-/π^+ ratio most of the resonance effects would be compensated if the resonance contributes to only one of the isospin amplitudes. This feature is particularly evident in the Δ_{33} region, where the isovector amplitude is dominant. In the energy region above 550 MeV the ratio starts to show the structure which is expected

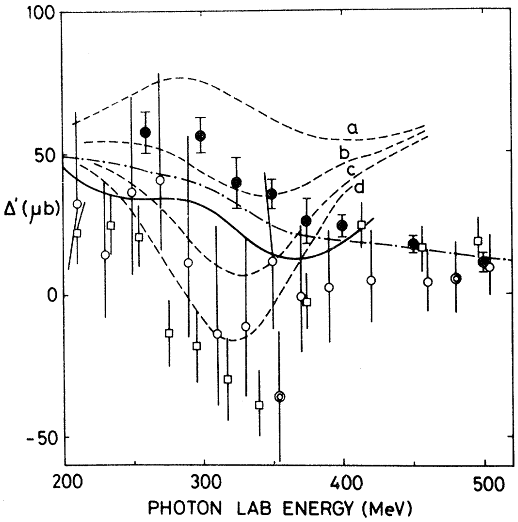

FIG. 2. Energy dependence of $\Delta'(k)$. Closed circles, obtained from our π^-/π^+ ratio data (see text); open circles, from Ref. 18; squares, from Ref. 19; and double circles, from the data of inverse reaction (Ref. 20). Dashed lines show predictions by Sanda and Shaw (Ref. 4), where a, b, c, and d correspond $x = 0.0$, -0.1, -0.2, and -0.3, respectively. The solid line is a prediction by Noelle and Pfeil (Ref. 8), dot-dashed line is by Walker (Ref. 14).

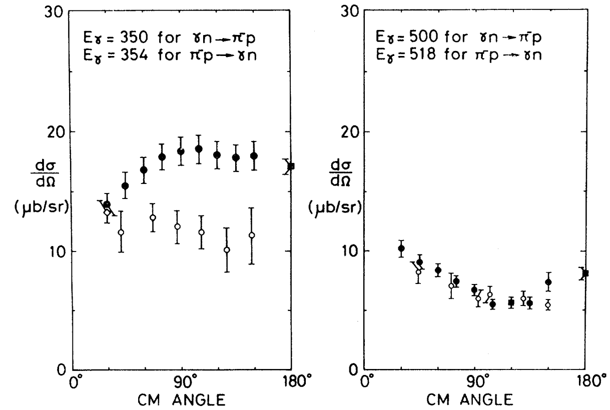

FIG. 3. Differential cross section for $\gamma n \to \pi^- p$ at $k = 350$ and 500 MeV. Closed circles, results calculated using our π^-/π^+ ratios; closed square, a result of direct measurement at 180° (Ref. 10); open circles and a diamond, results obtained from the inverse reactions by Berardo *et al.* (Ref. 20) and Favier *et al.* (Ref. 21), respectively.

from the mixture of isospin amplitudes. Among several $I = \frac{1}{2}$ resonances in this energy region, $S_{11}(1525)$ is known to contribute to the isoscalar amplitude.[10]

For the dip test of the isotensor current, we have calculated the following quantity:

$$\Delta'(k) = \frac{2\pi k^*}{q^*}\int_{-1}^{1}[R(k, \theta^*) - 1]\frac{d\sigma^+}{d\Omega^*}(k, \theta^*)\, d\cos\theta^*$$

using our measured ratio

$$R(k, \theta^*) = \frac{d\sigma^-/d\Omega^*}{d\sigma^+/d\Omega^*}$$

for incident energies between 260 and 500 MeV. The values of $d\sigma^+(k, \theta^*)/d\Omega^*$ were obtained by performing a Moravcsik fit[15] to the recent data of Fischer *et al.*,[16] Betourne *et al.*,[17] and Fugii *et al.*[10] Systematic normalization errors of 6% in these data were added to the fitted values of $d\sigma^+(k, \theta^*)/d\Omega^*$. It should be noted that the value of $\Delta'(k)$ strongly depends on the measurement in the backward direction where $R(k, \theta^*)$ deviates substantially from 1.

The result is shown in Fig. 2 together with the results of previous measurements and some theoretical predictions. Early bubble-chamber experiments[18,19] and the measurement of the inverse reaction[20] $\pi^- p \to \gamma n$ seemed to indicate a dip around the first resonance, corresponding to $x = -0.2$ to -0.3. In contrast, our measurement shows a smooth variation which is quite different in shape from any prediction based on the model of Sanda and Shaw.[4] As seen in the figure, our observed energy dependence can be explained by introducing small modifications of the parameters in the conventional multipole analysis without an isotensor term.[5,8] It has been reported that the dip effect has disappeared in a new version of bubble-chamber data[22] with increased statistics and a revised analysis of the deuteron corrections.[22] Furthermore, the recent measurement on electroproduction of pions[23] has placed an upper limit of 7% on the isotensor current.

In Fig. 3, the angular distributions of $\gamma n \to \pi^- p$, based on our measured ratio and a Moravcsik fit as mentioned above, are compared with those obtained via detailed balance from the inverse reaction[20] $\pi^- p \to \gamma n$ at $k = 350$ and 500 MeV. There definitely exists a large difference in shape and magnitude at $k = 350$ MeV, while the agreement is much better at $k = 500$ MeV. There has been mentioned another speculation on a possibility of time-reversal–invariance violation at the $\Delta N\gamma$ vertex, related to the isotensor term.[6,24] Since the existence of the isotensor term is not established, a further experimental investigation, especially on the inverse reaction, is desirable to solve this discrepancy.

We have also measured the angular distribution of $\gamma p \to \pi^+ n$ with a free-proton target in the same angular and energy range. The detailed analysis on cross sections and deuteron effects will be published later. We are grateful to Professor S. Yamaguchi and his staff for the steady operation of the INS electron synchrotron. Thanks are also due to Mr. K. Ukai and Mr. A. Imanishi for the successful operation of on-line computer facilities, and to Mr. M. Kasuya, Mr. Y. Doi, and Mr. T. Kitami for their technical assistance.

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Neutron and Proton Form Factors

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A possible explanation is given for the dipole behavior of the neutron and proton electromagnetic form factors.

Part of the puzzle of the neutron and proton electromagnetic form factors is that the experimental data are summarized by a form factor[1,2] which depends upon the momentum transfer as $(k^2+a^2)^{-n}$ with $n=2$ rather than $n=1$. This is particularly surprising at low momentum transfer where a can be taken[1] as the mass of the ρ meson and where the usual assumptions that the γ, ρ and the ρ-nucleon vertices are independent of k^2 should be valid. The purpose of this paper is to provide a possible explanation, from fundamental principles, of this "dipolelike" behavior at low momentum transfer.

The argument is based upon the difference between the analytic properties of the propagators for stable and unstable particles. For a vector boson, it was recently shown[3] that the exact single-parti-