

DIFFERENTIAL CROSS SECTIONS FOR NEUTRAL-PION ELECTROPRODUCTION  
NEAR THE FIRST PION-NUCLEON RESONANCE\*

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Electron-proton coincidences from the reaction  $e^- + p \rightarrow e^- + p + \pi^0$  have been measured for pion-nucleon center-of-mass energies in the region of the  $N^*(1236)$  resonance at four-momentum transfers near 1, 3, 6, and 10  $F^{-2}$  [0.05 to 0.4 (BeV/c)<sup>2</sup>]. Data have been obtained for pion polar angles between 100° and 180° c.m. over a wide range of azimuthal angles. The results are compared with the dispersion theories of Adler and Zangury.

An extensive set of angular-distribution measurements has been made for the reactions  $e^- + p \rightarrow e^- + p + \pi^0$  and  $e^- + p \rightarrow e^- + n + \pi^+$  at the Cambridge Electron Accelerator. The main aim of this program is to extract information on the charge form factor of the positive pion using dispersion theory<sup>1,2</sup> to estimate background to the one-pion-exchange contribution in the charged-pion reaction.<sup>3</sup> The cross sections presented in this Letter provide information about the closely related dynamics of neutral-pion electroproduction<sup>4</sup> and represent the most stringent test of the theory presently available.

The apparatus was similar to that used in recent measurements of elastic electron-proton scattering and quasielastic electron-deuteron scattering at Harvard.<sup>5,6</sup>

An external electron beam was incident upon a 2-in. long, liquid-hydrogen target and electrons scattered within a 15% momentum interval centered on the peak of the  $N^*(1236)$  resonance were detected in a half-quadrupole spectrometer followed by a gas Cherenkov counter and a lead-Plexiglas shower counter. The electron momentum resolution of approximately 1.5% (full width at half-maximum) corresponded to a resolution of approximately 40 MeV in the pion-nucleon center-of-mass energy.

Protons and positive pions were detected in coincidence with scattered electrons by a counter array consisting of three scintillation counters, a 12×12 scintillator hodoscope, and a Plexiglas Cherenkov counter, protected from the background flux of low-energy charged particles by a sweeping magnet. The hodoscope subtended a laboratory solid angle of approximately 200 msr at the target.

The data associated with each event were processed by an on-line PDP 1 computer and stored on magnetic tape. The recorded information included pulse-height information from several

counters, the status of the 35 electron-counter and 24 hodoscope-counter discriminators, and various experimental parameters needed for bookkeeping purposes. Because of this facility, it was not necessary to separate pions from protons during data taking. Particle identification was accomplished during subsequent analysis using pulse-height information from the first two proton scintillation counters and the Plexiglas Cherenkov counter. This procedure permitted the simultaneous measurement of cross sections for both neutral- and charged-pion production. The separation of protons from the minimum ionizing pions became more difficult at the higher four-momentum transfers, where the proton pulse height decreased, but in all cases this problem contributed an error of less than 3% to the neutral-pion cross sections.

The rate of data collection was limited by random coincidences caused by the large flux of charged particles through the proton counters. However, since between 60 and 80% of the real coincidence events were produced by protons, the beam intensity was actually limited for the sake of the positive pion data, and the subtraction for random coincidences was usually less than a 4% correction to the proton events.

Since the momentum of the particles in the proton arm was not measured, the identification of events depended upon the assumption that the real coincidences were associated with either the  $p + \pi^0$  or the  $n + \pi^+$  final state. This inability to reject multiple-pion events limited the analysis to energies less than approximately 1320 MeV in the isobar system, where photoproduction data<sup>7</sup> indicate that double-pion contamination is less than 3%.

A further constraint was placed on the analysis by the fact that the proton energy at any laboratory angle is double valued, a considerably lower energy being associated with protons emitted

at large angles in the isobar system. All of the cross sections presented in this Letter were measured in angular regions where the "backward" protons had insufficient energy to reach the hodoscope. A uniform 6% correction for nuclear scattering and absorption was applied to the forward proton events.

