Investigation of the conjectured nucleon deformation at low momentum transfer.

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We report new precise $H(e, e'p)\pi^0$ measurements at the $\Delta(1232)$ resonance at $Q^2 = 0.127$ $(GeV/c)^2$ using the MIT/Bates out-of-plane scattering (OOPS) facility. The data reported here are particularly sensitive to the transverse electric amplitude ($E2$) of the $\gamma^* N \rightarrow \Delta$ transition. Analyzed together with previous data yield precise quadrupole to dipole amplitude ratios $EMR = (-2.3 \pm 0.3_{stat+sys} \pm 0.6_{model})\%$ and $CMR = (-6.1 \pm 0.2_{stat+sys} \pm 0.5_{model})\%$ and for $M_{1+}^{3/2} = (41.4 \pm 0.3_{stat+sys} \pm 0.4_{model})(10^{-3}/m_{\pi^+})$. They give credence to the conjecture of deformation in hadronic systems favoring, at low Q^2, the dominance of mesonic effects.

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The conjectured deviation of hadron shapes from sphericity [1] is the subject of numerous experimental [2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12] and theoretical [13, 14, 15, 16, 17, 18, 19, 20] investigations. The signature of the deformation of the nucleon is most often sought through the isolation of resonant quadrupole amplitudes in the $\gamma^* N \rightarrow \Delta$ transition [21, 22]. The origin of the deformation is attributed to different effects depending on the theoretical approach adopted. In the constituent-quark picture of the nucleon, a quadrupole resonant amplitude would result from a d-state admixture in the 3-quark wave function, a consequence of the color-hyperfine interaction among quarks. In dynamic models of the πN system, the presence of the pion cloud gives rise to quadrupole amplitudes which dominate in the low Q^2 region [13, 16]. At $Q^2 = 0.127$ $(GeV/c)^2$ where the reported measurements have been performed, the pionic contribution is predicted to be maximal.

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 ($C2$) photon absorption multipoles (or the corresponding pion production multipoles $M_{1+}^{3/2}$, $E_{1+}^{3/2}$ and $S_{1+}^{3/2}$, respectively) to contribute. The ratios $CMR = Re(S_{1+}^{3/2}/M_{1+}^{3/2})$ and $EMR = Re(E_{1+}^{3/2}/M_{1+}^{3/2})$ are routinely used to present the relative magnitude of the amplitudes of interest.

The cross section of the $H(e, e'p)\pi^0$ reaction is sensitive to four independent partial cross sections ($\sigma_T, \sigma_L, \sigma_{LT}$ and σ_{TT}) proportional to the corresponding response functions [17] :

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

where the kinematic factor $v_{LT} = \sqrt{2\epsilon(1+\epsilon)}$ and 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.

The $E2$ and $C2$ amplitudes manifest themselves most prominently through interference with the dominant dipole ($M1$) amplitude. The interference of the $C2$ amplitude with the $M1$ leads to Longitudinal - Transverse (LT) response while the interference of the $E2$ amplitude with the $M1$ leads to Transverse - Transverse (TT) responses. The $\sigma_o = \sigma_T + \epsilon\cdot\sigma_L$ partial cross section is dominated by the M_{1+} multipole.

$E2$ and EMR are more difficult to isolate in electropion production than $C2$ and CMR because the transverse responses are dominated by the $|M_{1+}|^2$ term which is of course absent in the longitudinal sector. As a result the precision with which both EMR and CMR have been determined in previous measurements is limited due to the poor determination of EMR and the correlation in the EMR and CMR extraction [23]. In order to address this difficulty and to access $E2$ (EMR) with the

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highest precision we have defined [24] the partial cross section σ_{E2} which was measured for the first time in this experiment. $\sigma_{E2}(\theta^*_{pq})$ is defined as:

$$\sigma_{E2}(\theta^*_{pq}) \equiv \sigma_o(\theta^*_{pq}) + \sigma_{TT}(\theta^*_{pq}) - \sigma_o(\theta^*_{pq} = 0^0)$$

σ_{E2} exhibits far greater sensitivity to the EMR compared to the σ_{TT}; this becomes obvious in a multipole expansion of σ_{E2} up to S and P waves:

$$\sigma_{E2} = 2Re[E^*_{o+}(3E_{1+} + M_{1+} - M_{1-})](1 - cos\theta^*_{pq})$$
$$-12Re[E^*_{1+}(M_{1+} - M_{1-})]sin^2\theta^*_{pq}$$

$$\sigma_{TT} = 3sin^2\theta^*_{pq}[\frac{3}{2}|E_{1+}|^2 - \frac{1}{2}|M_{1+}|^2$$
$$-Re\{E^*_{1+}[M_{1+} - M_{1-}] + M^*_{1+}M_{1-}\}]$$

