π⁰ ELECTROPRODUCTION IN THE Δ(1232) REGION AT MAMI

H. SCHMIEDEN
Institut für Kernphysik, Johannes Gutenberg-Universität, J. J. Becher-Weg 45, D-55099 Mainz, Germany
E-mail: hs@kph.uni-mainz.de

The extraction of the CMR from a p(\vec{e}, e'\vec{p})π⁰ measurement is discussed. Preliminary results from further asymmetry measurements with polarized and unpolarized electron beam indicate that the imaginary background is well under control in the MAID2000 parameterization, but not the real (Born-) amplitudes.

1 Introduction

Similar to the ground state properties of the nucleon, the ratio of quadrupole to dipole strength in the N → Δ(1232) transition since a long time was considered as one of the key observables for the understanding of nucleon structure. Several mechanisms had been proposed for the breaking of spherical symmetry which is required for non-zero values for that ratio.

While the resonance structure of the nucleon has been revealed almost entirely by π-N scattering, the Δℓ = 2 positive parity transitions require electromagnetic excitations. Due to the Δ(1232) decay branching ratio of 99.4% into the πN channel, the electric (transverse) and Coulombic (longitudinal) quadrupole to magnetic dipole ratios, EMR and CMR, respectively, are measured in pion photo- and electroproduction. These ratios are defined as

\[ \text{EMR} = 3m\{E_{1+}^{3/2}\}/3m\{M_{1+}^{3/2}\} \]
\[ \text{CMR} = 3m\{E_{1+}^{3/2}\}/3m\{M_{1+}^{3/2}\} \]

where the pion multipoles, \( A_{I+}^{l±} \), are characterized through their magnetic, electric or longitudinal (scalar) nature, \( A \), the isospin, \( I \), and the pion-nucleon relative angular momentum, \( l_π \), whose coupling with the nucleon spin is indicated by \( ± \). However, in pion production the Δ(1232) channel is intimately related to non-resonant mechanisms, which hamper the extraction of the EMR and CMR. The separation of resonant and non-resonant contributions, in principle, remains ambiguous [1]. What experimentally can be achieved is the isospin separation required for the EMR and CMR.

However, a complete experiment with regard to a multipole decomposition seems out of reach yet. It requires the complete angular distributions of at least 7 or 11 independent observables in single pion photo- and electroproduction, respectively. The EMR and CMR thus can only be extracted using a truncated multipole basis or model assumptions. Therefore, it is desirable to
measure the small quadrupole amplitudes in different combinations with the unwanted, but unavoidable, non-resonant background. In particular, the measurement of polarization observables is mandatory. A first double-polarization experiment for the extraction of the CMR has been completed at MAMI.

2 Results of the $p(e',e'p)\pi^0$ experiment

High sensitivity to the CMR is provided in the $p(e',e'p)\pi^0$ reaction measured in parallel kinematics, both in the proton polarization component $P_x$ and in the polarization ratio $P_x/P_z$. 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, and $\vec{q} = \vec{k}_i - \vec{k}_f$ denotes the momentum transfer. The experiment was carried out at MAMI with a 15 µA electron beam of $P_e = 75\%$ longitudinal polarization impinging on a 5 cm long liquid hydrogen target. The scattered electrons were detected in Spectrometer B of the 3-Spectrometer-Setup in coincidence with the protons in Spectrometer A. This spectrometer was equipped with a focal plane proton polarimeter. Due to the spin precession in the magnetic spectrometer and the helicity flip of the electron beam, it was possible to determine all three proton polarization

Figure 1. Results for the polarization components measured in the $p(e',e'p)\pi^0$ reaction at $W = 1232$ MeV, $Q^2 = 0.12 (\text{GeV/c})^2$ and $\epsilon = 0.71$ 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 $\epsilon$ and, though measured at the same $Q^2$, slightly shifted for clarity.
Figure 2. $\text{Re}\{E_{1+}^*/|M_{1+}|^2\}$ (left) and $\text{Re}\{S_{1+}^*/|M_{1+}|^2\}$ (right) as a function of the invariant energy. The full and broken curves represent MAID2000 calculations in the isospin 3/2 and the $p\pi^0$ charge channel, respectively, for $Q^2 = 0.2\text{ (GeV/c)}^2$ (black) and 1.0\text{ (GeV/c)}^2 (grey). The zero crossing of $\text{Re}\{M_{1/2}^3\}$ is indicated by the vertical dashed line.

components, $P_x$, $P_y$ and $P_z$, simultaneously. The results are depicted in Figure 1. They were averaged over the experimental acceptance and projected to nominal parallel kinematics ($W = 1232\text{ MeV}$, $Q^2 = 0.12\text{ (GeV/c)}^2$, $\epsilon = 0.71$, $\Theta_{cm} = 180^\circ$) using MAID2000. A consistency relation among the reduced polarizations seems to be violated. With the present statistical accuracy the origin of this remains unclear.