The resolution of proton angles was limited by uncertainties in the direction of the three-momentum transfer  $\vec{q}$  caused by the finite-electron-momentum resolution and the vertical extent of the electron aperture. The effect of the horizontal dimension of the aperture was minimized by dividing the aperture into  $0.2^\circ$  bins by means of vertical counters placed at the rear of the electron spectrometer. The overall resolution was approximately  $\pm 2.5^\circ$  (lab) in both vertical and horizontal directions.

The solid angles subtended by the hodoscope bins were determined with an accuracy of  $\pm 2\%$  by tracing the particle trajectories through the field of the sweeping magnet. The polar and azimuthal angles associated with each hodoscope bin were also corrected for the effects of the sweeping field.

In order to obtain angular distributions as a function of isobar energy, the events were grouped into electron-energy bins which spanned approximately 2% of the scattered electron energy on the  $N^*$  peak at four-momentum transfers of 1, 3, and 6  $F^{-2}$  and 1.5% at 10  $F^{-2}$ . The actual energy acceptances of these bins were determined experimentally with an accuracy of  $\pm 5\%$ .<sup>8</sup>

The cross sections were corrected for the effects of real and virtual radiators. For a typical electron-energy bin, a 25% correction was made for the loss of electrons which radiated out of the bin and a 10% subtraction was made for electrons which radiated into the bin from the threshold side of the resonance. The effect of the latter on the proton angular distribution was estimated to be small compared with the statistical errors. The normalization error associated with the radiative corrections was estimated to be  $\pm 4\%$ .

The measured triple-differential cross section can be related to the pion angular distribution by the expression

$$d^3\sigma/dE'd\omega_e d\Omega_\pi = \Gamma_T d\sigma/d\Omega_\pi,$$

where

$$\Gamma_T = \frac{\alpha}{4\pi^2} \left[ \frac{W^2 - M^2}{2Mq^2} \right] \frac{E'}{E} \left[ 2 + \frac{\cot^2(\frac{1}{2}\theta_e)}{[1 + (E - E')^2/q^2]} \right].$$

$\omega_e$  is the laboratory solid angle for electron detection,  $\Omega_\pi$  is the center-of-mass solid angle for pions,  $E$  and  $E'$  are the incident and scattered electron energies,  $q^2$  is the square of the invariant four-momentum transfer,  $\theta_e$  is the electron scattering angle,  $W$  is the center-of-mass energy of the pion-nucleon system, and  $M$  is the proton mass.

Assuming one-photon exchange, the form of the angular distribution is<sup>3</sup>

$$\frac{d\sigma}{d\Omega_\pi} = \frac{d\sigma_T}{d\Omega_\pi} + \epsilon \frac{d\sigma_0}{d\Omega_\pi} + \epsilon T(\theta_\pi^*) \sin^2 \theta_\pi^* \cos 2\varphi_\pi + \left[ \frac{1}{2} \epsilon(\epsilon + 1) \right]^{1/2} S(\theta_\pi^*) \sin \theta_\pi^* \cos \varphi_\pi,$$

where  $\epsilon$  is the polarization of the transverse components of the virtual photon,  $\theta_\pi^*$  is the center-of-mass pion polar angle measured with respect to  $\vec{q}$ , and  $\varphi_\pi$  is the pion azimuthal angle, defined to be zero in the electron scattering plane between  $\vec{q}$  and the incident beam direction (see Fig. 1).

