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

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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 $\mathrm{H}(e,e'p)\pi^0$ data obtained at $Q^2=0.070$ $(\mathrm{GeV}/c)^2$ and invariant mass of $W=1155$ MeV using the out-of-plane detection technique with the OOPS spectrometers. The σ_{LT} and $\sigma_T+\epsilon\sigma_L$ response functions were isolated. These results, along with those of previous measurements at $W=1172$ MeV and $Q^2=0.127$ $(\mathrm{GeV/c})^2$, aim in elucidating the interplay between resonant and nonresonant amplitudes.

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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 three-quark wave function of the nucleon. Such a *d*-state component is expected as a consequence of the color-hyperfine interaction among quarks. In dynamical models of the πN system, the presence of the pionic cloud also gives rise to resonant quadrupole amplitudes.

A number of experimental programs [2–8] have been active in photopion and electropion production in the Δ region at all the itermediate 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 nonresonant 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 Refs. [9–11].

We present here the results pertaining to the measurement of the σ_{LT} and $\sigma_o=\sigma_T+\epsilon\sigma_L$ response functions in an $\mathrm{H}(e,e'p)\pi^0$ reaction at $Q^2=0.070\,(\mathrm{GeV}/c)^2$ and at $W=1155$ MeV, on the rising shoulder of the Δ resonance. The motivation for the experiment was twofold: (a) to understand the interplay between resonant and nonresonant 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 $Q^2=0.127\,(\mathrm{GeV}/c)^2$, a point where the database is by now quite rich as a result of measurements at Bates, Mainz, and Bonn [7,12–14]. 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 [15,18].

Spin-parity selection rules in the $N(J^\pi=1/2^+)\rightarrow\Delta(J^\pi=3/2^+)$ 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 $M_{l\pm}^{I}$, $E_{l\pm}^{I}$, and $S_{l\pm}^{I}$, 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 $CMR=R_{SM}=\mathrm{Re}(S_{1+}^{3/2}/M_{1+}^{3/2})$ and the electric quadrupole to magnetic dipole ratio as $EMR=R_{EM}=\mathrm{Re}(E_{1+}^{3/2}/M_{1+}^{3/2})$. 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 [15–18] 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 weak quadrupole amplitudes manifest themselves through interference with the dominant dipole amplitude. The interference of the $C2$ amplitude with the $M1$ leads to longitudinal-transverse (LT) type responses. The determination of the σ_{LT} response was the primary objective of this experiment.

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

$$\frac{d^5\sigma}{d\omega d\Omega_e d\Omega_{pq}^{cm}} = \Gamma(\sigma_T + \epsilon\sigma_L - v_{LT}\sigma_{LT}\cos\phi_{pq} + \epsilon\sigma_{TT}\cos 2\phi_{pq}), \tag{1}$$

where the kinematic factor $v_{LT} = \sqrt{2\epsilon(1+\epsilon)}$ and ϵ is the transverse polarization of the virtual photon, Γ the virtual photon flux, and ϕ_{pq} is the proton azimuthal angle with respect to the momentum transfer direction.

In the experiment reported here, we have measured the σ_{LT} response function, which contains the interference term $\mathrm{Re}(S_{1+}^* M_{1+})$ in leading order [19], and the $\sigma_T + \epsilon\sigma_L$ which is dominated by the σ_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 $\phi_{pq} = 45°$ and 135° with respect to the momentum transfer direction—in the so-called "half-$\times$ configuration"—we have the advantage of eliminating out in leading order the σ_{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 σ_{LT} and $\sigma_T + \epsilon\sigma_L$ responses. The A_{LT} asymmetry is also measured which is proportional to the σ_{LT} response and inversely proportional to $\sigma_T + \epsilon\sigma_L$:

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

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

$$A_{LT} = \frac{d\sigma(\phi_{pq} = \pi/4) - d\sigma(\phi_{pq} = 3\pi/4)}{d\sigma(\phi_{pq} = \pi/4) + d\sigma(\phi_{pq} = 3\pi/4)}. \tag{4}$$

The measurements were performed simultanously with two identical proton spectrometers enabling 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.

