Measurement of the LT-asymmetry in $\pi^0$ electroproduction at the energy of the $\Delta(1232)$ resonance

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Received: date / Revised version: date

Abstract. The reaction $p(e,e'p)\pi^0$ has been studied at $Q^2=0.2$ (GeV/c)$^2$ in the region of $W=1232$ MeV. From measurements left and right of $q$, cross section asymmetries $\rho_{LT}$ have been obtained in forward kinematics $\rho_{LT}(\theta_{cm}^{LT}=20^\circ) = (11.68 \pm 2.30_{stat} \pm 2.30_{sys})$ and backward kinematics $\rho_{LT}(\theta_{cm}^{LT}=160^\circ) = (12.18 \pm 0.52_{stat} \pm 0.82_{sys}) \pi^0$. Multipole ratios $R(S^0_{1+},M_{1+}|/|M_{1+}|^2$ and $R(S_{1+},M_{1+}|/|M_{1+}|^2$ were determined in the framework of the MAID2003 model. The results are in agreement with older data. The unusually strong negative $R(S_{1+},M_{1+}|/|M_{1+}|^2$ required to bring also the result of Kalleicher et al. in accordance with the rest of the data is almost excluded.

PACS. 13.60.Le Meson production – 13.40.-f Electromagnetic processes and properties – 14.20.Gk Baryon resonances with $S=0$

1 Introduction

The nucleon ground- and excited state properties presently elude a consistent description in terms of QCD as the basic theory of strong interaction, due to the nonlinear, non-perturbative interaction of quarks and gluons. Over the last years, considerable efforts aimed at a better understanding of this complicated structure, both theoretically and experimentally. One important issue is the understanding of the ‘shape’ of the nucleon. Despite its spin of $1/2$ and, in consequence, the vanishing spectroscopic quadrupole moment, the nucleon wave function might have quadrupole components which are expected to exhibit in the transition of the ground state to the spin $3/2$ $\Delta(1232)$ excitation. Within constituent quark models those components originate from tensor forces generated by a color hyperfine interaction [4,41,44]. Larger quadrupole strengths are expected from models emphasizing the particular role of pions via exchange currents [5] or the ‘pion cloud’ [45,46,47,48] and, also in first quenched Lattice QCD calculations [49]. Dynamical approaches [11,12,13] enable a decomposition into the “bare” contributions, as described in quark models, and the “dressing” by the pion cloud.

The quadrupole strength is usually characterized by the ratios $R_{EM} = E_{1+}/M_{1+}$ and $R_{SM} = S_{1+}/M_{1+}$ of the $\pi N$ multipoles in the $\Delta(1232) \rightarrow N\pi$ decay, which are uniquely related to the photon multipoles of electromagnetic excitation [17,18]. Hence, these ratios can be measured in photo- and electroproduction of pions in the energy region of the $\Delta(1232)$ resonance. Since unwanted non–resonant contributions are strongly suppressed in the $\pi^0$ channel compared to the charged pion production, most measurements focused on the $\gamma^{(e)} p \rightarrow p\pi^0$ reaction.

A number of studies pursued at the laboratories providing cw electron beams yielded precise coincidence data based on high luminosity beams and high resolution de-

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1 Exact definition and aspects of isospin separation see [15].

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ectors with large angular coverage. Partially single or double polarization observables have been measured. The evolution of $R_{EM}$ and $R_{SM}$ with negative squared four-momentum transfer, $Q^2$, has been investigated over a large range in $Q^2$ up to 4 (GeV/c)$^2$ [19,20,21]. The extraction of the quadrupole ratios from the measured cross sections is non-trivial. For the $R_{SM}$ discussed here, it is more reliable at lower $Q^2$ where $M_{1+}$ dominance is more pronounced than at higher $Q^2$ and single [22,23] and double polarization results [24,25] are already available in addition to unpolarized recent measurements [26,27,28,29,30].

