Measurement of the $R_{LT}$ response function for $\pi^0$ electroproduction at $Q^2 = 0.070$ (GeV/c)$^2$ in the $N \rightarrow \Delta$ transition

(March 30, 2022)

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Abstract

Quadrupole amplitudes in the $\gamma^*N \rightarrow \Delta$ transition are associated with the issue of nucleon deformation. A search for these small amplitudes has been the focus of a series of measurements undertaken at Bates/MIT by the OOPS collaboration. We report on results from $H(e,e'p)\pi^0$ data obtained at $Q^2 = 0.070 \text{ (GeV/c)}^2$ and invariant mass of $W=1155 \text{ MeV}$ using the out-of-plane detection technique with the OOPS spectrometers. The $\sigma_{LT}$ and $\sigma_T+\epsilon \cdot \sigma_L$ response functions were isolated. These results, along with those of previous measurements at $W=1172 \text{ MeV}$ and $Q^2 = 0.127 \text{ (GeV/c)}^2$, aim in elucidating the interplay between resonant and non resonant amplitudes.

1 Introduction

The signature of the conjectured deformation of the nucleon [1] is mostly sought through the isolation of resonant quadrupole amplitudes in the $\gamma^*N \rightarrow \Delta$ transition. Such quadrupole contributions provide a sensitive probe of the internal nucleon structure and the underlying quark dynamics. Quadrupole amplitudes and the origin of deformation is attributed to different effects depending on the theoretical approach adopted. In a constituent-quark picture of the nucleon, a quadrupole resonant amplitude would point to a d-state admixture in the 3-quark wave function of the nucleon. Such a d-state component is expected as a consequence of a spin-spin tensor or color-hyperfine interaction among quarks. In dynamical models of the $\pi N$ system, the effect of the pionic cloud will also allow the appearance of quadrupole amplitudes.

A number of experimental programs [2, 3, 4, 5, 6, 7, 8] have been active in photo- and electro-pion production in the $\Delta$ region at all the intermediate energy electromagnetic facilities. Results emerging from these programs strongly support the notion of a deformed nucleon although the magnitude and the origin of this effect is still under exploration. The principal difficulty derives from the ”contamination” of the quadrupole amplitudes from coherent processes, such as Born terms or tails of higher resonances. The isolation of the contributions of the non resonant terms has emerged as a key task in the experimental program exploring the issue of nucleon deformation. Recent reviews on this issue can be found in [9, 10, 11].

We present here the results pertaining to the measurement of the $\sigma_{LT}$ and $\sigma_o = \sigma_T+\epsilon \cdot \sigma_L$ response functions in an $H(e,e'p)\pi^0$ reaction at $Q^2 = 0.070$
(GeV/c)$^2$ and at $W=1155$ MeV, on the rising shoulder of the $\Delta$ resonance. The motivation for the experiment was twofold: a) to understand the interplay between resonant and non resonant amplitudes which is best explored by following the $W$ dependence of the various responses and b) to commence a series of measurements at a lower $Q^2$ than $Q^2 = 0.127$ (GeV/c)$^2$, a point where the database is by now quite rich as a result of measurements at Bates, Mainz and Bonn [7, 12, 13, 14]. The reason of focusing on low momentum transfer region is driven by the need to understand the pion cloud effects which are expected to dominate the E2 and C2 transition matrix elements in the low $Q^2$ (large distance) scale.

Spin-parity selection rules in the $N(J^p = 1/2^+) \rightarrow \Delta(J^p = 3/2^+)$ transition, allow only magnetic dipole ($M1$) and electric quadrupole ($E2$) or Coulomb quadrupole ($C2$) multipoles to contribute. The resonant photon absorption multipoles $M1, E2,$ and $C2$ correspond to the pion production multipoles $M_{1+}^{3/2}, E_{1+}^{3/2},$ and $S_{1+}^{3/2},$ respectively, following the notation $M_{I,\pm}^l, E_{I,\pm}^l,$ and $S_{I,\pm}^l,$ where $I$ and $J = l \pm \frac{1}{2}$ correspond to their isospin and orbital angular momentum respectively. The quadrupole amplitudes are typically referred to in terms of their ratio to the dominant magnetic dipole amplitude $M_{1+}^{3/2}$. The Coulomb quadrupole to Magnetic Dipole Ratio is defined as $CMR = R_{SM} = Re(S_{1+}^{3/2}/M_{1+}^{3/2})$ and the Electric quadrupole to Magnetic Dipole Ratio as $EMR = R_{EM} = Re(E_{1+}^{3/2}/M_{1+}^{3/2})$. In the spherical quark model of the nucleon, the $N \rightarrow \Delta$ excitation is a pure $M1$ transition. Models of the nucleon which are in reasonable agreement with the known experimental facts [15, 16, 17, 18] predict values of $R_{SM}$ in the range of -1% to -7%, at momentum transfer square $Q^2 \approx 0.1$ (GeV/c)$^2$.

