Measurement of the Recoil Polarization in the $p(\vec{e}, e'\vec{p})\pi^0$ Reaction at the $\Delta(1232)$ Resonance

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The recoil proton polarization has been measured in the $p(\vec{e}, e'\vec{p})\pi^0$ reaction in parallel kinematics around $W = 1232$ MeV, $Q^2 = 0.121$ (GeV$/c)^2$, and $\epsilon = 0.718$ using the polarized cw electron beam of the Mainz Microtron. All three proton polarization components, $P_x/P_e = (-11.4 \pm 1.3 \pm 1.4)\%$, $P_y = (-43.1 \pm 1.3 \pm 2.2)\%$, and $P_z/P_e = (56.2 \pm 1.5 \pm 2.6)\%$, could be measured simultaneously. The Coulomb quadrupole to magnetic dipole ratio, $\mathrm{CMR} = (-6.4 \pm 0.7_{\mathrm{stat}} \pm 0.8_{\mathrm{syst}})\%$, was determined from P_x in the framework of the Mainz Unitary Isobar Model. The consistency among the reduced polarizations and the extraction of the ratio of longitudinal-to-transverse response is discussed.

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In a very simple approximation the nucleon is composed of three spin 1/2 constituent quarks. This structure manifests itself in well known properties of the nucleon like the large anomalous magnetic moments or the nonzero polarizabilities. The finite charge radius of the neutron, in this picture, is related to the nonuniform radial distribution of the oppositely charged up and down quarks. Moreover, the hyperfine part of the color interaction between the quarks is expected to generate a D admixture in the quark wave function [1] and thus a quadrupole deformation of the nucleon's charge distribution [2]—in analogy to the deuteron in nuclear physics. However, the spectroscopic quadrupole moment of the nucleon vanishes due to its spin 1/2. In contrast, a quadrupole moment is allowed for the spin 3/2 $\Delta(1232)$ resonance, which is excited from the nucleon ground state predominantly through the spin flip of one of the constituent quarks. A direct measurement, however, is prohibited by the short lifetime.

On the other hand, in the electromagnetic $N \to \Delta(1232)$ excitation a D admixture will be visible as small quadrupole admixtures to the dominating M1 transition. In the decay of the $\Delta(1232)$ resonance into the $N\pi$ channel, this quadrupole mixing is associated with nonzero electric quadrupole to magnetic dipole (EMR) and Coulomb quadrupole to magnetic dipole ratios (CMR). These can be defined as $\mathrm{EMR} = \mathrm{Im}\{E_{1+}^{3/2}\}/\mathrm{Im}\{M_{1+}^{3/2}\}$ and $\mathrm{CMR} = \mathrm{Im}\{S_{1+}^{3/2}\}/\mathrm{Im}\{M_{1+}^{3/2}\}$, where the pion multipoles, $A_{l_\pi\pm}^{I}$, are characterized through their magnetic, electric, or longitudinal (scalar) nature, $A = M, E, S$, the isospin, I, and the pion-nucleon relative angular momentum, l_π, whose coupling with the nucleon spin is indicated by $\pm$.

Recently, the EMR was determined at squared four-momentum transfer $Q^2 = 0$ with linearly polarized real photons in the reaction $p(\vec{\gamma}, p)\pi^0$ [3]. The result is $\mathrm{EMR} = (-2.5 \pm 0.2 \pm 0.2)\%$, in agreement with the combined partial wave analysis from $p(\vec{\gamma}, p)\pi^0$ and $p(\vec{\gamma}, \pi^+)n$ which allows an isospin decomposition of the multipoles [4–6].

The determination of the longitudinal quadrupole mixing requires pion electroproduction experiments. In the one-photon exchange approximation the $N(e, e'\pi)N$ cross section can be split into photon flux and the virtual photon cross section. Without target or recoil polarization, the latter is given by [7]

$$\frac{d\sigma_v}{d\Omega_\pi} = \lambda[R_T + \epsilon_L R_L + \sqrt{2\epsilon_L(1+\epsilon)}\, R_{LT}\cos\Phi + \epsilon R_{TT}\cos 2\Phi + P_e\sqrt{2\epsilon_L(1-\epsilon)}\, R_{LT'}\sin\Phi]. \quad (1)$$