The low $Q^2$ results are almost all compatible with each other, yielding $R_{SM} \simeq -6 \%$, cf. fig. 5. The only exception is the result of Kalleicher et al. [22]. However, due to the particular kinematics it could be interpreted in line with the other results, if the ratio $S_{0+}/M_{1+} \simeq -10 \%$ [16]. $S_{0+}$ is related to the spin $1/2 \rightarrow 1/2$ transition. This amplitude was neglected in the analysis of [24]. Both magnitude and sign of such an $S_{0+}$ are however unexpected from models, e.g. MAID2003 [15], but not excluded by older measurements with large errors [31,32] which yielded slightly positive values with errors of the order 10% absolute.

In order to investigate this issue, measurements of $\pi^0$ electroproduction in forward and backward direction have been performed, which are reported in this paper. It is organized as follows: In the next section the cross section formalism is briefly summarized and the method is motivated. The description of the experiment is then followed by a discussion of the data analysis, systematic error contributions and the results in sections 3 and 4.

2 Cross section of pion electroproduction

In one-photon-exchange approximation the fivefold differential cross section of pion electroproduction

$$\frac{d^5\sigma}{dE_e d\Omega_e d\Omega_{cm}} = \Gamma \frac{d^2\sigma_v}{d\Omega_{cm}}$$

factorizes into the virtual photon flux

$$\Gamma = \frac{\alpha E'}{2\pi^2} \frac{k_\gamma}{E Q^2} \frac{1}{1 - \epsilon}$$

and the virtual photon cm cross section $d^2\sigma_v/d\Omega_{cm}$.

Here $\alpha$ denotes the fine structure constant, $k_\gamma = (W^2 - m_e^2)/2m_e$, the laboratory energy of a real photon for the excitation of the target with mass $m_e$ to the cm energy $W$, and $\epsilon = \frac{1}{2}(\frac{Q^2}{Q^2})\tan^2\frac{q}{\rho}$ the photon polarization parameter. $Q^2 = |q|^2 - \omega^2$ is the negative squared four-momentum transfer, $q$ and $\omega$ are the three-momentum and energy transfers, respectively, and $E$, $E'$ the incoming and outgoing electron energy and the electron scattering angle in the laboratory frame.

The unpolarized cross sector for pion production with virtual photons is given by [17,18]

$$\frac{d^2\sigma_v}{d\Omega_{cm}} = \sigma_v = \sigma_T + \epsilon_L \sigma_L
+ \sqrt{2} \epsilon_L (1 + \epsilon) \sigma_{LT} \cos \phi + \epsilon \sigma_{TT} \cos 2\phi.$$  (3)

The partial differential cross sections, for which we use the short-hand notation $\sigma_i$, describe the response of the hadronic system to the polarization of the photon field, characterized by the degrees of transverse (T) and longitudinal (L) polarization, $\epsilon$ and $\epsilon_L = \frac{Q^2}{2E}$, respectively. The angle $\phi$ is the tilting angle between the electron scattering plane and the reaction plane. At $\phi = 0^\circ$ and $180^\circ$ ($\phi = 90^\circ$ and $270^\circ$) pions are ejected in (perpendicularly) to the scattering plane.

3 Method

The partial cross section $\sigma_{LT}$ is sensitive to both $S_{0+}$ and $S_{1+}$. It can be determined from a fit of the $\phi$-dependence of the cross section of eq. (3). To this end, two measurements left ($\phi = 0^\circ$) and right ($\phi = 180^\circ$) of the $q$ direction are sufficient, which allow to form the asymmetry

$$\rho_{LT}(\theta_{\pi^0}) := \frac{\sigma_v(\phi = 0^\circ) - \sigma_v(\phi = 180^\circ)}{\sigma_v(\phi = 0^\circ) + \sigma_v(\phi = 180^\circ)}$$

as a function of the $\pi^0$ center-of-mass polar angle, $\theta_{\pi^0}$. According to eq. (4), it is related to the partial cross sections via

$$\rho_{LT}(\theta_{\pi^0}) = \frac{\sqrt{2} \epsilon L (\epsilon + 1) \sigma_{LT}}{\sigma_T + \epsilon_L \sigma_L + \epsilon \sigma_{TT}}.$$  (5)

