

## BRIEF REPORTS

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### Induced proton polarization for $\pi^0$ electroproduction at $Q^2=0.126$ GeV $^2/c^2$ around the $\Delta(1232)$ resonance

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We present a measurement of the induced proton polarization  $P_n$  in  $\pi^0$  electroproduction on the proton around the  $\Delta$  resonance. The measurement was made at a central invariant mass and a squared four-momentum transfer of  $W=1231$  MeV and  $Q^2=0.126$  GeV $^2/c^2$ , respectively. We measured a large induced polarization,  $P_n = -0.397 \pm 0.055 \pm 0.009$ . The data suggest that the scalar background is larger than expected from a recent effective Hamiltonian model. [S0556-2813(98)02012-3]

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At low  $Q^2$ , the  $N \rightarrow \Delta$  transition is dominated by the magnetic dipole amplitude. In a simple SU(6) model in which all

the quarks occupy  $S$  states in the  $N$  and  $\Delta$  wave functions, the  $N \rightarrow \Delta$  transition is a spin flip of a single quark. If the quarks are allowed to occupy  $D$  states as well as  $S$  states in the  $N$  or  $\Delta$  wavefunctions, then electric and Coulomb quadrupole transitions are allowed [1,2]. The ratios of these quad-

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rpole amplitudes to the dominant magnetic dipole amplitude, referred to as the  $R_{EM}$  and  $R_{CM}$ , are indicative of the relative importance of the  $D$  state in the nucleon and  $\Delta$  wave function in this model.

A sensitive probe of the  $N \rightarrow \Delta$  transition is pion production on the free nucleon. However, many processes in addition to the  $N \rightarrow \Delta$  transition contribute to pion production: nonresonant nucleon excitation, photon–vector-meson coupling and excitation of other resonances. Rescattering of the final-state hadrons also affects the pion production observables [3]. We refer to the nonresonant processes as “background” [4]. In order to extract information about the  $N \rightarrow \Delta$  transition from pion production observables, one must understand the contributions from the background processes.

Electroproduction experiments were performed in the late 1960s and early 1970s in which the  $R_{CM}$  was extracted by performing multipole analysis of  $(e, e'p)$  data acquired over a wide range of energies and angles [5]. These analyses extracted an average  $R_{CM}$  of roughly  $-7\%$  for  $Q^2$  up to  $1 \text{ GeV}^2/c^2$ . In 1993, an  $(e, e' \pi^0)$  experiment was conducted at ELSA at  $Q^2 = 0.127 \text{ GeV}^2/c^2$  [6]. The analysis of this experiment yielded a large  $R_{CM}$  of  $-0.127 \pm 0.015$ , in agreement with the analysis by Crawford [7] of earlier  $(e, e'p)$  data at the same  $Q^2$ .

We conducted a series of  $H(e, e'p)\pi^0$  measurements at the same  $Q^2$  as the ELSA measurement. We measured two types of observables: (1) the cross section over a range of proton scattering angles with respect to the momentum transfer for a wide range of the invariant mass around the  $\Delta$ , (2) the induced proton polarization in parallel kinematics in which the proton is detected along the direction of the momentum transfer. The cross section measurements allow for the extraction of the  $R_{CM}$ . The induced polarization measurement is sensitive to the background contributions. We discuss in this paper the results of the polarization measurement, which is a measurement of the  $N \rightarrow \Delta$  transition.

Past electroproduction measurements were performed over a wide range of  $Q^2$ , but only the angular dependence of the coincidence cross section was extracted from the data [5]. This data constrains only the real part of the interference response tensor [6]. In parallel kinematics the induced polarization  $P_n$  is proportional to the imaginary part of a longitudinal-transverse interference response tensor; hence, it is proportional to the interference of the resonant and background amplitudes. In this manner,  $P_n$  is sensitive to the same physics as the beam helicity asymmetry proportional to  $R_{LT'}$ , the “fifth response function” [8]. Thus  $P_n$  is in a new class of pion production observables.