The structure functions, R_i, parametrize the response of the hadronic system to the various polarization states of the photon field, which are described by the transverse and longitudinal polarization, ϵ and ϵ_L, respectively, and by the longitudinal electron polarization, P_e. The ratio $\lambda = |\vec{p}_\pi^{\,\mathrm{cm}}|/k_\gamma^{\mathrm{cm}}$ is determined by the pion cm momentum $\vec{p}_\pi^{\,\mathrm{cm}}$ and $k_\gamma^{\mathrm{cm}} = \frac{1}{2}(W - \frac{m_p^2}{W})$, which is the photon equivalent energy for the excitation of the target with mass m_p to the cm energy W. Φ denotes the tilt angle between electron scattering and reaction plane.

Because of the smallness of the $E_{1+}^{3/2}$ and $S_{1+}^{3/2}$ multipoles compared to the dominating $M_{1+}^{3/2}$ amplitude, all experimental information so far is based on the extraction of $\mathrm{Re}\{E_{1+}^* M_{1+}\}$ and $\mathrm{Re}\{S_{1+}^* M_{1+}\}$ from the R_{TT} and R_{LT} structure functions [3,4,8–14]. The interference terms are closely related to the EMR and CMR, respectively. Because of the unavoidable non-delta-resonant contributions in the structure functions, it is important to measure the resonant amplitudes in several different combinations with the background amplitudes.

This possibility is offered by double polarization observables [15,16], which furthermore benefit from their insensitivity to experimental calibration uncertainties. The general cross section for the $p(\vec{e}, e'\vec{p})\pi^0$ reaction with longitudinally polarized electrons and measurement of the recoil proton polarization is composed of 18 structure functions [7,17]. In parallel kinematics, where the proton is detected along the direction of the momentum transfer, the three components of the proton polarization take the simple form [16] (here the notation of Ref. [7] is used)

$$\sigma_0 P_x = \lambda P_e \sqrt{2\epsilon_L(1-\epsilon)}\, R_{LT'}^{t}\,, \qquad (2)$$

$$\sigma_0 P_y = \lambda \sqrt{2\epsilon_L(1+\epsilon)}\, R_{LT}^{n}\,, \qquad (3)$$

$$\sigma_0 P_z = \lambda P_e \sqrt{1-\epsilon^2}\, R_{TT'}^{l}\,. \qquad (4)$$

The proton polarization independent cross section σ_0 is dominated by $|M_{1+}|^2$. The axes are defined by $\hat{y} = \vec{k}_i \times \vec{k}_f / |\vec{k}_i \times \vec{k}_f|$, $\hat{z} = \vec{q}/|\vec{q}|$, and $\hat{x} = \hat{y} \times \hat{z}$, where $\vec{k}_i$ and $\vec{k}_f$ are the momenta of incoming and scattered electron, respectively.

The structure functions of Eqs. (2)–(4) can be decomposed into multipoles of the $\pi^0 p$ final state, which are related to the isospin multipoles by $A_{l\pm} = A_{l\pm}^{1/2} + \frac{2}{3} A_{l\pm}^{3/2}$. Displaying only the leading resonance terms with the dominant M_{1+} amplitude and subsuming all other amplitudes in nonleading order (nlo) contributions, the polarization components,

$$\sigma_0 P_x = \lambda P_e c_- \eta\, \mathrm{Re}\{4S_{1+}^* M_{1+} + \mathrm{nlo}\}\,, \qquad (5)$$

$$\sigma_0 P_y = -\lambda c_+ \eta\, \mathrm{Im}\{4S_{1+}^* M_{1+} + \mathrm{nlo}\}\,, \qquad (6)$$

$$\sigma_0 P_z = \lambda P_e \sqrt{1-\epsilon^2}\, |M_{1+}|^2 + \mathrm{nlo}\,, \qquad (7)$$

exhibit their sensitivity to the $S_{1+}^* M_{1+}$ interference. $\eta = \omega_{\mathrm{cm}}/|\vec{q}_{\mathrm{cm}}|$ denotes the ratio of cm energy and momentum transfer and $c_\pm = \sqrt{2\epsilon_L(1 \pm \epsilon)}$.