The sensitivity to $S_{0+}$ and $S_{1+}$ is shown by a partial wave decomposition of eq. (5), where only the leading multipoles are retained. At the $\Delta(1232)$ resonance position the asymmetry

$$\rho_{LT}(\theta_{\pi^0}) \simeq \frac{f(\theta_{\pi^0}) \cdot \Re\{(S_{0+} + 6 S_{1+} \cos \theta_{\pi^0}) M_{1+}\}}{|M_{1+}|^2}$$

is obtained. Thus measurements of $\rho_{LT}$ in the forward ($\theta_1$) and backward cm-hemisphere ($\theta_2 = \pi - \theta_1$) allow the extraction of $S_{1+}/M_{1+}$ and $S_{0+}/M_{1+}$:

$$\Re\{S_{1+} M_{1+}\} = f_1(\theta_1) \cdot [\rho_{LT}(\theta_1) - \rho_{LT}(\theta_2)] + C_1$$

$$\Re\{S_{0+} M_{1+}\} = f_0(\theta_1) \cdot [\rho_{LT}(\theta_1) + \rho_{LT}(\theta_2)] + C_0.$$  (7)

The functions $f_0(\theta_{1,2})$ and $f_1(\theta_{1,2})$ denote kinematical factors, $C_0$ and $C_1$ contain contributions of multipoles beyond the approximation.

4 Experiment

The $p(e,e'p)\pi^0$ experiment was performed at the Mainz Microtron MAMI [33] using a beam energy of 855 MeV and currents of $\sim 33 \mu A$ which were measured with high precision by a Förster probe in the recirculation path of the 3rd microtron stage. The beam hit a liquid hydrogen target. Specifically designed for this experiment, the
Fig. 1. Typical coincidence-time (a,b,c) and missing-mass (a’,b’,c’) spectra for Kin. I, II and IIa. Light spectra result from standard cuts without phase-space restrictions. Shaded time spectra (FWHM peaks: (a) 0.8 ns, (b) 2.7 ns, (c) 3.0 ns) result from missing-mass cuts (dashed vertical lines in the missing-mass plots) around the π0 mass; in Kin. I and Ia (not shown) the cut eliminates the π−-time peak and at Kin. II and IIa the prompt time peak becomes symmetric (see text). The shaded missing-mass spectra result similarly from the indicated cuts around the coincidence-time peak.

∅ 1 cm cylindrical target cell with 6.25 μm Havar walls enabled the detection of very low-energetic protons. The scattered electrons were detected at a central angle of \( \theta_{lab} = 44.45^\circ \) and central momentum of \( p = 408.7 \text{ MeV/c} \) in Spectrometer A of the Three-Spectrometer setup of the A1-collaboration \[35\]. It consists of a QSDD magnetic system and is equipped with two double planes of vertical drift chambers for measurement of particle trajectories in the focal plane. During the course of the measurements presented here, the standard Cherenkov detector for π−/e−-discrimination was not available, since it was replaced by a focal-plane proton polarimeter \[36\] for other experiments \[24,37\]. In coincidence with the scattered electron, the recoil protons of the \( p(e,e'p)\pi^0 \) reaction were detected in Spectrometer B with a similar focal-plane instrumentation. The smallest possible angle between Spectrometer B and the exit beam-pipe is 9° and the momentum-threshold for the proton-detection is 250 MeV/c. Hence \( Q^2 = 0.2 \text{ (GeV/c)}^2 \) was the minimum possible momentum transfer that could be reached at \( W = 1232 \text{ MeV} \). The four different kinematic settings are summarized in table 1. In order to check for false asymmetries, possibly caused by inefficiencies of the focal plane detectors in the proton arm, Spectrometer B was displaced by 1° against the nominal setting for part of the measurements.

