Exp.-Nr.: A1/ –98
Eingang:
an PAC:

Mainz Microtron MAMI

Collaboration A1: Virtual Photons

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Proposal for an Experiment

Amplitudes of π^0 electroproduction at $Q^2 = 0.18(GeV/c)^2$ in the Δ-region

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1 Motivation

A controversially discussed topic in the understanding of nucleon structure is the quadrupole excitation of the $\Delta(1232)$ resonance. The corresponding multipole amplitudes, E2 and C2, respectively E_{1+} and S_{1+} in the pion-nucleon frame, can, in principle, be accessed in pion photo- and electroproduction.

The Δ-resonance completely dominates this process in the magnetic dipole amplitude, M1 (the M_{1+} pion multipole), which, in the simple constituent quark picture, corresponds to the spin flip of one of the quarks. For the small quadrupole amplitudes, however, this dominance is much weaker. Therefore, significant non-resonant "background" in the extraction of the electric and Coulomb quadrupole to magnetic dipole ratios, EMR and CMR, cannot be a priori excluded.

Essential progress has been achieved at the photon point ($Q^2 = 0$). A recent MAMI experiment with linearly polarized real photons has, for the first time, achieved an isospin decomposition of the amplitudes [1]:

$$\frac{E2}{M1} = \frac{\Im\{E_{1+}^{3/2}\}}{\Im\{M_{1+}^{3/2}\}} = (-2.5 \pm 0.2_{\mathrm{stat}} \pm 0.2_{\mathrm{syst}})\,\%. \tag{1}$$

The dispersion theoretical analysis, which also included additional polarization observables, confirmed this result on top of the $\Delta(1232)$ resonance [2].

The situation is much less clear in the case of pion electroproduction. First generation coincidence experiments yielded results with considerable systematic uncertainties in the longitudinal response [3, 4, 5, 6, 7, 8, 9, 10]. There is ongoing experimental activity at different laboratories in order to improve this situation [11, 12, 13, 14]. From a recently published measurement at ELSA the surprisingly large CMR value of

$$\frac{\Re\{S_{1+}^{*} \cdot M_{1+}\}}{|M_{1+}|^2} = (-12.7 \pm 1.5)\,\% \tag{2}$$

was extracted, essentially with the approximation of negligible non-resonant background in the $p(e, e'\pi^0)p$ channel [15].

The (unpolarized) pion electroproduction cross section off the nucleon can be written in the form [16]:

$$\frac{d^5\sigma}{dE_{e'}\,d\Omega_{e'}\,d\Omega_\pi^{cm}} = \Gamma \cdot \frac{d\sigma_v}{d\Omega_\pi^{cm}} \tag{3}$$

with the flux of virtual photons, Γ, and the differential virtual photon pion production cross section in the center-of-mass frame

$$\frac{d\sigma_v}{d\Omega_\pi^{cm}} = \frac{|\vec{p}_\pi^{\,cm}|}{k_\gamma^{cm}} \left[R_T + \epsilon_L R_L + \sqrt{2\epsilon_L(1+\epsilon)}\,R_{LT} \cdot \cos\Phi + \epsilon R_{TT} \cdot \cos 2\Phi \right]. \tag{4}$$

Here $\vec{p}_\pi^{\,cm}$ is the pion momentum in the center-of-mass frame. $k_\gamma^{cm} = \frac{W^2 - m_p^2}{2W}$ is the cm energy necessary for a real photon to excite a proton of mass m_p to a hadronic system with cm energy W. Φ is the tilt angle between the electron scattering plane and the reaction plane of outgoing pion and recoil proton. The electron kinematics is contained in the degree of transverse polarization of the virtual photon, $\epsilon = (1 + \frac{2|\vec{q}|^2}{Q^2}\tan^2\frac{\vartheta_e}{2})^{-1}$, and in the degree of longitudinal polarization, $\epsilon_L = \frac{Q^2}{\omega^2}\epsilon$. $Q^2 = |\vec{q}|^2 - \omega^2 > 0$ is the squared four-momentum transfer and ϑ_e is the electron scattering angle.