The experiment was conducted in 1995 in the South Hall of M.I.T.-Bates. A 0.85% duty factor, 719 MeV electron beam was incident on a cryogenic liquid-hydrogen target. Electrons were detected with the medium energy pion spectrometer (MEPS) [9] which was located at  $44.17^\circ$  and set at a central momentum of  $309 \text{ MeV}/c$ . Coincident protons were detected with the one-hundred-inch proton spectrometer (OHIPS) [10] which was located at  $-23.69^\circ$  and set at a central momentum of  $674 \text{ MeV}/c$ . The final-state proton polarization components were measured with the focal plane polarimeter (FPP) [11]. The central invariant mass and the squared four-momentum transfer were  $W = 1231 \text{ MeV}$  and  $Q^2 = 0.126 \text{ GeV}^2/c^2$ . We sampled data over a range of  $W$

between 1200 and 1270 MeV.

The focal plane asymmetries were calculated following the procedure detailed in Ref. [11]. This procedure involved the use of polarimetry data of elastic scattering from hydrogen [12] to determine the false asymmetries of the polarimeter. In the one-photon exchange approximation with unpolarized electrons, elastically scattered protons cannot be polarized. Therefore, any measured nonzero polarization is due to false asymmetries. The resulting false asymmetries were small,  $< 0.004$ .

The polarization of the protons at the polarimeter is the asymmetry of the secondary scattering divided by the  $p$ - $^{12}\text{C}$  inclusive analyzing power. We determined the analyzing power by using calibration data of the FPP taken at the Indiana University Cyclotron Facility [13]. From our data taken with an incident proton energy of 200 MeV and the world’s data for analyzing power for energies between 150 and 300 MeV [14,15], we determined a new fit to the functional form of the analyzing power according to Aprile-Giboni *et al.* [14]. The uncertainty in the analyzing power for this measurement was 1.5%.

In a magnetic spectrometer such as OHIPS, the polarizations at the target and focal plane are related by a spin precession transformation. This transformation depends on the precession of the spin in the spectrometer and on the population of events across the acceptance. For this measurement, the transformation simplified to a simple multiplicative factor for the induced polarization because the electron beam was unpolarized and the protons were detected along the direction of the momentum transfer.

To determine this transformation, we used the Monte Carlo program MCEEP [16] modified to use the spin-transfer matrices of COSY [17]. We populated events across the acceptance using a preliminary electroproduction model by Sato and Lee (SL) based on their photoproduction model described in Ref. [3]. The transformation was

$$P_n = (-1.070 \pm 0.016) P_X, \quad (1)$$

where  $P_X$  is the polarization component extracted from the azimuthal asymmetry of the secondary scattering, and  $P_n$  is the normal-type polarization at the target. We varied parameters in the COSY and MCEEP models by their measured uncertainties to determine the uncertainty of the spin precession transformation.

To compare to theoretical models, we corrected the measured polarization for finite acceptance effects. We determined the correction with MCEEP using the SL pion production model:

$$\frac{P_n \text{ for point acceptance}}{P_n \text{ for full acceptance}} = 1.159 \pm 0.011. \quad (2)$$

This correction is mostly due to the large electron acceptance. The uncertainty in the acceptance correction reflects uncertainties in the experimental acceptance.

Applying the spin-transformation factor and the acceptance correction, we determined that the induced polarization for a point acceptance was

$$P_n = -0.397 \pm 0.055 \pm 0.009, \quad (3)$$

where the first uncertainty is statistical and the second is systematic. Our analysis does not depend on the absolute scale of the model predictions. Thus, the smooth variations of the cross section and of the induced polarization over the experimental phase space predicted by the model of Sato and Lee suggest that the model sensitivity should be sufficiently small to be neglected for this measurement. Corrections to  $P_n$  due to radiative processes are small, 0.02%, and were not included.

In parallel kinematics all the response functions can be constructed from two complex amplitudes which we label  $S$  and  $T$  [18]. In terms of the Chew-Goldberger-Low-Nambu amplitudes [19] and multipole amplitudes expanded up to  $p$  wave [8], these two amplitudes are

$$S = F'_5 - F'_6 \approx S_{0+} - S_{1-} - 4S_{1+},$$

$$T = F_1 + F_2 \approx E_{0+} + M_{1-} - 3E_{1+} - M_{1+}. \quad (4)$$

In parallel kinematics,  $P_n$  is proportional to the imaginary part of a longitudinal-transverse interference divided by the unpolarized cross section [18]. In terms of  $S$  and  $T$ ,