Table 1. Proton kinematics.

| Kin. | \( \theta^\text{lab} \) (°) | \( \phi \) (°) | \( p^\text{lab} \) (MeV/c) | \( \theta^\text{lab} \) (°) |
|------|----------------|--------|----------------|----------------|
| I    | 160            | 0      | 741.7          | 33.0/32.0      |
| Ia   | 180            | 0      | 265.02         | 44.2/43.7      |
| II   | 20             | 0      | 265.02         | 44.2/43.7      |
| IIa  | 180            | 0      | 265.02         | 44.2/43.7      |

Precise measurements of electron beam current and dead time allowed an accurate determination of the effective luminosity.

5 Data analysis

Typical coincidence-time and missing-mass spectra are shown in fig. 1. The overdetermined kinematics allows...
the reconstruction of the unobserved \(\pi^0\) by its missing mass, \(m_{\pi^0\text{miss}}\). Basic background reduction is obtained by coincidence-time cuts and subtraction of random coincidences via sidebands. In addition to the almost background-free \(e^+\pi^0\) coincidence peak, the time spectrum for the high proton-momentum kinematics shows a smaller second peak at \(\sim 2.2\) ns (Kin. I, cf. fig. 1a). It is caused by negative pions, predominantly from \(\pi^+\pi^-\) reactions, of which are detected in the electron spectrometer after a longer flight time compared to electrons. These events can be eliminated by the coincidence-time cut indicated in fig. 1. However, for Kin. II and IIa, the unwanted negative pions can no longer be separated by coincidence time, due to insufficient time resolution caused by multiple scattering at the low proton-momentum. Instead, additional missing-mass cuts are used to suppress these events. As also illustrated in fig. 1 with a cut around \(m_{\pi^0}(a', b', c')\) the \(\pi^-\) peak vanishes in Kin. I (shaded area of fig. 1). Under the conditions of Kin. II/IIa the resulting coincidence-peak time becomes symmetric after the missing-mass cut.

Standard cuts ensure valid track reconstruction in both spectrometers. No target-vertex cuts were applied in order to avoid artificial \(\rho_{LT}\)-asymmetries from the very different vertex-resolution along the beam-direction for the different settings. Spectrometer acceptances were normalised with standard Monte-Carlo phase-space simulations, which also include the radiative corrections [39].

The limited spectrometer acceptances cause different correlations between \(W, Q^2, \epsilon, \theta_{\pi^0}^{\text{cm}}\) and \(\phi\) for the settings left and right of \(q\), as illustrated in fig. 2. Due to these correlations, equal binning in the variables nevertheless leads to unequal distributions left and right of \(q\). Thus artificial \(\rho_{LT}\)-asymmetries can be generated, if the mean values of the kinematic variables differ between left and right. This is obvious, e.g., for a case where \(W_{\text{left}} = 1232 MeV - \delta\) and \(W_{\text{right}} = 1232 MeV + \delta\), since the trivial \(W\) dependence of the cross section produces a \(\rho_{LT} \neq 0\).

It is extremely important to base the experimental asymmetries on left-right bins with the same mean values of the variables \(W, Q^2, \theta_{\pi^0}^{\text{cm}}\) and \(\phi\). This is ensured by projection of the numbers measured in each bin to the same "nominal kinematics". For this projection we made use of the MAID2000 parametrisation. The projection factors are obtained as the calculated ratios of differential cross sections. In order to minimise the projection error, only data are used within the \(\theta_{\pi^0}^{\text{cm}}-W\) overlap region of the two acceptance bands in fig. 2. Remaining uncertainties are included in the systematic error.