In the usual s- and p-wave approximation, the multipole decomposition of the R_T and R_{LT} structure functions takes the form

$$R_T = |M_{1+}|^2 \cdot \left(\frac{5}{2} - \frac{3}{2}\cos^2\theta_\pi^{cm}\right) + 3\Re\{E_{1+}^* M_{1+}\} \cdot (1+\cos^2\theta_\pi^{cm}) + 2\Re\{E_{0+}^* M_{1+}\}\cos\theta_\pi^{cm} \tag{5}$$

$$R_{LT} = \sin\theta_\pi^{cm} \cdot \frac{\omega^{cm}}{|\vec{q}^{cm}|} \cdot \Re\{(S_{0+}^* + 6\cos\theta_\pi^{cm} S_{1+}^*)M_{1+}\} \tag{6}$$

when, for the sake of clarity, only terms at least linear in the dominant M_{1+} amplitude are retained.

The determination of the S_{1+} amplitude from a standard L/T separation of the cross section (Eq.4) is practically impossible because the relative contribution of R_L is only a few percent. Therefore all the above mentioned experiments measured the R_{LT} structure function, which contains the interference term $\Re\{S_{1+}^* M_{1+}\}$. The double polarization experiment $p(\vec{e}, e'\vec{p})\pi^0$, which, for the first time, has recently been performed at MAMI [17], is sensitive to the very similar $R_{LT'}^t$ structure function [18]. On top of the Δ-resonance ($W = 1232\,\mathrm{MeV}$), where $\Re\{M_{1+}\}$ almost vanishes, the R_{LT} structure function can be written

$$R_{LT} \sim \Im\{(S_{0+} + 6\cos\theta_\pi^{cm} S_{1+})\} \cdot \Im\{M_{1+}\}. \tag{7}$$

If, contrary to the assumption in [15], $\Im\{S_{0+}\}$ contributes substantially, then the R_{LT} structure function will be affected differently for the two kinematical situations where the pion is emitted in forward ($\cos\theta_\pi^{cm} > 0$) and backward ($\cos\theta_\pi^{cm} < 0$) direction. Therefore the extracted CMR will be affected differently, too. This is visualized in Fig. 1. Here the situation is compared for the ELSA result [15] (green band, $\bar{\theta}_{pi}^{cm} = 17.5°$) with that for the $p(\vec{e}, e'\vec{p})\pi^0$ measurement at MAMI (red band, $\theta_\pi^{cm} = 180°$) [17]. The points indicate the CMR resulting for $\Im\{S_{0+}\} = 0$. The still preliminary MAMI result is compatible with other new preliminary results from ELSA [12, 13] and MIT-Bates [11], but seems to contradict the large value of Kalleicher et al. [15]. A finite $\Im\{S_{0+}\}$, however, can change this situation and it is possible to find a region of $\Im\{S_{0+}\}$ versus $\Im\{S_{1+}\}$ where the measurement with the π^0 in forward direction [15] also becomes compatible with the other measurements, which detected the proton in forward direction. The sign of the resulting $\Im\{S_{0+}\}$, however, which in principle is related by the π-N scattering phases to the known dipole moment of the p-π^0 system at threshold ($\Re\{E_{0+}\}$), comes out unexpected [19, 20].

2 Method

The preceeding discussion of the influence of $\Im\{S_{0+}\}$ directly shows how this contribution can be measured: through the forward-backward asymmetry in the R_{LT} structure function. This requires a separation of R_{LT} from the cross section (Eq.4) in both kinematical situations. Due to its implicit dependence on $\sin\theta_\pi^{cm}$, R_{LT} can only be accessed away from strictly parallel or antiparallel kinematics. There, it can be extracted from the difference of cross sections left ($\cos\Phi = 0$) and right ($\cos\Phi = \pi$) of the direction of momentum transfer, $\vec{q}$. Dividing this difference by the sum of the two cross sections yields the ratio

$$\rho(\theta_\pi^{cm}) = \frac{R_{LT}}{R_T + \epsilon_L R_L + \epsilon R_{TT}} \simeq \frac{\sin\theta_\pi^{cm} \cdot \Re\{(S_{0+}^* + 6\cos\theta_\pi^{cm} S_{1+}^*)M_{1+}\}}{(\frac{5}{2} - \frac{3}{2}\cos^2\theta_\pi^{cm})|M_{1+}|^2} \tag{8}$$

no.	θ_π^{cm} (deg)	θ_{pq}^{lab} (deg)	p_p^{lab} (MeV/c)	Φ (deg)	θ_p^{lab} (deg)
I	160	6.3	722	0	33.4
Ia				180	20.9
II	20	18.4	249	0	45.5
IIa				180	8.8
III	180	0	733	–	27.2
IIIa	0	0	221	–	27.2

