Measurement of Inverse Pion Photoproduction Near the $P_{33}{}^0(1236)$ Resonance*

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The differential cross sections for $\pi^- + p \to \gamma + n$ at $40° < \tilde{\theta}_\gamma < 150°$ at c.m. total energies 1245 and 1337 MeV are presented. The results do not agree with predictions based on the $\Delta I \leq 1$ rule for the electromagnetic current and fixed-t dispersion relations. Our data can be fitted with the Sanda-Shaw model, in which the electromagnetic current contains an isotensor component. Our angular distribution at 1337 MeV agrees with the inverse reaction as deduced from γd work; however, there is some disagreement at 1245 MeV.

Measurements of the differential cross section for $\pi^- p \to \gamma n$ near the $P_{33}(1236)$ resonance are of interest for the following reasons:

(1) To test the validity of the isospin rule for electromagnetic interactions,

$$\Delta I \leq 1. \tag{1}$$

This test involves a comparison with existing pion photoproduction data obtained with a hydrogen target. There are four possible isospin amplitudes in pion photoproduction or its inverse: a scalar S and an isovector V, both involving $I = \frac{1}{2}$ πN states, and an isovector W and an isotensor X, involving $I = \frac{3}{2}$ πN states. The isospin decomposition of the relevant processes is

$$A(\gamma N \to \pi^\mp N) = \sqrt{2}\,[S \mp \tfrac{1}{3}V \pm \tfrac{1}{3}W + (1/15)^{1/2}X]. \tag{2}$$

The validity of the $\Delta I \leq 1$ rule implies that $X = 0$. Sanda and Shaw[1] have suggested an attractive way for testing the validity of Eq. (1) using just the reactions of Eq. (2). It is based on the isospin relation

$$\frac{\Gamma(P_{33}{}^0 \to n\gamma)}{\Gamma(P_{33}{}^+ \to p\gamma)} = \left|\frac{1+x}{1-x}\right|^2,$$

where $x = (\frac{3}{5})^{1/2}X/W$, and Γ is the radiative decay rate. Pion photoproduction near the invariant mass 1236 MeV is dominated by P_{33} production. A sizable variation in $\Delta = \sigma_t(\gamma n \to \pi^- p) - \sigma_t(\gamma p \to \pi^+ n)$ across the resonance region is the predicted evidence[1] for an isotensor, since Δ should be nearly constant if $x = 0$.

(2) To test time-reversal invariance in the electromagnetic interaction of hadrons.[2] This is accomplished by a comparison of $\pi^- p \to \gamma n$ with the inverse, $\gamma n \to \pi^- p$, measured in photoproduction experiments on deuterium. The test is very sensitive to T-invariance violation in the isovector amplitude. Christ and Lee have estimated[3] that a T-invariance violating phase of 20° in $M_{1+}{}^{3/2}$ has a 60% effect. Therefore, even if the differential cross section for the γn reaction is in error by as much as 15% due to uncertain deuteron corrections, one can still determine a limit to a possible T-invariance violation that is comparable to results of other recent experiments.[4-6]

(3) To test various detailed predictions for pion photoproduction.[7-9] The calculations are based on fixed-t dispersion relations, the $\Delta I \leq 1$ rule, and T invariance. The extensive data on $\gamma p \to \pi^+ n$ and $\gamma p \to \pi^0 p$ are in reasonable agreement with the calculations.

We present here the differential cross section for the reaction $\pi^- p \to \gamma n$ at $40° < \tilde{\theta}_\gamma < 150°$, at c.m. total energy $\tilde{E} = 1245$ MeV and at $\tilde{E} = 1337$ MeV. This work is an extension of the experiment at $\tilde{E} = 1363$ MeV, reported previously.[10] A detailed description of the apparatus is given in Ref. 10 and by Berardo.[11] The experiment was conducted at the 184-in. cyclotron of the Lawrence Radiation Laboratory with π^- beams of 316 and 450 MeV/c, using 32 neutron counters and a photon spark chamber. The neutron counters were carefully calibrated in a separate experiment[12] to an absolute accuracy of ±3%. The detection efficiency of our spark chamber for photons from the $n\gamma$ reaction, which varied in energy between 216 and 440 MeV, was determined[11] from a detailed analysis of shower lengths in the chamber and found to be (98 ± 2)%, not including a (4 ± 1)% correction for photons that converted and triggered an anti counter. The contamination of the π^- beam was (11 ± 3)% at 316

MeV/c and $6.4\pm1.7\%$ at 450 MeV/c. The composition for the 316-MeV/c beam was $(2\pm1)\%$ electrons, as determined with a gas Cherenkov counter in a similar beam; $(4\pm2)\%$ "on-momentum" muons, as determined from range curves; $(5\pm2)\%$ muons from pion decay, calculated for our beam and beam counters.[13] The value of the beam momentum is of particular importance for the 316-MeV/c data because of the rapidly varying cross section here. The central momentum, determined from range measurements, was 316 MeV/c with an uncertainty of ±6 MeV/c, and the momentum spread was ±3.5%. A valuable check on the beam momentum was made using $\pi^-p\to\gamma n$ events selected on the basis of coplanarity and time of flight. The analysis of these events gave a central momentum of 314 ± 7 MeV/c.