The fact that the amplitudes of interest contribute only to a very small fraction of the reaction cross section leads to the conclusion that the most sensitive responses, the ones that carry the signal of our interest, will be interference responses in which the weak quadrupole amplitudes will manifest themselves through interference with the dominant dipole amplitude. The interference of the $C2$ amplitude with the $M1$ will obviously lead to Longitudinal - Transverse (LT) type responses. The determination of the $\sigma_{LT}$ response was the primary target of this experiment.
2 Experimental method

The cross section of the $H(e, e'p)\pi^0$ reaction is sensitive to four independent response functions:

$$\frac{d^5\sigma}{d\omega d\Omega_e d\Omega_{pq}^{cm}} = \Gamma(\sigma_T + \epsilon \cdot \sigma_L - v_{LT} \cdot \sigma_{LT} \cdot \cos \phi_{pq}$$

$$+ \epsilon \cdot \sigma_{TT} \cdot \cos 2\phi_{pq})$$

where the kinematic factor

$$v_{LT} = \sqrt{2\epsilon(1 + \epsilon)}$$

and $\epsilon$ is the transverse polarization of the virtual photon, $\Gamma$ the virtual photon flux and $\phi_{pq}$ is the proton azimuthal angle with respect to the momentum transfer direction.

In the experiment reported here we have measured the $\sigma_{LT}$ response function, which contains the interference term $Re(S_1^* M_{1+})$ in leading order [19], and the $\sigma_T + \epsilon \cdot \sigma_L$ which is dominated by the $\sigma_T$ response and the $M_{1+}$ multipole. The measurement was performed using the technique of the out-of-plane detection with the OOPS spectrometers. By placing the two identical OOPS modules [20, 21] symmetrically at azimuthal angles $\phi_{pq} = 45^\circ$ and $135^\circ$ with respect to the momentum transfer direction - in the so called ”half-× configuration” - we have the advantage of eliminating out in leading order the $\sigma_{TT}$ response term from the cross section because of its $\cos 2\phi_{pq}$ dependence. Thus, combining the measurements from the two OOPS spectrometers we are able to separate the $\sigma_{LT}$ and $\sigma_T + \epsilon \cdot \sigma_L$ responses (eq. 2 and 3). The $A_{LT}$ asymmetry is also measured (eq. 4) which is proportional to the $\sigma_{LT}$ response and inversely proportional to $\sigma_T + \epsilon \cdot \sigma_L$

$$\sigma_{LT} = \frac{1}{\sqrt{2} v_{LT}} \left[ \frac{d^2\sigma}{d\Omega_p^{cm}(\phi_{pq} = \pi/4)} - \frac{d^2\sigma}{d\Omega_p^{cm}(\phi_{pq} = 3\pi/4)} \right]$$

$$\sigma_T + \epsilon \cdot \sigma_L = \frac{1}{2} \left[ \frac{d^2\sigma}{d\Omega_p^{cm}(\phi_{pq} = \pi/4)} + \frac{d^2\sigma}{d\Omega_p^{cm}(\phi_{pq} = 3\pi/4)} \right]$$

4
\[ A_{LT} = \frac{d\sigma(\phi_{pq} = \pi/4) - d\sigma(\phi_{pq} = 3\pi/4)}{d\sigma(\phi_{pq} = \pi/4) + d\sigma(\phi_{pq} = 3\pi/4)} \]
\[ = \frac{v_{LT} \cdot \sigma_{LT}}{\sqrt{2}(e \cdot \sigma_L + \sigma_T)} \] (4)

The fact that the measurements were performed simultaneously with two identical proton spectrometers enabled us to minimize the systematic errors. Minimization of the systematic errors is a key issue in this experiment since the quadrupole amplitude of interest contributes only as a very small part of the reaction cross section.