The appropriately normalised and projected numbers of events left (l) and right (r) of \(q\) are determined by

\[
\rho_{LT}(\theta_{\pi^0}^{\text{cm}}) = \frac{n_l - n_r}{n_l + n_r}. \tag{10}
\]

6 Systematic errors

The systematic error has been estimated for Kin. I/ia from the data themselves by variation of all kinematic cuts. For the data with low proton-momentum (Kin. II/IIa) such an analysis is limited by the available statistics and experimental resolution. The sliding cuts in the variables \(W\) and \(m_{\pi^0\text{miss}}\) resulted in non-negligible systematic errors (table 3b, 3c). The sliding cut in \(m_{\pi^0\text{miss}}\) sets a limit on remaining radiative effects beyond those included in the phase-space simulation. The spectrometer correction, which was determined by elastic measurements, has been taken into account both in analysis (track reconstruction) and simulation. The value given in table 3b: results from the variation of the angle of Spectrometer B by \(\pm 0.1^{\circ}\). Potential error contributions of the MAID-projection were estimated through relative variation of \(M_{1+}\) by \(\pm 5\%\) and, simultaneously, of \(S_{1+}\) and \(S_{0+}\) by \(\pm 50\%\) in the full MAID2000 calculation. The largest deviation is given in table 3d. Additional errors for the luminosity determination are not required. The maximum variations of 2%-relative were corrected, and the remaining effect is negligible. All kinematic settings were measured repeatedly to avoid time-dependent effects, e.g. efficiency variations. These data sub-sets were combined for the left- and right-kinematics.

| Table 3. Absolute systematic errors (\(\Delta \rho_{LT}\)) of high proton-momentum kinematics |
|-----------------------------------------------|
| a) \(W\) cut | 0.29 % |
| b) \(m_{\pi^0\text{miss}}\) cut | 0.23 % |
| c) Spectrometer corrections | 0.57 % |
| d) MAID2000 projection | 0.46 % |
From eq. 10 the asymmetries

\[
\rho_{LT}(\theta^m_{\pi^0} = 160^\circ) = (12.18 \pm 0.27_{\text{stat}} \pm 0.82_{\text{sys}})\%
\]

\[
\rho_{LT}(\theta^m_{\pi^0} = 20^\circ) = (-11.68 \pm 2.30_{\text{stat}} \pm 2.36_{\text{sys}})\%
\]

are determined. The total systematic error is obtained by quadratic summation of the individual contributions in table 3. For the forward measurement a systematic error of the same size as its statistical one is assumed as a worst case estimate. Using these new data in conjunction with the previous measurement of the \(\rho_{LT}\) asymmetry (fifth structure function) of Bartsch et al. [23], we performed a re-fit of the MAID2003 parameters. We obtained sensitivity to real and imaginary parts of the \(S_{1+}\) and \(S_{0+}\) amplitudes in the \(p\pi^0\) channel. The results for \(\rho_{LT}\) and \(\rho_{LT}\) are depicted in fig. 3 and 4, which, for comparison, also shows the standard MAID2003 and the calculation within the dynamical models of Kamalov/Yang (DMT2001) [11, 12] and Sato/Lee [13].

From our MAID re-fit we extract the results given in the first row in table 4. The denoted errors are due to the re-fit of \(S_{1+}\) and \(S_{0+}\) within the MAID2003 analysis taking into account the statistical and systematical errors. The model dependence of the extraction can be estimated from the truncated multipole result given in the second row in table 4. Within the errors it agrees with the MAID2003 re-fit, the depicted errors are only statistical.