The first term in the cross section is entirely due to transverse interactions and reduces to the corresponding photoproduction cross section in the limit of the square of zero four-momentum transfer. The second is unique to electroproduction and is due to scalar (longitudinal) interactions. Several experiments involving only the detection of the scattered electron have measured the integrals of these two terms, summed over both decay modes of the  $N^*$ .<sup>9-13</sup> The third term is due to interference between amplitudes involving the transverse components of the electromagnetic field and has been measured using real polarized photons<sup>14,15</sup> and in positive-pion electroproduction.<sup>16</sup> Because the virtual proton polarization in the present experiment was ap-

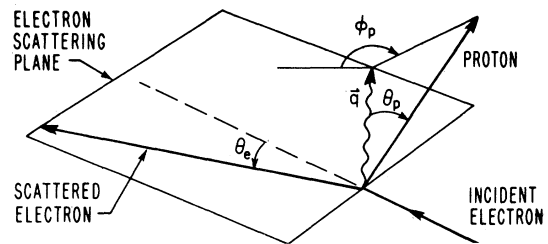


FIG. 1. Experimental geometry.  $\theta_p$  is the proton laboratory polar angle and  $\phi_p$  is the proton azimuthal angle. The undetected neutral pion is not shown. Its azimuthal and polar angles can be deduced from the relations  $\varphi_\pi = \varphi_p + 180^\circ$  and  $\theta_\pi^* = 180^\circ - \theta_p^*$ , where  $\theta_p^*$  is the proton c.m. polar angle.

proximately 98%, this  $\cos 2\phi_\pi$  dependence is clearly evident in the results.

The last term in the cross section is due to scalar-transverse interference and was expected to be small for neutral-pion production. Its presence at four-momentum transfers of 3 and 6  $F^{-2}$  is one of the most surprising aspects of the data.

Several representative angular distributions  $d\sigma/d\Omega_\pi$  are shown in Fig. 2, plotted as a function of pion azimuthal angle for fixed  $\theta_\pi^*$ . In addition to the statistical errors shown in the figure, there is an overall normalization uncertainty of approximately 10%.

The solid and dashed lines are the dispersion theory predictions of Adler and Zagury, respectively, which have been evaluated with the pion form-factor set equal to the proton charge form factor  $G_{Ep}$ , and with the nucleon form factors as-

sumed to obey the scaling law and the dipole fit<sup>5,6</sup>:

$$G_{Ep} = \frac{G_{Mp}}{\mu_p} = \frac{G_{Mn}}{\mu_n} = \left[ 1 + \frac{q^2}{0.71 (\text{BeV}/c)^2} \right]^{-2},$$

$$G_{En} = 0.0.$$

However, since the dipole fit departs systematically from the electron-proton elastic-scattering data in this four-momentum-transfer region, the theoretical predictions have been multiplied by the ratio of elastic-scattering cross sections measured during the present experiment to those given by the dipole fit. This change in normalization was -6% in the largest case ( $q^2 = 6 F^{-2}$ ).