3 Experiment and results

The experiment was performed in the South Hall of M.I.T.-Bates Laboratory. A 0.85% duty factor, 820 MeV unpolarized pulsed electron beam was employed on a cryogenic liquid-hydrogen target. The beam average current was 5 \( \mu \)A. Protons were detected with two OOPS spectrometers [20, 21, 22]. They were symmetrically positioned at \( \phi_{pq} = 45^\circ \) and \( 135^\circ \) with respect to the momentum transfer direction for a fixed \( \theta_{pq}^* = 55^\circ \) and were set at a central momentum of 428 MeV/c. The uncertainty in the determination of the central momentum was 0.1% for the proton arm and 0.15% for the electron arm. Electrons were detected with the OHIPS spectrometer [23] which was located at an angle of 22.9\(^\circ\) and was set at a central momentum of 541 MeV/c. The uncertainty in the determination of the beam energy was 0.1%. The spectrometers were aligned with a precision better than 1 mm and 1 mrad, while the uncertainty in the determination of the total beam charge was 0.1%. The central invariant mass and the squared four-momentum transfer were \( W = 1155 \) MeV and \( Q^2 = 0.070 \) GeV\(^2\)/c\(^2\) respectively. A third OOPS was set to detect elastically scattered electrons and was used as a luminosity monitor throughout the experiment. It was placed in-plane at an angle of 75.8\(^\circ\) and was set at a central momentum value of 494 MeV/c.

The OHIPS spectrometer employed two Vertical Drift Chambers for the track reconstruction. Two layers of 14 Pb-Glass detectors and a Cherenkov detector were responsible for identification of electrons from the \( \pi^- \) background. The timing information for OHIPS derived from 3 scintillator detectors. The OOPS spectrometers used three Horizontal Drift Chambers for
the track reconstruction followed by three scintillator detectors for timing and for the separation of the protons from the strong $\pi^+$ background coming from the $\gamma^*p \rightarrow \pi^+ n$ processes on hydrogen in the target.

The data taking period was preceded by a commissioning period. Elastic scattering data for calibration purposes were taken using liquid-hydrogen and carbon targets and a 600 MeV beam. Measurements were conducted with and without sieve slits in all spectrometers. The sieve slit runs were used to determine the optical matrix elements for all spectrometers [24], while the runs without sieve slits were used for the elastic cross sections and normalization studies.

The "on line" coincidence time-of-flight peak had a FWHM of 6 ns. After the time-of-flight corrections were applied to account for differences in the particle path length, particle velocities, different light-times in the scintillators and time walk effects in the scintillators, the FWHM was reduced to 2 ns. The missing mass spectrum with the peak corresponding to the reconstruction of the $\pi^0$ mass was characterized by a width of 8 MeV (FWHM) and was successfully simulated by the Monte Carlo simulation. A cut of a 5.5 ns time window on the corrected time-of-flight and of $\pm$10 MeV around the missing mass peak was used to select good events throughout the analysis.

The Monte Carlo program AEEXB [25] was used to model the experimental setup. A detailed simulation of the spectrometers involved was necessary in order to determine the coincidence phase space volume. The precise knowledge of this volume was essential for the determination of absolute cross sections.

The conventional set of three independent kinematic variables that is used to describe the cross section is the center-of-mass opening angle, the four momentum transfer squared and the invariant mass $\{\theta^*_pq, Q^2, W\}$. Extraction of $A_{LT}$ and $\sigma_{LT}$ requires that the phase space of the detected protons is identical in the two OOPS spectrometers. However, due to the extended acceptances and the different convolution with the electron acceptance, the accessible range in these three variables differ for the two proton arms. For this reason, the cross sections were measured individually for the two spectrometers with their respective coincident phase space volumes $\{\theta^*_pq, Q^2, W\}$ matched. To facilitate comparison with theoretical predictions, we corrected our measured cross sections for finite acceptance effects using theoretical models by comparing the model cross section for point kinematics to the same model averaged over the full acceptance.
The cross sections for the forward (with respect to the beam) OOPS \((\phi_{pq} = \frac{\pi}{4})\) and the backward OOPS \((\phi_{pq} = \frac{3\pi}{4})\), along with the \(A_{LT}\) space asymmetry and the responses \(\sigma_{LT}\) and \(\sigma_{T}+\epsilon \cdot \sigma_{L}\) are summarized in Table 1. The results are compared with the recent theoretical models MAID 2000 [16, 17] and the Dynamical Models of DMT (Dubna - Mainz - Taipei) [18] and Sato-Lee [15]. Results from these models have been widely used in comparisons with recent experimental results. We will therefore forego a summary of their physical content which is presented in the original papers and other recent experimental investigations.

