MEASUREMENT OF THE $\pi^- p \to n\gamma$ DIFFERENTIAL CROSS SECTION NEAR THE ROPER RESONANCE, $P_{11}(1460)$†

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We measured six differential cross sections for $\pi^- p \to n\gamma$ at 490-MeV/c incident π^- momentum. Our data do not agree with recent theoretical predictions. We find no evidence, in the sense suggested by Donnachie, for the classification of the Roper resonance, $P_{11}(1460)$, in an SU(3) antidecuplet. Our angular distribution is consistent with the classification of the Roper resonance in an octet, as predicted by the simplest quark models. Using detailed balance, our results agree well with the reported cross sections for the inverse reaction, which are deduced from γd data.

We report results of a measurement of the differential cross section for $\pi^- p \to n\gamma$, which tests whether the Roper resonance[1]$-P_{11}(1460)$, with $I(J^P)=\frac{1}{2}(\frac{1}{2}^+)$—can be strongly photoproduced from neutrons.[2] The Roper resonance has been seen in many experiments involving peripheral interactions of $\pi^\pm$, $K^\pm$, p, or $\bar{p}$ with p and d targets.[3] The Roper resonance has not been observed in π^+ or π^0 photoproduction from protons,[4,5] which could be explained by a small radiative decay rate of the resonance. Another possibility, emphasized by Donnachie,[2] is that only the charged Roper resonance has a small radiative decay rate. Thus, $P_{11}{}^+ \to p\gamma$ is forbidden, but $P_{11}{}^0 \to n\gamma$ is allowed. This follows from U-spin conservation, provided that the Roper resonance belongs to an SU(3) antidecuplet, as originally proposed by Lovelace[6] and recently by Brehm and Cook.[7]

In terms of a conventional multipole analysis, the Donnachie interpretation means that the two relevant isospin components[8] of the resonance-producing M_1 multipole cancel one another in photoproduction from protons and enhance one another in photoproduction from neutrons. This remarkable behavior of the M_1 multipole is very apparent in the parameter-free multipole analysis of Berends, Donnachie, and Weaver.[9] Their analysis is based on fixed-t dispersion relations and is in good agreement with most photoproduction experiments, all of which employ a proton target.

The SU(3) classification of the Roper resonance is of particular interest for the following reason. One expects the existence of an antidecuplet in the eightfold way[10] since

$$\underline{8}\times\underline{8}=\underline{1}\oplus\underline{8}\oplus\underline{8}\oplus\underline{10}\oplus\underline{10}^*+\underline{27}.$$

However, the simplest quark models exclude the antidecuplet and predict an octet classification of the Roper resonance.[11] In these models the baryon resonances are formed from three quarks, and

$$\underline{3}\times\underline{3}\times\underline{3}=\underline{1}\oplus\underline{8}\oplus\underline{8}\oplus\underline{10}.$$

Moorhouse[12] has pointed out that in the nonrelativistic quark model one expects the photoproduction of the Roper resonance to be suppressed with both proton and neutron targets. A similar suppression appears in the quark-model calculations of Copley, Karl, and Obryk.[13,14]

The shape and magnitude of the differential cross section for $\gamma n \to p\pi^-$ are necessary to determine the isospin decomposition of the pion photoproduction multipoles and serve to distinguish between the conflicting symmetry classifications of the Roper resonance. In the absence of a neutron target, our approach is to investigate the reaction $\pi^- p \to n\gamma$. The incident π^- momentum selected is 490 MeV/c, corresponding to an invariant mass of 1363 MeV/c^2. It is the maximum energy for which the multipole analysis of Berends, Donnachie, and Weaver[9] is thought to be reliable and is sufficiently high to observe possible Roper-resonance production.[2]

The experiment was done at the 184-in. cyclotron of the Lawrence Radiation Laboratory. The layout of the π^- beam and the detection apparatus are shown in Fig. 1. The apparatus consists of four beam hodoscope planes, each with eight to eleven counters; a pion timing counter; a 4-in.-diam liquid hydrogen target in the form of two independent half cylinders, which gives us an option on the target thickness; an array of charged-particle anti counters surrounding the target;