The experiment was performed in the South Hall of MIT-Bates Laboratory. A 0.85% duty factor, (0.820 ± 0.008) GeV unpolarized pulsed electron beam was employed on a cryogenic liquid-hydrogen target. The beam average current was 5 μA. Electrons were detected with the OHIPS spectrometer [23] that was located at an angle of 22.9° and was set at a central momentum of 541 MeV/c. Protons were detected with two OOPS spectrometers [20–22], symmetrically positioned at $\phi_{pq} = 45°$ and 135° with respect to the momentum transfer direction for a fixed $\theta_{pq}^* = 55°$ and 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. 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 used as a luminosity monitor detecting elastically scattered electrons.

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 π^- background. The timing information for OHIPS derived from three 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 π^+ background coming from the $\gamma^* p \to \pi^+ n$ process.

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 with and without sieve slits for all spectrometers allowed the determination of the optical matrix elements for all spectrometers [24] and their absolute efficiency.

The "on line" coincidence time-of-flight peak had a full width at half maximum (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 for the reconstructed π^0 mass was characterized by a width of 8 MeV (FWHM) and was successfully described by the Monte Carlo simulation. A cut of a 5.5 ns time window on the corrected time-of-flight and of ± 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 σ_{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

TABLE I. Derived experimental quantities followed by the assigned statistical and systematic errors, respectively.

W	1155	MeV
Q^2	0.070	$(\mathrm{GeV}/c)^2$
θ^*_{pq}	55°	
$\frac{d\sigma}{d\Omega}\left(\phi_{pq}=\frac{\pi}{4}\right)$	$9.72\pm0.25\pm0.39$	μb/sr
$\frac{d\sigma}{d\Omega}\left(\phi_{pq}=\frac{3\pi}{4}\right)$	$11.05\pm0.21\pm0.44$	μb/sr
A_{LT}	$-6.4\pm1.6\pm1.8$	%
σ_{LT}	$0.53\pm0.13\pm0.14$	μb/sr
$\sigma_o=\sigma_T+\epsilon\sigma_L$	$10.39\pm0.16\pm0.27$	μb/sr

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.

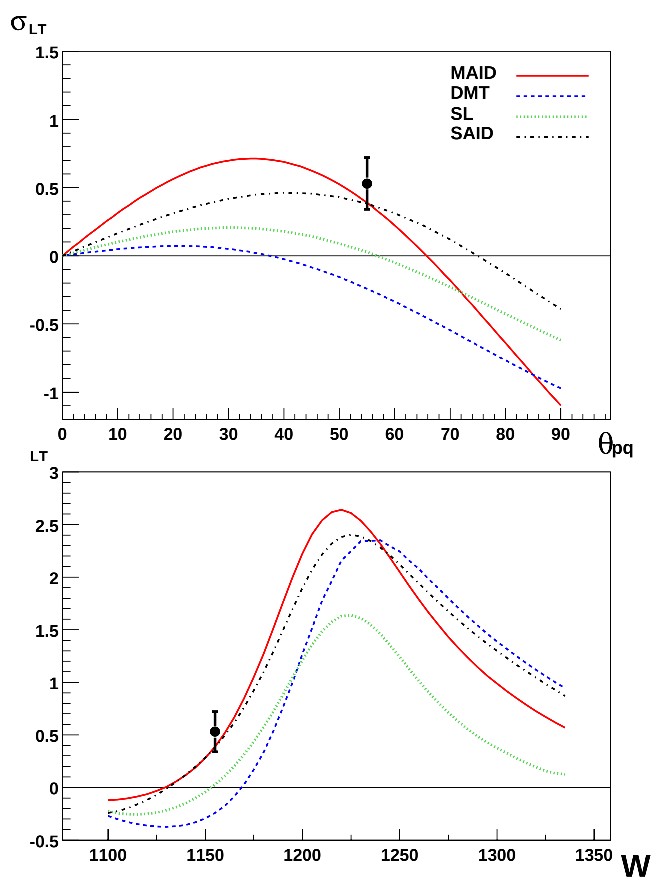

FIG. 1. The σ_{LT} response function measured at this experiment is plotted as a function of θ^*_{pq} (top) and as a function of the invariant mass W (bottom) along with the predictions of the MAID, DMT, Sato-Lee, and SAID model calculations. Units are in μb/sr, MeV, and degrees for σ_{LT}, W, and θ^*_{pq}, respectively.