In the MAID analysis CMR is extracted without truncation of the multipole series. Directly at the zero crossing of the real part of the $M_{1/2}^3$ amplitude, i.e. at $W = 1232\text{ MeV}$, the result obtained in the $p\pi^0$ channel is almost identically with the isospin 3/2 channel. This is demonstrated in Figure 2, where the relevant interferences are shown as a function of $W$ in both channels. Therefore, the CMR can be reliably extracted from the $p(e,e'\pi^0)$ reaction, without explicit isospin separation. In Figure 3 our result for $\text{Re}\{S_{1+}^*/|M_{1+}|^2\}$ in the $p\pi^0$ channel is compared to previous results and the preliminary results of ongoing experiments. The curves show the calculations of Ref. 18, 19, 20.

The double-results at high $Q^2$ are due to different analyses of the same data. The model dependence of the analyses is reduced at smaller $Q^2$. Here all results agree, except that of Ref. 11, where, in contrast to the recoil polarization measurement, the $\pi^0$ was detected in forward direction and all multipoles other than $M_{1+}$ and $S_{1+}$ were neglected. The effect of an additionally non-zero $\Im m S_{0+}/\Im m M_{1+}$ on the extracted $\Im m S_{1+}/\Im m M_{1+}$ is visualized in Figure 4.
The extracted $3mS_{1+}/3mM_{1+}$ is plotted as a function of $3mS_{0+}/3mM_{1+}$. Within MAID2000 the imaginary part of $S_{0+}$ has a strong impact on the extraction of the CMR, too. $3mS_{0+}$ can be measured via the forward-backward asymmetry of LT-type structure functions.

3 Forward and backward LT-asymmetry in $p(e,e'p)\pi^0$

Due to a different angular weight of $ReS^*_1M_{1+}$ and $ReS^*_0M_{1+}$, their relative strength can be extracted from the $\Theta^*_{cm}$ angular distribution. This requires the LT structure function or the related asymmetry

$$\rho_{LT} = \frac{d\sigma^L - d\sigma^R}{d\sigma^L + d\sigma^R}$$

to be measured over a large angular range.

$d\sigma^L$ and $d\sigma^R$ denote the differential cross sections left and right of $\vec{q}$.

At the squared 4-momentum transfer of $Q^2 = 0.2$ (GeV/c)$^2$ of the MAMI experiment, the forward ($\Theta^*_{cm} = 20^\circ$) and backward ($\Theta^*_{cm} = 160^\circ$) kinematics require very different settings of the proton spectrometer both in angle and

![Graph](https://example.com/graph.png)

Figure 3. Results for $Re\{S^*_1M_{1+}\}/|M_{1+}|^2$ extracted from different experiments. The pre 1980 data are indicated as full diamonds. The full grey square is from [11]. Full triangles represent the analyses of [12]. The result from the only double polarization measurement is indicated by the full circle with statistical (inner) and quadratic sum of statistical and systematical (outer) error. Preliminary data are also shown from Bates [13] (open triangle), TJNAF/CLAS [14] (open diamonds) ELSA [15] (open squares) and MAMI [16], [17] (open circle). The curves are calculations within Heavy Baryon Chiral Perturbation Theory [18] (short dashed), the Chiral Quark Soliton Model [19] SU(2) (dashed-dotted) and SU(3) (long dashed), the dynamical model of [20] (long-short dashed), and dressed (full) and bare (dotted) solutions of the dynamical model of [21].
momentum. They are summarized in Table 1. A 10 µA (unpolarized) beam was used on a LH$_2$ target with a diameter of only 1 cm, in order to minimize the energy loss of the low energy protons of the forward settings (c.f. Table 1). The scattered electrons were detected in Spectrometer A and the protons in Spectrometer B.