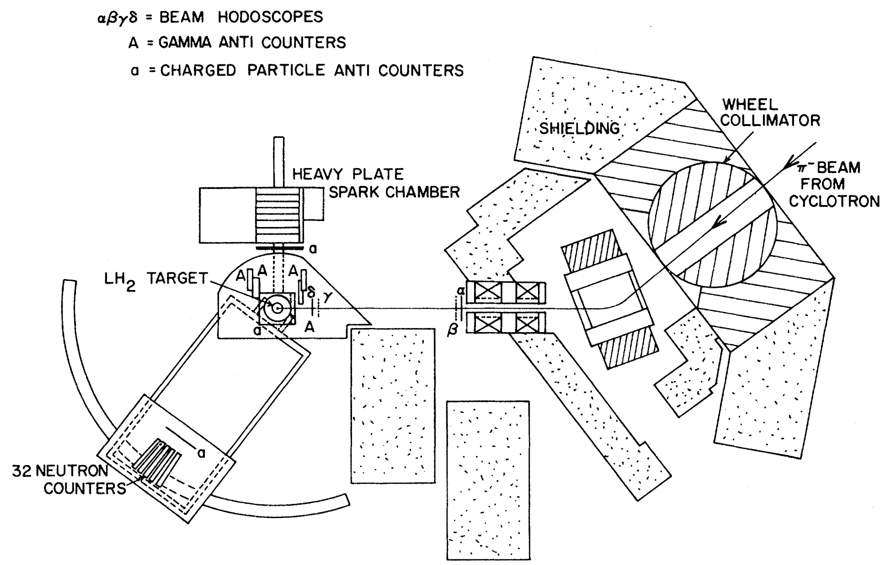

FIG. 1. Beam layout and experimental apparatus.

eight lead-scintillator-sandwich counters to reduce the $\pi^-p\rightarrow n\pi^0$ background; and a neutron detector and a gamma detector, each faced with a charged-particle anti counter. The neutron detector consists of 32 independent, cylindrical, liquid scintillator counters, each $2\frac{3}{4}$ in. in diameter and 18 in. long. Each counter points at the hydrogen target when at a distance of 12 ft. The efficiency (40 to 50%) of the detector, as well as the neutron-counter cross-scattering probability, have been determined in a separate experiment.[15] The gamma detector consists of a 40-plate optical spark chamber, 30×30 in., containing 10 radiation lengths of lead. Interspersed between the modules of the chamber are eight sets of trigger counters, each 24 in. high and 27 in. wide. A model PDP-5 computer collects, monitors, and transfers the digital data to magnetic tape. The spark chamber pictures are scanned and measured by an automatic model PDP-5 vidicon system.

An event is defined as a coincidence of signals in the beam hodoscope, one neutron counter, and two gamma counters, provided no anti counters fired. For each event we determine the neutron and gamma angles relative to the incident π^- and the neutron time of flight. The beam energy has been measured separately. All events are analyzed assuming $\pi^-p\rightarrow n\gamma$.

To separate the $n\gamma$ from the charge-exchange process, which occurs about a hundred times as frequently, we use three parameters determined for each event, namely, the reconstructed π^- momentum and the measured neutron time of flight and coplanarity. Coplanarity is defined at the neutron array as the perpendicular distance between the center of the triggered neutron counter and the $\pi\gamma$ plane. We define the normalized deviation in each parameter as the difference between measured and expected values divided by the non-Gaussian uncertainty introduced by the finite target size, beam divergence, and resolution of the detectors. The expected values are the known beam momentum, the neutron time of flight appropriate for the γ angle and mean beam momentum, and the absolute coplanarity. The distribution of normalized deviations in the three parameters for each run is a check on the alignment of the apparatus, the timing calibration, and the mean beam momentum