The $|M_{1+}|^2$ term which dominates the σ_{TT} and suppresses the sensitivity to the $Re(E^*_{1+}M_{1+})$ term at $\theta^*_{pq} = 90^0$ is cancelled out in the σ_{E2} while at the same time the $Re(E^*_{1+}M_{1+})$ term is magnified by a factor 12. This is the reason that lead us to perform our measurements at $\theta^*_{pq} = 90^0$. The very definition of σ_{E2} clearly shows that its experimental determination presents formitable challenges including the issue of containment of the systematic error.

The measurements reported here were performed using the technique of the out-of-plane detection [25] with the Out-Of-Plane Spectrometer (OOPS) [26, 27, 28] system. Three identical OOPS modules [26, 27, 28] were placed symmetrically at azimuthal angles $\phi_{pq} = 60^0$, 90^0 and 180^0 with respect to the momentum transfer direction for the measurement at central kinematics of θ^*_{pq}=90^0 and thus we were able to isolate σ_{TT}, σ_{LT} and $\sigma_o = \sigma_T + \epsilon \cdot \sigma_L$. An OOPS spectrometer module was also positioned along the momentum transfer direction. This measurement provided directly the parallel cross section determination $\sigma_o(\theta^*_{pq} = 0^0)$. Measurements were taken at $W = 1232$ MeV, $Q^2 = 0.127$ GeV$^2/c^2$ and central proton angles of θ^*_{pq}=0^0 and 90^0 while the extensive phase space coverage of the spectrometers allowed the extraction of the responses at θ^*_{pq}=85^0, 90^0 and 95^0. It completes a series of earlier $N \to \Delta$ Bates measurements [8, 9, 12] and is the first one to measure the σ_{TT} and σ_{E2}, the partial cross sections sensitive to the Electric Quadrupole amplitude $E2$.

The experiment was performed in the South Hall of M.I.T.-Bates Laboratory. A high duty factor 950 MeV unpolarized electron beam was employed on a cryogenic liquid-hydrogen target. The beam average current was 7 μA. Electrons were detected with the OHIPS spectrometer [29] and protons were detected with the OOPS spectrometers [26, 27, 28], symmetrically positioned with respect to the momentum transfer direction. The OHIPS spectrometer employed two Vertical Drift Chambers for the track reconstruction. Two layers of 18 Pb-Glass detectors and a Cherenkov detector were responsible for identification of electrons from the π^- 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 π^+ background coming from the $\gamma^* p \to \pi^+ n$ process. 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 and the spread of the beam energy were 0.3% and 0.03% respectively. An OOPS spectrometer was used throughout the experiment as a luminosity monitor detecting elastically scattered protons. A detailed description of all experimental uncertainties and their resulting effects in the measured responses is presented in [30].

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 and their absolute efficiency. The consistency of the new with the previous measurements [8] is confirmed through their excellent agreement in the parallel cross section $\sigma_o(\theta^*_{pq} = 0^0)$.

In Figure 1 we present the experimental results for σ_{TT}, σ_{LT}, $\sigma_T + \epsilon \cdot \sigma_L$ and σ_{E2} along with those of earlier Bates experiments [8, 9]. They are compared with the SAID multipole analysis [19], the phenomenological model MAID 2000 [14, 15], the Aznauryan dispersion analysis [18], the Dynamical Models of Sato-Lee (SL) [13] and of DMT (Dubna - Mainz - Taipei) [16]. Results from these models have been widely used in comparisons with recent experimental results [2, 3, 4, 5, 6, 7]; a description of their physical content is presented in the original papers.

The SAID multipole analysis [19] is capable of successfully describing the new data, as can be seen in Figure 1, but not the corresponding recoil polarization data [7, 11]. The data basis at $Q^2 = 0.127$ GeV^2/c^2 is found to be not rich enough to provide a stable solution. It is hoped that the addition of the $H(e, e'\pi^+)$ data (same Q^2) which are now being analyzed will provide sufficiently rich basis for an independent solution.

The MAID model [14, 15] which offers a flexible phenomenology also provides a successful description of the new data especially when its parameters are re-adjusted. In addition it offers consistently good description of all available measurements [8, 9, 11] at this Q^2; it is the only model that succeeds in this very demanding task.