In Figure 5 the preliminary results are shown in comparison with calculations. The full curve corresponds to the full MAID calculation which has the standard ratios $\Im mS_{1+}/\Im mM_{1+} = -6.6\%$ and $\Im mS_{0+}/\Im mM_{1+} = +6.0\%$. The other curves are due to a truncated multipole basis where only $M_{1+}$, $S_{1+}$, and $S_{0+}$ partial waves are included. The differences between the full and dashed curves indicate the quality of this approximation. From the result of Ref. 11, the dotted curve would be expected, while the dashed-dotted line

Table 1. Kinematics of the $p(e,e'p)\pi^0$ experiment. $\Theta_p^{\text{lab}}$ and $p_p^{\text{lab}}$ are the proton laboratory angles and momenta, respectively, and $\Theta_{pq}^{\text{lab}}$ denotes the relative angle between recoiling proton and momentum transfer. For all settings the angle of the momentum transfer is 26.9$^\circ$ relative to the incoming electron beam.

| kinematics | $\Theta_{\pi}^{\text{cm}}$ | $\Theta_p^{\text{lab}}$ | $p_p^{\text{lab}}$ (MeV/c) | $G_p^{\text{lab}}$ |
|------------|-----------------|-----------------|-----------------|-----------------|
| b (right)  | 160$^\circ$     | 6.1$^\circ$     | 741.7           | 33.0$^\circ$    |
| b (left)   |                 |                 |                 | 20.9$^\circ$    |
| f (right)  | 20$^\circ$      | 17.2$^\circ$    | 265.0           | 44.2$^\circ$    |
| f (left)   |                 |                 |                 | 9.7$^\circ$     |
corresponds to the overlap region in Figure 4. The new data do not yet indicate any discrepancy with the standard MAID parameterization concerning the $\Im m S_{1+}/\Im m M_{1+}$ and $\Im m S_{0+}/\Im m M_{1+}$ ratios. Thus, the imaginary parts of the relevant amplitudes seem well under control.

4 Fifth structure function in $p(\vec{e}, e'p)\pi^0$

In contrast to the imaginary parts, the real background is more problematic. This is indicated by the discrepancy between MAID calculation and data for $P_y$ (c.f. Figure 3, middle). $P_y$ is related to the imaginary part of a longitudinal-transverse interference. In parallel kinematics the leading terms in s and p wave approximation read:

$$P_y \propto \Im m \{(S_{0+} - 4S_{1+} + S_{1-})^*M_{1+}\}. \quad (1)$$

This is very similar to the fifth structure function in $p(\vec{e}, e'p)\pi^0$:

$$R_{LT'} \propto P_e \sin \Theta_\pi^m \Im m \{(S_{0+} + 6 \cos \Theta_\pi^m S_{1+})^*M_{1+}\}. \quad (2)$$
Therefore, we measured the helicity asymmetry $\rho_{LT'}$ with regard to the flip of the electron beam helicity between $+$ and $-$. This required detection of the recoiling proton in Spectrometer B with its $10^\circ$ out of plane capability. The preliminary result is shown in Figure 6. Obviously, the MAID parameterization, very similarly to $P_y$, also overestimates the magnitude of $\rho_{LT'}$. It is therefore concluded that this is not caused by the $S_{1-}$ amplitude, which only contributes to $P_y$ (Eq. 1), but is rather related to the real (Born) background in the imaginary parts of the interferences of Eqs. 1 and 2. Such a real background to first order does not affect the extraction of the CMR from $P_x$ at the resonance energy.

5 Summary

From a first $p(\vec{e}, e'\vec{p})\pi^0$ double polarization experiment $\text{CMR} = (-6.4 \pm 0.7_{\text{stat}} \pm 0.8_{\text{syst}})\%$ has been deduced within the MAID2000 parameterization. Imaginary background amplitudes investigated by forward and backward $\rho_{LT}$ measurements are in agreement with MAID. Contrary, MAID consistently overestimates the magnitude of $P_y$ as well as of $\rho_{LT'}$, which was measured with out of plane detection of the recoiling protons. This seems due to real amplitudes which, at the resonance energy, to first order don’t affect the extraction of the CMR. Its model uncertainty is thus estimated of the order of
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