For each event a pseudo χ^2 value is calculated from two of the three parameters, and its frequency distribution is displayed versus the number of standard deviations of the third parameter. Also, a χ^2 distribution is made which uses all three parameters simultaneously. The detection of the $n\gamma$ and $n\pi^0$ reactions are independently simulated by an extensive Monte Carlo program. The same analysis of the Monte Carlo–simulated events produces χ^2 distributions separately for the signal and background. The number of $n\gamma$ events is obtained from a χ^2 frequency distribution by a maximum-likelihood fit of the Monte Carlo $n\gamma$ and $n\pi^0$ χ^2 distributions to the data distribution. The commonly used χ^2 distribution is based on coplanarity and reconstructed π^- momentum for events with neutron time of flight within 3.5 standard deviations. A good example

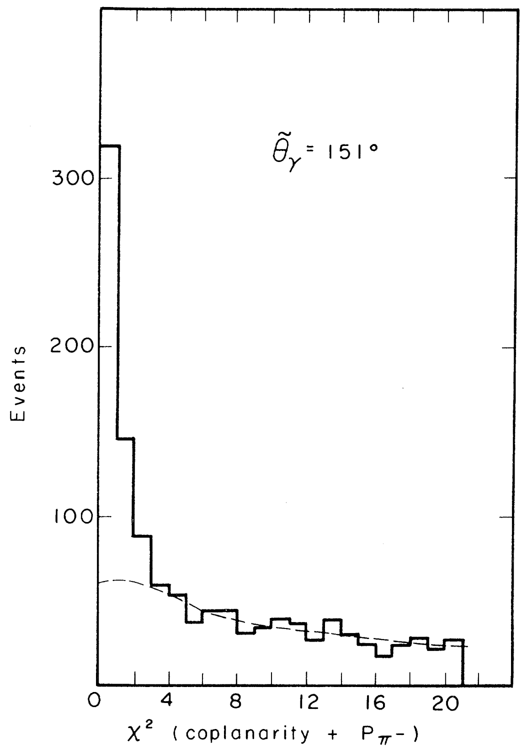

FIG. 2. χ^2(coplanarity and momentum) frequency distribution with 3.5-standard-deviation gate on neutron time of flight.

of such a distribution is shown in Fig. 2. The $n\gamma$ peak stands out clearly above the $n\pi^0$ background. The dashed line is the Monte Carlo–generated background.

Our results for the differential cross section for $\pi^-p \to n\gamma$ have been converted to the reaction $\gamma n \to \pi^-p$ under the assumption of time-reversal invariance. They are listed in Table I and displayed in Fig. 3. The errors shown include the statistical uncertainties only. There is about a

Table I. Experimental differential cross sections for $\pi^-p \to n\gamma$, with 490-MeV/c incident π^-.[a]

$\tilde{\theta}_\gamma$ (deg)	$d\tilde{\sigma}(\pi^-p \to n\gamma)/d\tilde{\Omega}$ (μb/sr)	$d\tilde{\sigma}(\gamma n \to p\pi^-)/d\tilde{\Omega}$ (μb/sr)
44	19.8 ± 1.2	9.4 ± 0.7
72	22.1 ± 1.6	10.5 ± 0.8
92	15.0 ± 1.7	7.2 ± 0.8
111	11.7 ± 1.4	5.7 ± 0.7
132	13.0 ± 0.8	6.2 ± 0.4
151	12.9 ± 0.8	6.2 ± 0.4

[a] The third column lists the calculated cross sections for $\gamma n \to p\pi^-$ corresponding to 520-MeV (lab) incident photons. The errors include statistical uncertainties only. The normalization uncertainty is 7%.