The fixed t dispersion analysis applied by I. Aznauryan [18] provides an alternative phenomenological approach to describing the data and extracting the multipole information of interest. It is also able to fit the new data remarkably well; the same holds for the case of earlier measurements at the same Q^2 but it still disagrees with

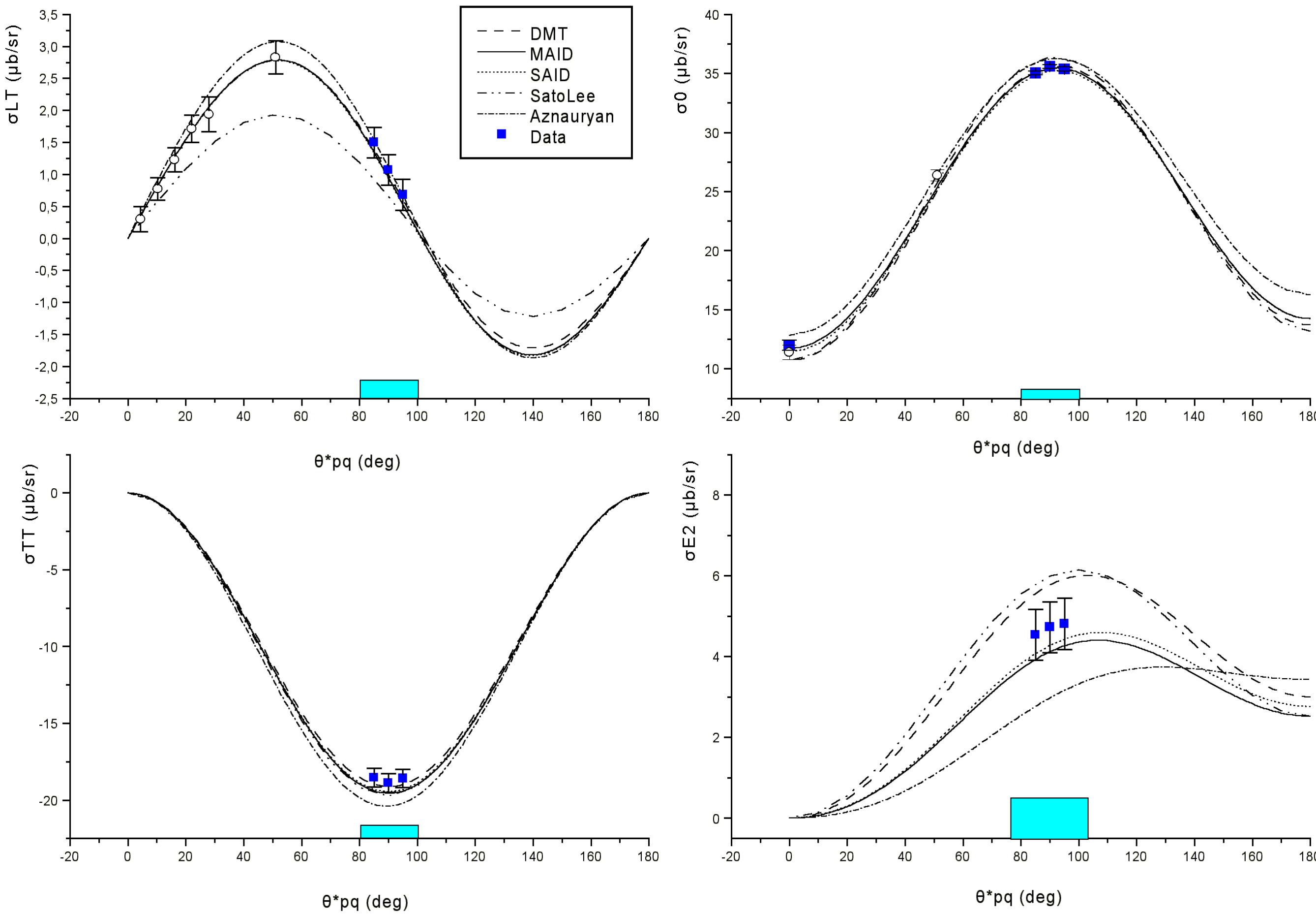

FIG. 1: The measured σ_{LT}, σ_{TT}, $\sigma_o = \sigma_T + \epsilon \cdot \sigma_L$ and σ_{E2} partial cross sections as a function of θ^*_{pq}. Solid square points depict this experiment's results while the open circle points correspond the results from the previous Bates experiments [8, 9]. The shaded bands depict the corresponding systematic uncertainty.

our σ_{LT} measurement at W=1170 MeV [9] .