Table 1: Kinematics of the proton arm of the $p(e,e'p)\pi^0$ experiment. The protons will be detected in spectrometer B.

From the difference between ρ^f (forward direction) and ρ^b (backward direction) it is possible to extract the desired ratios of multipoles:

$$\frac{\Re\{S_{1+}^* M_{1+}\}}{|M_{1+}|^2} = \alpha \cdot [\rho^f - \rho^b] + n.l.o. \tag{9}$$

$$\frac{\Re\{S_{0+}^* M_{1+}\}}{|M_{1+}|^2} = \beta \cdot [\rho^f + \rho^b] + n.l.o., \tag{10}$$

with kinematical factors α and β. As estimated by the MAID program [20] the next-to-leading order corrections, $n.l.o.$, are of the order of 20 % relative.

The forward-backward asymmetry in strictly parallel and anti-parallel kinematics yields in a very similar way $\Re\{E_{0+}^* M_{1+}\} + n.l.o.$, because R_T in forward (f) and backward (b) direction can be written as

$${R_T}^{f,b} = |M_{1+}|^2 + 6\Re\{E_{1+}^* M_{1+}\} \pm 2\Re\{E_{0+}^* M_{1+}\} \tag{11}$$

2.1 Kinematics

The recoil proton momenta are very different for the forward and backward kinematical situations. Therefore kinematics have been chosen such that
(i) the minimum proton momenta can be safely detected,
(ii) the maximum proton momenta still fit into the spectrometer's momentum range and
(iii) the requested proton angular range can be covered by the spectrometers.
Proton kinematics are summarized in Table 1. Electron kinematics is the same for all setups:

incoming energy	E_e	=	855 MeV
energy transfer	ω	=	436 MeV
scattering angle	ϑ_e	=	41.5°
angle of $\vec{q}$	ϑ_q	=	27.2°
4-momentum squared	Q^2	=	0.18 (GeV/c)^2
cm energy	W	=	1232 MeV

The electrons will be detecded in spectrometer A, protons in spectrometer B. Both the full momentum range of spectrometer B and its capability to reach very small scattering angles are required.

kinematics	times (hours)
I	96
II	60
III	36
empty target	30
elastic	40
overhead	18
TOTAL	**280**

Table 2: Summary of the requested beamtime

3 Beamtime

The required beamtimes are estimated with the interactive program MAID [20], assuming

(i) 2 cm diameter LH_2 target cell, yielding $n_p = 0.84 \cdot 10^{23}\,\mathrm{cm}^{-2}$

(ii) $\Delta\Omega_e = 21$ msr solid angle of spectrometer A

(iii) $\Delta E_e = 83$ MeV, corresponding to 20 % momentum acceptance of spectrometer A

(iv) $\Delta\Omega_p = 5.6$ msr solid angle of spectrometer B

The accepted ω range will be subdivided into three energy bins. This allows, in addition to the central value, a determination of the amplitudes 30 MeV below and above the resonance.

In backward kinematics (nos. I and Ia of Table 1) the covered proton angular range corresponds to a large variation in θ_π^{cm}. Therefore the angular acceptance must be subdivided into 10 bins of θ_π^{cm}. The situation is different for forward kinematics (II and IIa), where one θ_π^{cm} bin will be sufficient.