$$P_n = \frac{-\sqrt{2\epsilon_s(1+\epsilon)} \text{Im} S^* T}{|T|^2 + \epsilon_s |S|^2}, \quad (5)$$

$$= \frac{-\sqrt{2\epsilon_s(1+\epsilon)}(\beta_S - \zeta_S \beta_T)}{(1 + \beta_T^2) + \epsilon_s(\beta_S^2 + \zeta_S^2)}, \quad (6)$$

where  $\epsilon = (1 + 2q_{\text{lab}}^2/Q^2 \cdot \tan^2 \frac{1}{2} \Theta_e)^{-1}$ ,  $\epsilon_s = Q^2/q_{cm}^2 \cdot \epsilon$ ,  $q_{\text{lab}}$  ( $q_{cm}$ ) is the three-momentum transfer in the lab (center-of-momentum) frame,  $\Theta_e$  is the scattering angle of the electron with respect to the beam,  $\beta_{S(T)} = \text{Re} S(T)/\text{Im} T$  and  $\zeta_S = \text{Im} S/\text{Im} T$ .

The zeroth-order approximation to  $P_n$  is obtained by assuming only a purely resonant  $N \rightarrow \Delta$  transition contributes. Then at resonance, the contributing amplitudes are purely imaginary, and thus

$$\beta_S = \beta_T = 0 \quad \text{and} \quad \zeta_S = 4 \frac{R_{CM}}{1 + 3 \cdot R_{EM}}. \quad (7)$$

This approximation gives  $P_n = 0$ . A nonzero  $\beta_S$  and/or  $\beta_T$  at resonance, comes from background contributions. In this manner,  $P_n$  is sensitive to the background.

In Fig. 1 our result is compared to two different pion production models plotted over a range of the invariant mass  $W$  at a fixed  $Q^2 = 0.126$  (GeV/c)<sup>2</sup>. Results from a preliminary electroproduction model based off the published SL photoproduction model [3] are plotted for 0 and 1.4% probability of a  $D$  state in the  $\Delta$  wave function. The model of Mehrotra and Wright for the simultaneous fit to  $\pi^0$  and  $\pi^+$  production data requiring unitarity (MW) [20] is also plotted. This model does not consider  $\Delta$  resonance quadrupole amplitudes. Neither of these models successfully reproduces the measured  $P_n$ .

The constraints on the ratios due to this measurement are illustrated in Fig. 2. The two bands denote the regions of  $\{\beta_T, \beta_S\}$  consistent with this measurement for  $\zeta_S = 0$  and  $-0.4$ . These values of  $\zeta_S$  correspond to an  $R_{CM} = 0$  and

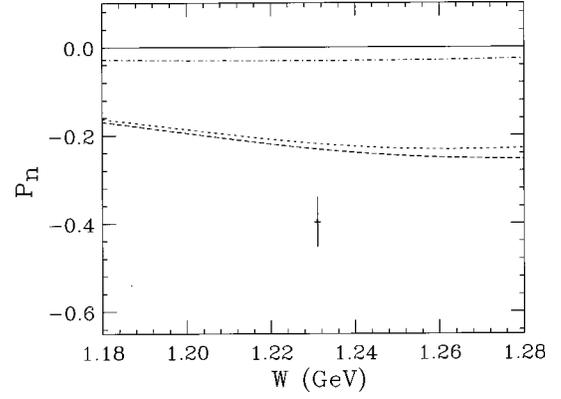


FIG. 1. Comparison of measured  $P_n$  with the two models. The dot-dash is from MW. The long (short) dash is from SL with a 0% (1.4%) probability of a  $D$  state in the  $\Delta$  wave function. The solid line at  $P_n = 0$  is the approximation of no background contributions. The uncertainty shown is the statistical and systematic uncertainties added in quadrature.

$R_{CM} = -9.1\%$  when calculated from Eq. (7) with  $R_{EM} = -3\%$ . Also shown are the  $\{\beta_T, \beta_S\}$  points for the SL and MW models. The SL model with a deformed (nondeformed)  $\Delta$  has  $\zeta_S = 0.001$  ( $-0.047$ ), which violates the simple relation of Eq. (7) because of a strong imaginary  $S_{0+}$ . The MW model does not consider imaginary scalar contributions so that  $\zeta_S = 0$ . Since  $\zeta_S$  of these models are approximately zero, the points on the graph should be compared to the vertically hatched region.