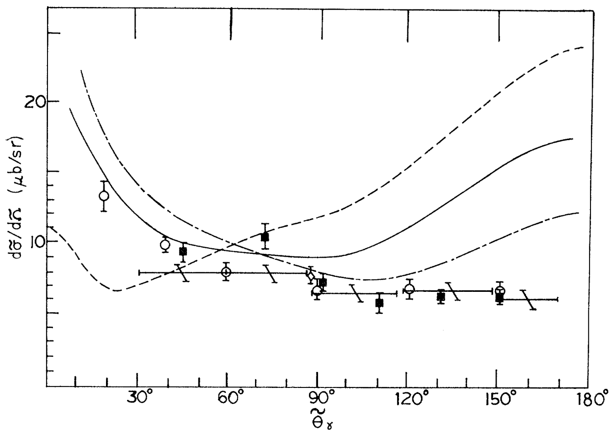

FIG. 3. Differential cross section for $\gamma n \to \pi^-p$ at $E_\gamma = 520$ MeV. The theoretical predictions, calculated for $E_\gamma = 500$ MeV, are due to Berends, Donnachie, and Weaver, Ref. 9, indicated by the dashed line; Karlsruhe group, Refs. 16 and 17, indicated by the solid line; and Donnachie, Ref. 2, indicated by the dash-dotted line. The experimental points are open circle, from Ref. 18, π^-/π^+ ratio; cross, from Ref. 19, bubble chamber; open diamond, from Ref. 20, spark chamber; and closed square, from this experiment, namely, $\pi^-p \to n\gamma$ at $P_{\pi^-} = 490$ MeV/c.

7% normalization uncertainty. Also shown in Fig. 3 are the results of three experiments in which the $\gamma n \to \pi^-p$ cross section has been deduced from γd investigations.[18-20] The cross sections reported by Neugebauer, Wales, and Walker[18]—which are obtained by multiplying the ratio $(\gamma d \to \pi^-x)/(\gamma d \to \pi^+y)$ by the $\gamma p \to \pi^+n$ cross section—have been updated by using more recent γp measurements[21] and they have been linearly interpolated to our energy. The results of a bubble-chamber experiment[19] on $\gamma d \to \pi^-pp$ have been averaged over 30° bins; we averaged these data because they have large error bars and the cross section appears to be smooth. Finally, we have included in Fig. 3 the theoretical predictions by Berends, Donnachie, and Weaver[9] and by the Karlsruhe group[16,17] and the speculation by Donnachie[2] (M_1 multipole set to zero, otherwise equal to Berends, Donnachie, and Weaver), all made for 500-MeV photons.

Our results disagree strongly with the predictions of Berends, Donnachie, and Weaver.[9] This casts doubt on their treatment of the M_1 multipole. We find no evidence, in the sense suggested by Donnachie, for the classification of the Roper resonance in an antidecuplet. The flatness of our measured differential cross section is suggestive of a small M_1 multipole and a small radiative decay rate of the neutral Roper resonance.

This is consistent with the classification of the Roper resonance in an octet as done in the simplest quark models.[12-14] When we vary the magnitude of the M_1 multipole, keeping the other multipoles fixed at the values of Berends, Donnachie, and Weaver,[9] we do not obtain an acceptable overall fit. This result, and the fact that our measurements disagree with the predictions of the Karlsruhe group,[16,17] who calculate the M_1 multipole from dispersion integrals without contributions from the Roper resonance, lead to the conclusion that in this energy region the results of the above dispersion-relation calculations[9,16] are not useful without some revision of the multipoles or, perhaps, their isospin decomposition.[22]

Using detailed balance, our results agree very well with the reported cross sections for the inverse reaction, as deduced from γd data. There is no apparent violation of time-reversal invariance in this process at this energy, barring unexpected cancellation of time-reversal effects by the deuterium corrections.

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[1]L. D. Roper, Phys. Rev. Letters 12, 340 (1964).

[2]A. Donnachie, Phys. Letters 24B, 420 (1967).