Equations (5) and (7) show that, in the $p\pi^0$ channel, $\widetilde{\mathrm{CMR}} = \mathrm{Re}\{S_{1+}^* M_{1+}\}/|M_{1+}|^2$ can be determined through either P_x or the polarization ratio P_x/P_z [16]. Furthermore, the ratio R_L/R_T of longitudinal to transverse response is model-independently accessible without Rosenbluth separation [18].

At the Mainz Microtron MAMI [19] a $p(\vec{e}, e'\vec{p})\pi^0$ experiment with longitudinally polarized electron beam and measurement of the recoil proton polarization has been performed. The polarized electrons were produced by photoemission from strained GaAsP crystals using circularly polarized laser light [20]. During the experiment the beam helicity was randomly flipped with a frequency of 1 Hz in order to eliminate instrumental asymmetries. Longitudinal polarization after acceleration was achieved by the fine-tuning of the energy of the microtron to 854.4 MeV. A 5 cm thick liquid hydrogen target was used. Beam currents up to 15 μA with an average polarization of $P_e = 75\%$ were available.

The scattered electrons were detected at $\theta_e = 32.4°$ in Spectrometer B of the three spectrometer setup of the A1 Collaboration [21]. At $Q^2 = 0.121\ (\mathrm{GeV}/c)^2$ a range of invariant energies of $W = 1200$ to 1260 MeV was covered. The recoil protons were detected in Spectrometer A at an angle of $\theta_p = 27°$ with a coincidence time resolution of 1 ns. The unobserved π^0 was identified with a resolution of 3.8 MeV (FWHM) via its missing mass. After all cuts, the experimental background was reduced to 0.4% of the accepted π^0 events and thus neglected.

The proton polarization was measured with a focal plane polarimeter using inclusive p-^{12}C scattering [22]. The detector package of Spectrometer A, consisting of two double planes of vertical drift chambers for particle tracking and two planes of scintillators for triggering purposes [21], was supplemented by a 7 cm thick carbon scatterer followed by two double planes of horizontal drift chambers. This setup allowed the eventwise reconstruction of the proton carbon scattering angles Θ_C and Φ_C with a resolution of 2 mrad. The proton polarization could be extracted from the azimuthal modulation of the cross section

$$\sigma_C = \sigma_{C,0}[1 + A_C(P_y^{\mathrm{fp}} \cos\Phi_C - P_x^{\mathrm{fp}} \sin\Phi_C)]\,. \qquad (8)$$

$\sigma_{C,0}$ denotes the polarization-independent part of the inclusive cross section and A_C the analyzing power, which was parametrized according to [23] for $\Theta_C < 18.5°$ and according to [22] for $\Theta_C \geq 18.5°$.

The two polarization components P_x^{fp} and P_y^{fp} are measured behind the spectrometer's focal plane. It is possible to determine all three components at the electron scattering vertex due to the spin precession in the spectrometer and the additional information provided by the helicity flip of the electron beam. The spectrometer's "polarization optics" is described by a five-dimensional spin precession matrix [22]. It was checked through a series of measurements of the focal plane polarization of protons from elastic $p(\vec{e}, e'\vec{p})$ scattering where the polarization is given by electron kinematics and the proton elastic form factors. From these measurements also the absolute value of P_e was determined, because in this case the error of A_C cancels out in the determination of the quantities P_x/P_e and P_z/P_e.

The spin-precession matrix was used for the extraction of the recoil proton polarization in the $p(\vec{e}, e'\vec{p})\pi^0$ experiment. In order to account for the finite acceptance around nominal parallel kinematics [$W = 1232$ MeV, $Q^2 = 0.121\ (\mathrm{GeV}/c)^2, \epsilon = 0.718$], averaged polarizations $\bar{P}_{x,y,z}^{\mathrm{MAID}}$ were generated with the Mainz Unitary

TABLE I. Results for the recoil proton polarization in nominal parallel kinematics. The quadratic sum of the systematic error contributions yields the total systematic error. The extrapolation to nominal parallel kinematics as well as the ratios S and R, which approximate the CMR, are explained in the text.