Table 4. Comparison of multipole ratios from data and calculations, as discussed in the text.

|                   | \(\frac{S_{1+}^m |M_{1+}|^2}{|M_{1+}|^2}\) (%) | \(\frac{S_{0+}^m |M_{1+}|^2}{|M_{1+}|^2}\) (%) |
|-------------------|---------------------------------------------|---------------------------------------------|
| MAID2003 re-fit   | -5.45\pm0.42                                | 2.56\pm2.25                                 |
| from eqs. [23]    | -1.78\pm0.69                                | 0.56\pm3.89                                 |
| MAID2003          | -6.65                                       | 7.98                                        |
| Sato/Lee          | -4.74                                       | 5.14                                        |

Fig. 3. The measured \(\rho_{LT}\) asymmetries compared with model predictions from MAID2003 [13] (dotted), DMT2001 [11, 12] (dashed), Sato/Lee [13] (dashed dotted). The full curve represents the MAID2003 re-fit reported in this paper. The depicted errors represent the statistical (inner bars) and the quadratic sum of the statistical and systematical errors (outer bars) as discussed in the text.

Fig. 4. Results for \(\rho_{LT}\) from reference [23] with model predictions from MAID2003 [13] (dotted), DMT2001 [11, 12] (dashed), Sato/Lee [13] (dashed dotted). The full curve represents the MAID2003 re-fit. The depicted errors are only statistical.
Fig. 5. Result for $\Re\{S_{1+}^* M_{1+}/|M_{1+}|^2\}$ with statistical and systematical errors as extracted from this experiment using the MAID2003 re-fit (full cross), compared to measurements. Data where only statistical errors are given: DESY [31] (open square), NINA [32] (open circles), Bonn synchrotron [30] (open triangle tip up) and ELSA [27] (full triangle tip down). Data, where statistical and systematical errors are given: ELSA [28] (full circle, to improve the presentation shifted from $Q^2=0.201$ (GeV/c)$^2$ to $Q^2=0.221$ (GeV/c)$^2$), MAMI [24] (open diamond), CLAS [21] (full triangles) and BATES [29,30] (full square). The curves show model calculations MAID2003 [18] (solid), DMT2001 [12] (dashed) and Sato/Lee [13] (dashed dotted).

and standard MAID2003 parametrisations. In view of the quite large experimental errors it is not yet clear whether this ratio differs from zero. But we can not support a large negative $S_{0+}/M_{1+}$ ratio.

A sensitive access to the ratio $S_{0+}/S_{1+}$ is provided by a precise measurement of the zero-crossing of $\rho_{LT}$ or $\sigma_{LT}$. By now it is possible to extract this ratio from available data close to the zero crossing at $Q^2=0.127$ (GeV/c)$^2$ [30], with the result compatible to the MAID2003 parametrisation. Other existing data [21] cover the full range of $\theta_{c.m.}^{\pi^0}$ at $Q^2=0.4-1.8$ (GeV/c)$^2$. However, at higher $Q^2$ the $S_{0+}$ extraction seems to be affected more strongly by higher partial waves than expected in the paper by Joo et al. [21]. This might be resolved by very recent polarisation data [11,12].

In future experiments at MAMI-C a more accurate determination of $S_{0+}$ at low $Q^2$ is feasible, using the Three-Spectrometer setup of the A1-collaboration complemented by the KaoS-spectrometer [43].

8 Summary

We have measured the $\rho_{LT}$ asymmetry in forward ($\theta_{c.m.}^{\pi^0}=20^\circ$) and backward ($\theta_{c.m.}^{\pi^0}=160^\circ$) kinematics of $\pi^0$ electroproduction off the proton at $Q^2=0.2$ (GeV/c)$^2$ around W=1232 MeV. The measurement of the two kinematic settings allows the extraction of $S_{1+}$ and $S_{0+}$ in a very transparent way within a simple s- and p-wave approximation or, alternatively, using the full MAID2003 parametrisation without any truncation. Our results for $S_{1+}/M_{1+}$ and $S_{0+}/M_{1+}$ are in agreement with existing measurements and calculations. Our result removes a remaining possibility to reconcile the datum of Kalleicher et al. [27] for the ratio $S_{1+}/M_{1+}$ with other measurements through a large negative $S_{0+}/M_{1+}$.

We thank T.-S.H. Lee and T. Sato for providing their cal-
calculations. This work was supported by the Deutsche Forschungsgemeinschaft (SFB 443).

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