For the wide range of  $\beta_T$  and  $\zeta_S$  in the figure,  $\beta_S$  is larger than 20%. It is possible to satisfy the restrictions of  $P_n$  with lower  $\beta_S$ , but this requires  $\zeta_S < -0.4$ . However, the sum  $\zeta_S^2 + \beta_S^2$  is limited by the small longitudinal contribution to the cross section [21]. The results from the companion cross section data will provide additional information to constrain the ratios.

For the SL model to describe the  $P_n$  data, the two extreme corrections to the model are to increase either  $\beta_S$  or

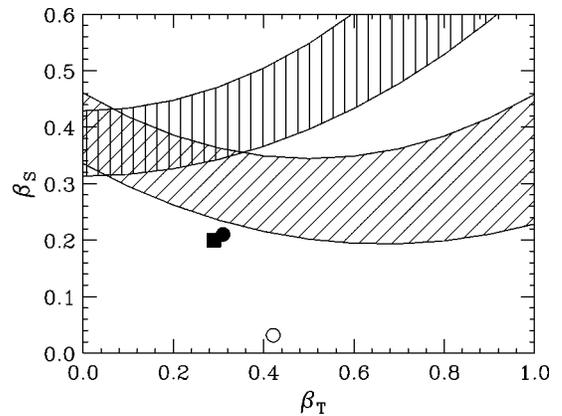


FIG. 2. Regions of  $\beta_S$  and  $\beta_T$  consistent with this measurement for two values of  $\zeta_S$ . The region filled with vertical (diagonal) lines corresponds to  $\zeta_S = 0.0$  ( $-0.4$ ). The regions for each  $\zeta_S$  denote the one standard deviation uncertainty in the constraint. The solid circle (square) indicates the  $\{\beta_T, \beta_S\}$  of the SL model for a deformed (nondeformed)  $\Delta$ . The empty circle is for the MW model. See text for a further description.

$-\zeta_S\beta_T$ . As the model differs from the measurement by roughly a factor of 2, we want to significantly change the ratios. Since the model describes the measured cross section as a function of the invariant mass well [22], we cannot radically alter the transverse contributions.  $\zeta_S$  differs by only 0.05 between the SL calculations with nondeformed and deformed  $\Delta$ , so any large change in the real or imaginary scalar amplitudes must come from nonresonant contributions. Following these conjectures, we conclude that the large  $P_n$  of this measurement indicates that the scalar background contributions are larger than expected from the SL model.

The inclusion of rescattering in the SL model has a significant effect on the scalar background contributions compared to the MW model. Both models use a similar description of the Born amplitudes at the tree level: pseudovector  $\pi NN$  coupling and  $\rho$  exchange. However, the real scalar contributions are quite different as demonstrated by the difference in the  $\beta_S$  values in Fig. 2. Thus, the rescattering procedure in the SL model significantly enhances the background scalar contributions.

It is difficult to directly compare the background of this measurement with that of measurements from which the  $R_{CM}$  is extracted. In general, the two observables can involve different combinations of multipole amplitudes. In addition,

$P_n$  is sensitive to the real part of the background, whereas the observables used to extract  $R_{CM}$  are sensitive to the imaginary part.

Previous extractions of the  $R_{CM}$  neglected the nonresonant terms under the assumption that they are small. Our data demonstrate that the background contributions are significant compared to the dominant resonant contributions and are not well described by recent models. Therefore, one cannot *a priori* neglect the background terms in the  $R_{CM}$  extraction.

In summary, we measured a large induced polarization for pion production at  $W=1231$  MeV and  $Q^2=0.126$  GeV<sup>2</sup>/c<sup>2</sup>. The data suggest that the scalar background is larger than expected from recent effective Hamiltonian models. We demonstrated that the large induced polarization of this measurement provides a significant constraint on scalar background contributions. Results from the companion M.I.T.-Bates cross sections measurements and from future experiments planned at several facilities will constrain theoretical approaches and improve our understanding of the  $N \rightarrow \Delta$  transition.

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