[3]Counter experiments: G. Cocconi et al., Phys. Letters 8, 134 (1964); C. M. Ankenbrandt et al., Nuovo Cimento 35, 1052 (1965); G. Belletini et al., Phys. Letters 18, 167 (1965); E. W. Anderson et al., Phys. Rev. Letters 16, 855 (1966); I. M. Blair et al., Phys. Rev. Letters 17, 789 (1966); K. J. Foley et al., Phys. Rev. Letters 19, 397 (1967). Bubble chamber experiments: P. Bareyre et al., Phys. Letters, 8, 137 (1964); S. L. Adelman, Phys. Rev. Letters 13, 555 (1964); S. P. Almeido et al., Nuovo Cimento 50A, 1000 (1967); R. B. Bell et al., Phys. Rev. Letters 20, 164 (1968); R. A. Jespersen et al., Phys. Rev. Letters 21, 1368 (1968); A. Shapira et al., Phys. Rev. Letters 21, 1835 (1968); R. Ehrlich et al., Phys. Rev. Letters 21, 1839 (1968); T. C. Bacon et al., Phys. Rev. Letters 22, 43 (1969). Some authors remain uncommitted about actually having observed the Roper resonance, e.g., P. Antich et al., Phys. Rev. Letters 22, 39 (1969).

[4]C. Betourne et al., Phys. Rev. 172, 1343 (1968).

[5]M. Beneventano et al., Nuovo Cimento 54A, 468 (1968).

[6]C. Lovelace, CERN Report No. TH-625, 1965 (to be published).

[7]J. J. Brehm and L. F. Cook, Phys. Rev. 170, 1387 (1968).

[8]The conventional isospin decomposition of the pion photoproduction amplitudes, assuming that the electromagnetic interactions are restricted to $I \leq 1$ transitions, is as follows:

$$\gamma p \to \pi^+ n, \quad A^+ = \sqrt{2}(S_0 + \tfrac{1}{3}V_1 - \tfrac{1}{3}V_3);$$

$$\gamma p \to \pi^0 p, \quad A^0 = S_0 + \tfrac{1}{3}V_1 + \tfrac{2}{3}V_3;$$

$$\gamma n \to \pi^- p, \quad A^- = \sqrt{2}(S_0 - \tfrac{1}{3}V_1 + \tfrac{1}{3}V_3);$$

where S_0 is the isoscalar amplitude; V_1 is the isovector amplitude, with $I_f = \frac{1}{2}$; and V_3 is the isovector amplitude, with $I_f = \frac{3}{2}$. The Roper resonance, P_{11}, is produced by S_0 and V_1 components of the M_1 multipole.

[9]F. Berends, A. Donnachie, and D. Weaver, Nucl. Phys. B4, 1 (1967).

[10]M. Gell-Mann and Y. Ne'eman, The Eightfold Way (Benjamin, New York, 1964).

[11]R. H. Dalitz, in Proceedings of the Thirteenth International Conference on High Energy Physics, Berkeley, 1966 (University of California, Berkeley, Calif., 1967).

[12]R. G. Moorhouse, Phys. Rev. Letters 16, 772 (1966).

[13]L. A. Copley, G. Karl, and E. Obryk, Phys. Rev. Letters 29B, 117 (1969).

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

[15]A. S. L. Parsons, P. Truoel, P. A. Berardo, R. P. Haddock, L. J. Verhey, and M. E. Zeller, University of California Lawrence Radiation Laboratory Report No. 19259 (to be published).

[16]J. Engels, A. Müllensieffen, and W. Schmidt, Phys. Rev. 175, 1751 (1968).

[17]W. Schmidt, private communication.

[18]G. Neugebauer, W. Wales, and R. L. Walker, Phys. Rev. 119, 1726 (1960).

[19]Aachen-Berlin-Bonn-Hamburg-Heidelberg-München Collaboration, Nucl. Phys. B8, 535 (1968).

[20]M. Beneventano et al., Lettere Nuovo Cimento 1, 113 (1969).

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

[22]G. Shaw, Nucl. Phys. B3, 338 (1967).