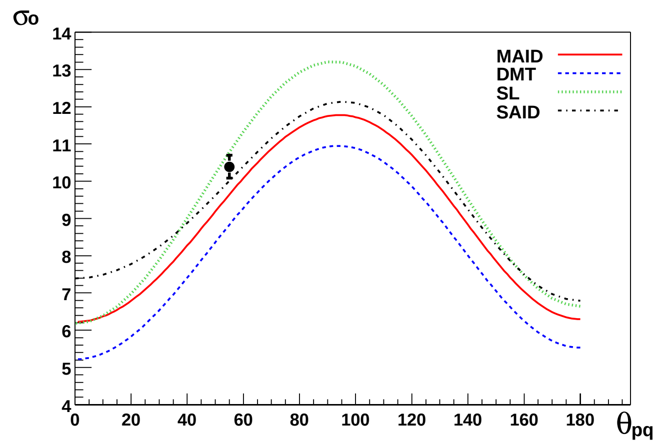

FIG. 2. The $\sigma_o=\sigma_T+\epsilon\sigma_L$ responses sum measured at this experiment is plotted as a function of θ^*_{pq} along with the model calculations. Units are in μb/sr and degrees for σ_o and θ^*_{pq}, respectively.

The cross sections for the *forward* (nearest to the dump) OOPS ($\phi_{pq}=\pi/4$) and the *backward* OOPS ($\phi_{pq}=3\pi/4$), along with the A_{LT} space asymmetry and the responses σ_{LT} and $\sigma_T+\epsilon\sigma_L$ are summarized in Table I. For all experimental quantities both the statistical and systematic errors are presented, which are in general of comparable magnitude. The systematic error is primarily driven by the uncertainty in the beam energy and the angular positioning of the spectrometers. A detailed breakdown of all sources of systematic error is presented in Ref. [27].

In Figs. 1 and 2 we present the experimental results for σ_{LT} and $\sigma_T+\epsilon\sigma_L$; the error shown represents the total experimental uncertainty (statistical plus systematic). The results are compared with the recent phenomenological model MAID 2000 [16,17], the dynamical model of DMT (Dubna-Mainz-Taipei) [18], the model of Sato-Lee [15] and the SAID multipole analysis prediction [28]. Results from these models have been widely used in comparisons with recent experimental results. We will therefore forego a summary of their physical content that is presented in the original papers and other recent experimental investigations.

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. The SAID prediction offers an equally good description to MAID to the data presented here. However, the two models exhibit different behavior away from the measured angle, pointing to the need of an expanded experimental angular coverage at these same kinematics. Surprisingly, the DMT calculation that 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 σ_{LT} response with results straggling the difference between the MAID and DMT models. The inadequacy of the dynamical models [15,18], especially at a Q^2 value where the pion cloud contribution is predicted to be maximum is troubling; their differences suggest that they may be capable of describing the data in a more satisfactory fashion with a readjustment of their phenomenological input.

Our earlier measurements [12,13,24] below the Δ resonance—at $W=1170$ MeV, $Q^2=0.127$ (GeV/c)^2, and at $\theta^*_{pq}=61°$—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. SAID offers a similar description to MAID to these data. The dynamical models, DMT and Sato-Lee, clearly exhibit deficiencies off resonance. These deficiencies taken together with the behavior 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 nonresonant 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 θ^*_{pq}, as it is evident from Figs. 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 behavior of the responses of the π^0 electroproduction in the $N\rightarrow\Delta$ transition; They are expected to elucidate further issues related to hadron deformation.

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