The maximum electron current will be limited by the single rates of protons and π^+'s in spectrometer B. According to an estimate with the codes of O'Connell and Lightbody [21] an incident electron current of $I = 50\,\mu A$ will keep singles in spectrometer B well below 50 kHz [1] and the ratio of random to true coincidences below 1 %. With this current, the beamtimes required for 10 % relative accuracy per bin in $\Im\{S_{0+}\}/\Im\{M_{1+}\}$ and $\Im\{E_{0+}\}/\Im\{M_{1+}\}$ have been estimated as summarized in Table 2. In order to achieve a corresponding level of systematic error, frequent checks with the elastic $p(e,e'p)$ measurements at small currents are considered to be necessary; the required times are also listed in Table 2.

In summary, with a total of 280 hours of beamtime it will be possible to determine the leading non-resonant background contributions to the R_{LT} structure function with a statistical precision of 10 % relative. This leads to a substantial reduction of the model dependence in the extraction of the CMR.

[1] This is the maximum proton count rate as limited by the current drawn by the vertical driftchambers

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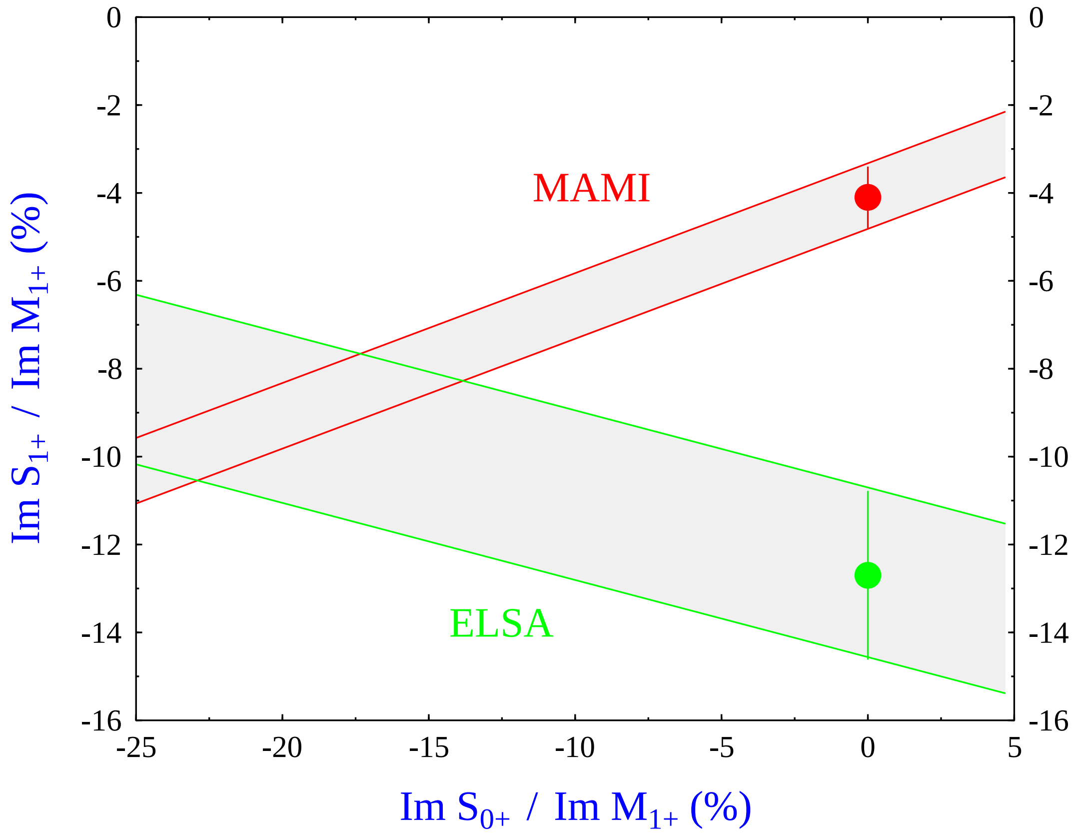

Figure 1: $\Im\{S_{1+}\}/\Im\{M_{1+}\}$ as extracted as a function of $\Im\{S_{0+}\}/\Im\{M_{1+}\}$ from measurements of R_{LT}-like structure functions with the pion in forward direction [15] (green band) and backward direction [17] (red band). The data points with errors correspond to the respectively results at $\Im\{S_{0+}\} = 0$.