To extract the desired $\pi^-p\to\gamma n$ events from the large charge-exchange background, we made use of three parameters: (1) the measured neutron time of flight τ_n; (2) the coplanarity φ, determined from the direction of the incident π^- and the point of interaction of the neutron and photon; (3) π^- momentum P_π, reconstructed from the $n\gamma$ opening angle. These three parameters were used to calculate four pseudo χ^2 values for each event as outlined in Refs. 10 and 11.

The detection of the desired events and the background of $n\pi^0$ and random events was simulated by an extensive Monte Carlo program. The Monte Carlo–generated events were then processed by the same kinematics reconstruction program followed by the same pseudo χ^2-value calculations and bookkeeping routines as the real data events. The number of $n\gamma$ events was obtained from a fit of the χ^2-value distributions of the data by the distribution of the Monte Carlo–generated $n\gamma$ and background. We found that the number of $n\gamma$ events usually agreed for all four χ^2-value distributions, but with different errors. Various checks were made to insure that the data were handled properly and to gauge the sensitivity of the analysis of the input parameters. This included varying the input momentum, the alignment of the apparatus, and the timing calibration in the reconstruction program.

The charge-exchange background is particularly severe at 316 MeV/c, so that the determination of the number of $n\gamma$ events is more difficult there. At backward angles we rely heavily on the correct evaluation of the background under the signal peak. As can be seen from Fig. 1, our Monte Carlo program accurately reproduced the shape of the background. We have also calculated the charge-exchange cross section using different regions of χ^2 (see Fig. 1) and found good agreement with the predictions from the CERN phase-shift analysis. This is a most satisfying test, since it checks the Monte Carlo and also all other aspects of the cross-section calculation. A detailed account of this will be given separately.[14]

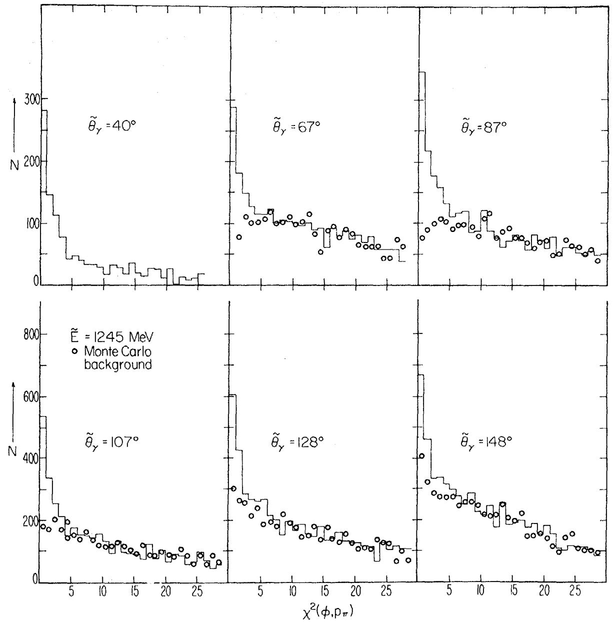

FIG. 1. χ^2(coplanarity and momentum) frequency distribution, with 3.5-standard-deviation gate on neutron time of flight.

The cross section for $\pi^-p\to\gamma n$ is related to that of its inverse via the detailed balance factor, provided the beam and target are unpolarized, as is the case in our experiment, and time-reversal invariance is valid. Our results for the inverse process are given in Table I. Included are the updated results of our previous experiments at $\tilde E = 1363$ MeV. Our results are shown in Fig. 2. They disagree with the theoretical predictions, based on fixed-t dispersion relations, by Berends, Donnachie, and Weaver,[7] by Schwela,[8] and by Schmidt.[9] Our results are explained satisfactorily by the Sanda-Shaw model[1] of an electromagnetic current with an isotensor component. The predictions of this model are based on the multipoles of Berends, Donnachie, and Weaver,[7] but with the isospin decomposition of Eq. (2), in such a way that the good fit to the π^+ and π^0 photoproduction data is maintained. By integration of our measured $d\sigma/d\Omega$, we find at $\tilde E = 1245$ MeV that $\sigma_t = 142\pm18$ μb, and at $\tilde E = 1337$ MeV that $\sigma_t = 86\pm11$ μb. Combined with

Table I. Differential cross section for $\gamma n \leftarrow \pi^- p$, obtained from our $\pi^- p \to \gamma n$ measurements assuming T invariance. The errors include statistical uncertainties only. The normalization uncertainty is 7%.