| \(W\)       | 1155       | MeV |
|-------------|------------|-----|
| \(Q^2\)     | 0.070      | (GeV/c)^2 |
| \(\theta^*_{pq}\) | 55°      |     |
| \(\frac{d\sigma}{d\Omega}(\phi_{pq} = \frac{\pi}{4})\) | 9.72±0.46 | \(\mu\text{b/sr}\) |
| \(\frac{d\sigma}{d\Omega}(\phi_{pq} = \frac{3\pi}{4})\) | 11.05±0.49 | \(\mu\text{b/sr}\) |
| \(A_{LT}\)  | -6.4±2.4   | \%  |
| \(\sigma_{LT}\) | 0.53±0.19 | \(\mu\text{b/sr}\) |
| \(\sigma_o = \sigma_{T}+\epsilon \cdot \sigma_{L}\) | 10.39±0.31 | \(\mu\text{b/sr}\) |

Table 1: Table of results.

In Figures 1 and 2 we present the experimental results for \(\sigma_{LT}\) and \(\sigma_{T}+\epsilon \cdot \sigma_{L}\) along with the above mentioned model calculations [15, 16, 18]. The MAID 2000 model offers consistently the best description of the data obtained so far [12, 24, 26] with a slight tendency to somewhat underpredict the strength of the measured responses. Surprisingly, the DMT calculation which had considerable success in describing data on resonance (at higher \(Q^2\) values), is incompatible with the experimental results presented here. The Sato-Lee model calculation, which as the DMT offers an economic phenomenological description anchored in a consistent microscopic framework, similarly underpredicts the \(\sigma_{LT}\) response with results straggling the difference between the MAID and DMT models. The inadequacy of the dynamical models but also their differences suggest that they may be capable of describing the data in a more satisfactory fashion with a re-adjustment of their phenomenological input. It is evident from both figures that data of similar or higher precision at several \(\theta^*_{pq}\) and \(W\)'s are needed to further enhance our understanding of the deficiencies of these models.
Our earlier measurements [12, 24] below the $\Delta$ resonance - at $W=1170$ MeV, $Q^2=0.127$ (GeV/c)$^2$ and at $\theta_{pq}^*=61^\circ$ - exhibit a similar trend when compared with the predictions from these models. MAID 2000, which provides an excellent account of the measured responses on resonance [12, 13, 24], offers a good description of the measured responses below resonance [12, 13, 24] with a tendency to slightly underpredict them. This may be due to multipoles that are not well determined in the model and which play a relatively more important role away from the peak of the resonance. The dynamical models, DMT and Sato-Lee, clearly exhibit deficiencies off resonance. These deficiencies taken together with the behaviour of the models on top of the resonance [12, 13, 24] indicate that the dynamic of models need further refinement in order to account for the delicate interplay between non resonant and resonant amplitudes, which is manifested most sensitively at the wings of the resonance. A better understanding of the interfering amplitudes and their isolation can be facilitated through an extensive and detailed mapping of the responses primarily in terms of $W$ and $\theta_{pq}^*$, as it is evident from figures 1 and 2, but also in terms of $Q^2$.

Recent measurements [27] at $Q^2=0.127$ (GeV/c)$^2$, on and above resonance utilizing the OOPS spectrometers are currently being analyzed and are expected to provide a more complete picture of the behaviour of the responses of the $\pi^0$ electroproduction in the $N \rightarrow \Delta$ transition; They are expected to elucidate further issues related to hadron deformation.

We are indebted and would like to thank Dr S.S. Kamalov, T.-S.H. Lee, L. Tiator and T. Sato for providing us with valuable suggestions on the overall program and these results in particular.

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Figure 1: The $\sigma_{LT}$ response function measured at this experiment is plotted as a function of $\theta_{pq}^*$ (top) and as a function of the invariant mass $W$ (bottom) along with the predictions of the MAID, DMT and Sato-Lee model calculations.
Figure 2: The $\sigma_o = \sigma_T + \epsilon \sigma_L$ responses sum measured at this experiment is plotted as a function of $\theta_{pq}^*$ along with the model calculations.