Observable	P_x/P_e (%)	P_y (%)	P_z/P_e (%)	S (%)	R (%)
Measurement	-11.4	-43.1	56.2	-5.2	-6.4
Stat error	± 1.3	± 1.3	± 1.5	± 0.6	± 0.7
False asymm	⋯	± 1.61	⋯	⋯	⋯
δP_e	± 0.45	⋯	± 2.25	± 0.21	⋯
δA_C	⋯	± 0.87	⋯	⋯	⋯
Spin precession	± 1.05	± 0.45	± 0.81	± 0.48	± 0.62
$\delta \rho$	± 0.9	± 1.2	± 1.0	± 0.41	± 0.51
Total systematic	± 1.4	± 2.2	± 2.6	± 0.7	± 0.8

Isobar Model (MAID2000) [24] for the event population of the experiment. With the ratios of nominal to averaged polarization, $\rho_{x,y,z} = P_{x,y,z}^{\mathrm{MAID}}/\bar{P}_{x,y,z}^{\mathrm{MAID}} = 1.247$, 1.238, and 0.946, respectively, the experimental polarizations were extrapolated to nominal parallel kinematics: $P_{x,y,z} = \rho_{x,y,z}\bar{P}_{x,y,z}$. An additional systematic error is assigned to the polarizations due to the model uncertainty in $\rho_{x,y,z}$. It is estimated by a $\pm 5\%$ variation of the M_{1+} multipole and a $\pm 50\%$ variation of the other multipoles in MAID.

The results are summarized in Table I along with the statistical and systematical errors. P_x and P_z are given normalized to the beam polarization. Under the assumptions that the nlo corrections in Eqs. (5) and (7) as well as the isospin-1/2 contributions in $\widetilde{\mathrm{CMR}}$ can be neglected, the quantities $S = \frac{1}{4\eta c_-} P_x/P_e$ and $R = \frac{\sqrt{1-\epsilon^2}}{4\eta c_-} \frac{P_x/P_e}{P_z/P_e}$ of the last two columns can be identified with the CMR.

The results for the three polarization components are shown in Fig. 1 along with MAID2000 calculations. The curves represent the calculations for four values of the CMR: 0, -3.2%, -6.4%, and -9.6%. P_x is most sensitive to the CMR and from this component CMR $= (-6.4 \pm 0.7_{\mathrm{stat}} \pm 0.8_{\mathrm{syst}})\%$ is extracted within MAID2000. The result for the MAID2000 analysis of the ratio P_x/P_z is CMR $= (-6.8 \pm 0.7_{\mathrm{stat}} \pm 0.8_{\mathrm{syst}})\%$. Both values agree very well and are also close to S and particularly to R. They do not rely on the approximations of Eqs. (5)–(7). Apparently, the various interference terms in the nlo corrections of Eqs. (5) and (7) are small or cancel to a large extent. From the above variation of the multipoles in MAID2000 a model dependence of the order of 1% absolute of the CMR extracted within MAID is estimated. The variation of the extracted CMR through the analysis with other models remains to be investigated. Because of the 20% discrepancy between MAID and the measured P_y, a simultaneous fit of P_x, P_y, and P_z would produce a smaller CMR. However, it should be realized that P_y, much more than P_x, is sensitive to interferences other than the CMR, which prohibits its extraction from P_y alone [25].

In order to compare our result to those from previous π^0 electroproduction experiments with unpolarized electrons, Fig. 2 shows $\widetilde{\mathrm{CMR}}$ instead of CMR. The MAID2000 analysis of P_x yields $\widetilde{\mathrm{CMR}} = (-6.6 \pm 0.7_{\mathrm{stat}} \pm 0.8_{\mathrm{syst}})\%$. The fact that CMR and $\widetilde{\mathrm{CMR}}$ agree so well demonstrates how accurately, at the resonance position, the $p\pi^0$ channel yields the CMR which is defined in the isospin $\frac{3}{2}$ channel. Our result agrees with older data [8–10] and preliminary new Bonn results [14], but a recent ELSA result [11] seems to be incompatible with all other data. Whether this has experimental or statistical origin or points to an unexpected $\mathrm{Im}S_{0+}$ background contribution—which was neglected in [11]—is still undecided [26].