The general features of the data can be sum-

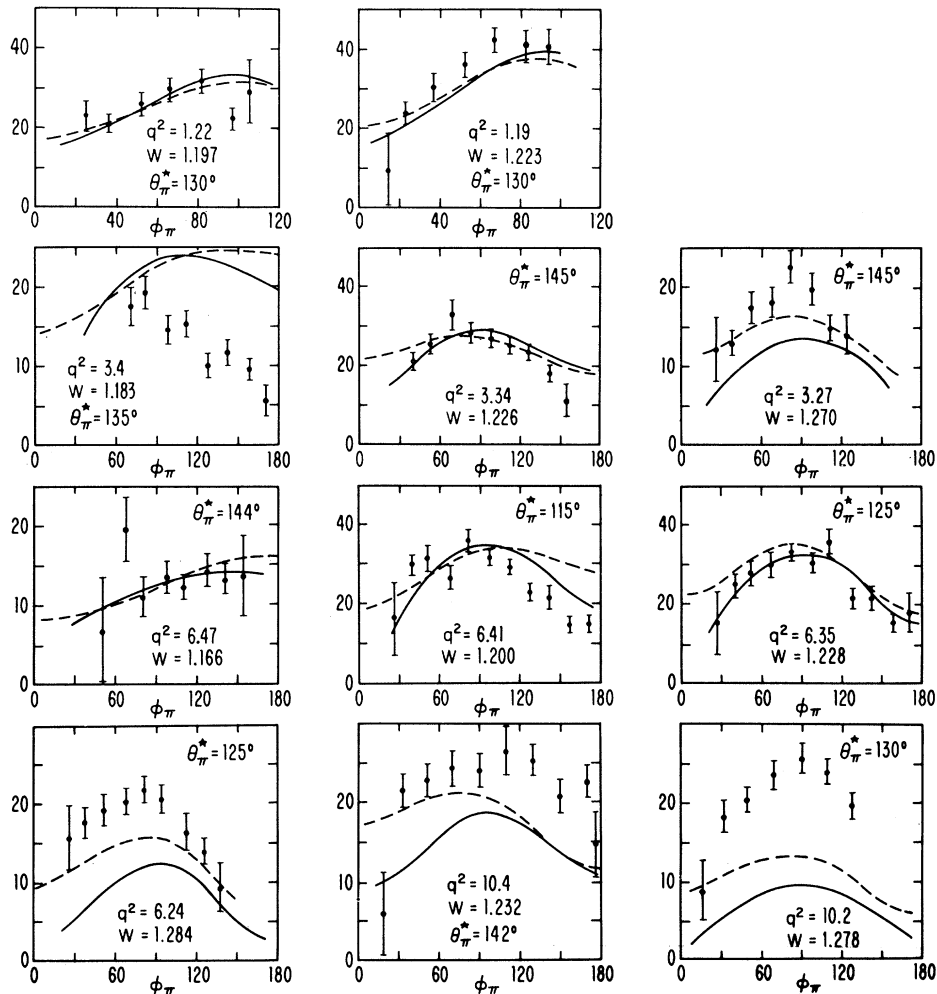


FIG. 2.  $d\sigma/d\Omega_\pi$  in  $\mu\text{b}/\text{sr}$  as a function of  $\phi_\pi$  at constant  $\theta_\pi^*$ .  $q^2$  is the square of the four-momentum transfer in  $F^{-2}$ .  $W$  (BeV) is the pion-nucleon c.m. energy. The solid and dashed lines are the theories of Adler and Zagury, respectively.

marized as follows:

(1) At all four-momentum transfers and center-of-mass energies the angular distributions are dominated by the  $\cos 2\varphi_\pi$  term.

(2) The dispersion theories of Adler and Zagury are similar and fit the data reasonably well on the top of the  $N^*$  peak at  $q^2 = 1, 3, \text{ and } 6 \text{ F}^{-2}$ , but are significantly low at  $q^2 = 10 \text{ F}^{-2}$ . This underestimation of the neutral-pion cross section is confirmed by recent data from Deutsches Elektronen-Synchrotron<sup>11</sup> at four-momentum transfers of  $20 \text{ F}^{-2}$ , where the results are generally higher than Zagury's predictions. A corresponding effect has been noted by Goitein<sup>17</sup> in the total cross section near threshold at momentum transfers up to  $130 \text{ F}^{-2}$ .

(3) The theories underestimate the cross section for pion-nucleon center-of-mass energies above the resonance at 3, 6, and  $10 \text{ F}^{-2}$  and overestimate it below the resonance at  $3 \text{ F}^{-2}$ .

(4) At  $q^2 = 3 \text{ and } 6 \text{ F}^{-2}$  the best fits to the cross section<sup>4</sup> require a larger scalar-transverse interference ( $\cos\varphi_\pi$ ) term than predicted by either theory. The measurements of Lynch, Allaby, and Ritson<sup>12</sup> and Bétourné et al.<sup>13</sup> have indicated significant scalar contributions to the total  $N^*$  production cross sections in this region. However, in these experiments it was not possible to associate any of this effect with neutral-pion production. No significant  $\cos\varphi_\pi$  term is observed at  $10 \text{ F}^{-2}$ , in agreement with Lynch's observation of a predominantly transverse total cross section there.

Approximately 15% of the neutral-pion measurements are shown in Fig. 2; the complete set of results will be presented in future publications.<sup>8</sup> A more extensive discussion based on all of the neutral-pion data is given in the following Letter.<sup>4</sup>

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