$\tilde{E}$ = 1245 MeV, P_π = 316 MeV/c, E_γ = 354 MeV		$\tilde{E}$ = 1337 MeV, P_π = 450 MeV/c, E_γ = 480 MeV		$\tilde{E}$ = 1363 MeV, P_π = 490 MeV/c, E_γ = 518 MeV	
$\tilde{\theta}_{\gamma\pi}$	$d\tilde{\sigma}/d\tilde{\Omega}$ (μb/sr)	$\tilde{\theta}_{\gamma\pi}$	$d\tilde{\sigma}/d\tilde{\Omega}$ (μb/sr)	$\tilde{\theta}_{\gamma\pi}$	$d\tilde{\sigma}/d\tilde{\Omega}$ (μb/sr)
41°	11.6 ± 1.7	43°	8.5 ± 1.2	44°	8.2 ± 0.9
67°	12.8 ± 1.2	71°	7.5 ± 1.3	72°	7.1 ± 1.1
87°	12.0 ± 1.4	91°	6.0 ± 0.7	92°	6.0 ± 0.7
107°	11.6 ± 1.4	110°	5.5 ± 0.5	112°	6.3 ± 0.7
128°	10.1 ± 1.9	134°	5.8 ± 0.7	130°	6.0 ± 0.6
148°	11.3 ± 2.4	150°	5.0 ± 0.7	151°	5.5 ± 0.4

the π^+ data of Beale, Ecklund, and Walker,[15] Betourné et al.,[16] and Fisher et al.,[16] this yields Δ(1245 MeV) = −32 ± 21 μb, and Δ(1337 MeV) = 5 ± 12 μb. From Ref. 15 we obtain that Δ(1120 MeV) = 40 ± 10 μb. Thus our measurement shows a dip in Δ near the peak of the P_{33} resonance and if the model of Sanda and Shaw is correct, we confirm the existence of an isotensor component of the electromagnetic current, as originally deduced by Sanda and Shaw from γd experiments. In the following Letter[17] we present a fit of our measured angular distributions to various sets of multipoles with and without an isotensor amplitude.

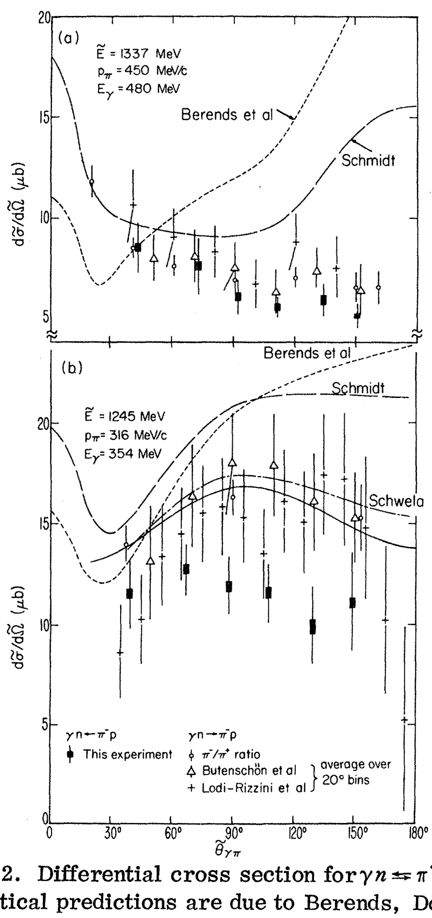

FIG. 2. Differential cross section for $\gamma n \rightleftarrows \pi^- p$. Theoretical predictions are due to Berends, Donnachie, and Weaver (Ref. 7), Schwela (Ref. 8), and Schmidt (Ref. 9).

Several groups[18-21] have published the cross section for $\gamma n \to \pi^- p$ obtained from γd experiments. These results are shown in Fig. 2 also. Considering the many corrections to the deuterium measurements, it is interesting that our $\pi^- p \to \gamma n$ measurements at $\tilde{E}$ = 1337 MeV agree with the inverse, indicating that the deuteron corrections are manageable, barring unexpected cancelations. It is intriguing that at $\tilde{E}$ = 1245 MeV there appears to be disagreement between $\pi^- p \to \gamma n$ and the inverse. Specifically, the deuteron measurements at $\varphi_\gamma \geq 90°$ are on the average some 30% larger than our $\pi^- p \to \gamma n$ measurements. At present we cannot exclude the possibility that the deuteron corrections are more severe than expected in the region of the P_{33} resonance or that the spectator model cannot be applied. More data are needed in the whole region of the P_{33} before a definite statement on the issue of time-reversal invariance in the electromagnetic interaction of hadrons[2] can be made.

In the meantime, one can use the measured difference between $\pi^- p \to \gamma n$ and the inverse to set a limit on the possible T-invariance violation. A detailed numerical analysis, based on a model by Christ and Lee, is presented in the following Letter.[17]

It is appropriate to mention the possibility that

T invariance is violated in the isotensor electromagnetic current.[22] Such a violation would be consistent with the results of other experiments (Refs. 4-6).

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