The ratio R_L/R_T of longitudinal to transverse response can be obtained in various ways from the so-called reduced polarizations (RPs) $\chi_{x,y,z}$ [18,27]. However, the

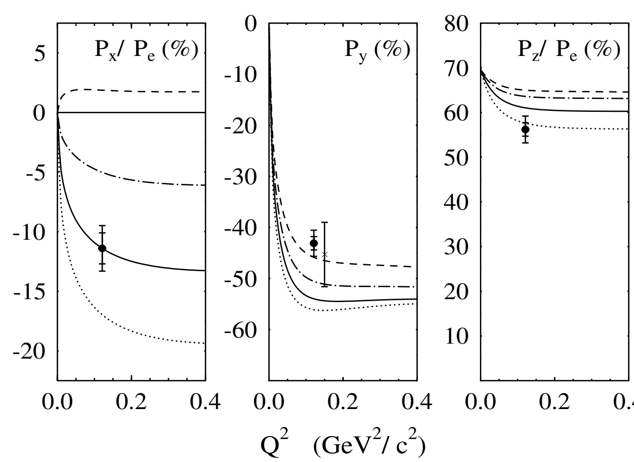

FIG. 1. Measured polarization components in comparison with MAID2000 calculations. The dashed, dot-dashed, full, and dotted curves correspond to CMR $= 0\%$, -3.2%, -6.4%, -9.6%, respectively. The MAMI data (full circles) are shown with statistical and systematical error. For the Bates P_y (cross) only the statistical error is indicated, the value is rescaled in ϵ, and, though measured at the same Q^2, it is slightly shifted for clarity.

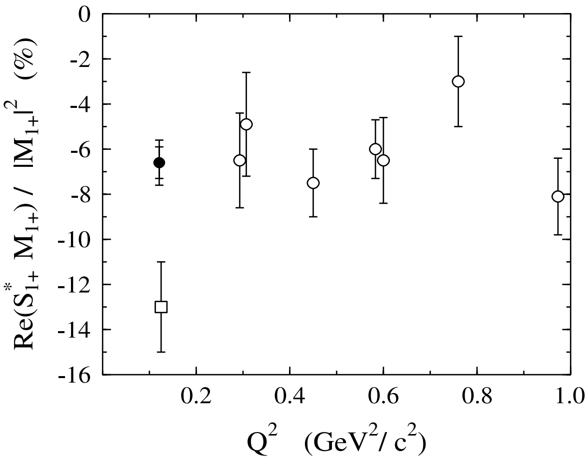

FIG. 2. Result for $\mathrm{Re}\{S_{1+}^{*}M_{1+}\}/|M_{1+}|^2$ as extracted from P_x/P_e of this experiment (full circle) with statistical and systematical error, compared to unpolarized measurements from DESY, NINA, the Bonn synchrotron [8–10] (open circles) and ELSA [11] (open square), where only the statistical errors are indicated.

results vary significantly. The smallest value, $R_L/R_T = (4.7 \pm 0.4_{\mathrm{stat}} \pm 0.6_{\mathrm{syst}})\%$, is extracted from the quadratic sum $\chi_x^2 + \chi_y^2$ of the transverse RPs and the largest one, $R_L/R_T = (12.2^{+1.7}_{-1.6_{\mathrm{stat}}}{}^{+2.9}_{-2.7_{\mathrm{syst}}})\%$, from χ_z alone. Despite the nonlinear error propagation in $R_L/R_T(\chi_z)$, the probability is only a few percent that this discrepancy has purely statistical origin. As a consequence, the consistency relation between the transverse and the longitudinal RPs derived in [18] seems to be violated. This presently prohibits a reliable extraction of R_L/R_T but stresses the importance of a simultaneous measurement of all polarization components with further improved accuracy.

In summary, we have measured the recoil proton polarization in the reaction $p(\vec{e}, e'\vec{p})\pi^0$ at the energy of the $\Delta(1232)$ resonance. Because of the spin precession in the magnetic spectrometer all three polarization components P_x, P_y, and P_z were simultaneously accessible. From P_x the Coulomb quadrupole to magnetic dipole ratio was determined in the framework of the Mainz Unitary Isobar Model as $\mathrm{CMR}(Q^2 = 0.121\ \mathrm{GeV}) = (-6.4 \pm 0.7_{\mathrm{stat}} \pm 0.8_{\mathrm{syst}})\%$, which is in good agreement with the result obtained from the polarization ratio P_x/P_z. There is only a moderate model dependence expected to remain. However, the consistency relation among the polarization components seems to be violated.

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