The SL [13] and DMT [16] dynamical models provide a nucleon description which incorporates physics of the pionic cloud. Both calculate the resonant channels from dynamical equations. DMT uses the background amplitudes of MAID with some small modifications. SL calculate all amplitudes consistently within the same framework with only three free parameters. Both models predict that large fraction of the $E2$ and $C2$ multipole strength arise due to the pionic cloud with the effect reaching a maximum value in the region of Q^2 of our measurements. The SL model disagrees with our σ_{LT} measurements but also with our earlier $\sigma_{LT'}$ and polarization results [9]. DMT offers a good agreement with our data at resonance but it fails to describe σ_o and σ_{LT} below resonance as well as the W dependence of the parallel cross section [9, 12]. The results of both SL and DMT taken together indicate that the dynamical models offer a promising phenomenology for exploring the role of the pionic cloud to the issue of deformation, but they have not yet achieved a satisfactory description of the data in the region where the pionic cloud effect is expected to be maximal.

In Table I the resonant $M_{1+}(3/2)$ and CMR and EMR derived or used by the aforementioned models are listed along with the results from a Truncated Multipole Expansion (TME) fit to our data [30]. In the TME fit, as in [8], it is assumed that only the resonant amplitudes ($M^{3/2}_{1+}$, $E^{3/2}_{1+}$ and $S^{3/2}_{1+}$) contribute. As documented in [8, 32] the results of the TME are compatible with

	$CMR(\%)$	$EMR(\%)$	$M_{1+}^{3/2}(10^{-3}/m_{\pi^+})$
TME	-6.9 ± 0.4	-3.1 ± 0.5	41.6 ± 0.3
SAID	-4.8	-1.4	39.7
MAID	-6.1 ± 0.2	-2.3 ± 0.3	41.4 ± 0.3
Aznauryan	-7.9 ± 0.9	-0.9 ± 0.5	40.8 ± 0.5
Sato Lee	-4.3	-3.2	41.7
DMT	-6.1 ± 0.3	-1.9 ± 0.3	41.5 ± 0.4

TABLE I: Values of CMR and EMR and M_{1+} for the SAID, MAID, Aznauryan, SL and DMT Models at $Q^2 = 0.127$ (GeV/c)^2. The values quoted with uncertainties result from an adjustment of the model parameters to fit our data. The result from the Truncated Multipole Expansion (TME) fit to the data is also presented.

those of MAID if the truncation (model) error due to the omission of higher waves is taken into account. Table I shows that an overall consistency in terms of the expected sign and magnitude has emerged; however, a quantitative agreement has not yet been achieved. The issue of model error not withstanding, such a comparison is not warranted since only one model, MAID, provides an overall agreement with the entire data base of our results at this momentum transfer. For this reason, and in accordance with earlier publications [7, 8] we adopt the values derived from the MAID fit [31] to our data: $M_{1+}^{3/2} = (41.4 \pm 0.3_{stat+sys} \pm 0.4_{model})(10^{-3}/m_{\pi^+})$, $EMR = (-2.3 \pm 0.3_{stat+sys} \pm 0.6_{model})\%$ and $CMR = (-6.1 \pm 0.2_{stat+sys} \pm 0.5_{model})\%$.

The quoted model error is a conservative estimate of the uncertainty arising from the employment of multipoles in MAID not constrained by our measurements[30, 32, 33]. The new results are consistent with our earlier results [8, 9] but significantly more accurate. They are the most accurately known CMR and EMR at any finite Q^2 value.

In conclusion, the new data, and in particular those concerning σ_{TT} and the newly introduced σ_{E2} partial cross sections, taken together with our previous measurements provide a precise determination of both EMR and CMR at Q^2= 0.127 (GeV/c)^2. Both ratios are substantially bigger (by an order of magnitude) than the values predicted by quark models on account of color hyperfine interaction. They are consistent in magnitude with the values predicted by models taking into account the mesonic degrees of freedom. This we interpret as a validation of the crucial role the pion cloud plays in nucleon structure, a consequence of the spontaneous breaking of chiral symmetry [22]. However, at this Q^2 where pionic effects are expected to be manifesting themselves maximally, dynamical models [13, 16] fail to describe the experimental quantities in detail. Finally, we observe that the non zero values of these resonant quadrupole amplitudes determined in this experiment confirm that the nucleon or its first excited state, the delta, or more likely both are deformed.

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