Investigation of the Conjectured Nucleon Deformation at Low Momentum Transfer

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We report new precise $\mathrm{H}(e, e'p)\pi^0$ measurements at the $\Delta(1232)$ resonance at $Q^2 = 0.127$ $(\mathrm{GeV}/c)^2$ obtained at the MIT-Bates out-of-plane scattering facility which are particularly sensitive to the transverse electric amplitude ($E2$) of the $\gamma^* N \rightarrow \Delta$ transition. The new data have been analyzed together with those of earlier measurements to yield precise quadrupole to dipole amplitude ratios: $\mathrm{Re}(E_{1+}^{3/2}/M_{1+}^{3/2}) = (-2.3 \pm 0.3_{\mathrm{stat+syst}} \pm 0.6_{\mathrm{model}})\%$ and $\mathrm{Re}(S_{1+}^{3/2}/M_{1+}^{3/2}) = (-6.1 \pm 0.2_{\mathrm{stat+syst}} \pm 0.5_{\mathrm{model}})\%$ for $M_{1+}^{3/2} = (41.4 \pm 0.3_{\mathrm{stat+syst}} \pm 0.4_{\mathrm{model}})(10^{-3}/m_{\pi^+})$. The derived amplitudes give credence to the conjecture of deformation in hadrons favoring, at low Q^2, the dominance of mesonic effects.

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Hadrons are composite systems with complex quark-gluon dynamics and as such there is no reason to expect that they will be spherical. The conjectured deviation of hadron shapes from sphericity [1,2] has been the subject of numerous experimental [3–13] and theoretical [14–22] investigations. The origin of the deformation is attributed to different effects depending on the theoretical approach adopted. In the constituent-quark picture of hadrons, it arises as a consequence of the noncentral color-hyperfine interaction among quarks [2,14], in direct analogy to the deformation of the deuteron which is generated by the noncentral internucleon forces. In dynamical models of the πN system, deformation also arises from the asymmetric coupling of the pion cloud to the quark core, an effect which is expected to manifest itself maximally at large distances, or equivalently at low momentum transfer (Q^2) [16,19]. At $Q^2 = 0.127$ $(\mathrm{GeV}/c)^2$ where the reported measurements have been performed, the pionic contribution is predicted to be maximal. Definitive measurement of a deformation and identification of the dynamics that give rise to it will have a profound impact on our understanding of hadrons and QCD in the confinement regime.

The spectroscopic quadrupole moment provides the most reliable and interpretable measurement of deformation. For the proton, the only stable hadron, it vanishes identically because of its spin 1/2 nature. Instead, the signature of the deformation of the proton is sought in the presence of resonant quadrupole amplitudes in the $\gamma^* N \rightarrow \Delta$ transition [23,24]. Nonvanishing resonant quadrupole amplitudes will signify that either the proton or the delta and more likely both are deformed; moreover, their Q^2 evolution is expected to provide insights on the mechanism that generates the deformation.

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 $\mathrm{CMR} = \mathrm{Re}(S_{1+}^{3/2}/M_{1+}^{3/2})$ and $\mathrm{EMR} = \mathrm{Re}(E_{1+}^{3/2}/M_{1+}^{3/2})$ are routinely used to present the relative magnitude of the amplitudes of interest.

The cross section of the $\mathrm{H}(e, e'p)\pi^0$ reaction is sensitive to four independent partial cross sections (σ_T, σ_L, σ_{LT}, and σ_{TT}), which are proportional to the corresponding response functions [20]:

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

where the kinematic factor $v_{\mathrm{LT}} = \sqrt{2\epsilon(1+\epsilon)}$ and ϵ is the transverse polarization of the virtual photon, Γ is 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 the transverse-transverse (TT) response. The $\sigma_0 = \sigma_T + \epsilon\sigma_L$ 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 [25]. In order to address this difficulty and to access $E2$ (EMR) with the highest precision we have defined [26] the partial cross section σ_{E2} which was measured for the first time in this experiment. $\sigma_{E2}(\theta^*_{pq})$ is defined as

$$\sigma_{E2}(\theta^*_{pq}) \equiv \sigma_0(\theta^*_{pq}) + \sigma_{\mathrm{TT}}(\theta^*_{pq}) - \sigma_0(\theta^*_{pq} = 0^0).$$

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:

$$\begin{aligned}\sigma_{E2} = {} & 2\mathrm{Re}[E^*_{0+}(3E_{1+} + M_{1+} - M_{1-})](1 - \cos\theta^*_{pq}) \\ & - 12\mathrm{Re}[E^*_{1+}(M_{1+} - M_{1-})]\sin^2\theta^*_{pq},\end{aligned}$$

$$\begin{aligned}\sigma_{\mathrm{TT}} = {} & 3\sin^2\theta^*_{pq}\bigg[\frac{3}{2}|E_{1+}|^2 - \frac{1}{2}|M_{1+}|^2 \\ & - \mathrm{Re}\{E^*_{1+}[M_{1+} - M_{1-}] + M^*_{1+}M_{1-}\}\bigg].\end{aligned}$$

The $|M_{1+}|^2$ term which dominates the σ_{TT} and suppresses the sensitivity to the $\mathrm{Re}(E^*_{1+}M_{1+})$ term at $\theta^*_{pq} = 90°$ is canceled out in σ_{E2} while at the same time the $\mathrm{Re}(E^*_{1+}M_{1+})$ term is magnified by a factor of 12. For this reason the measurements were carried out at $\theta^*_{pq} = 90°$. The very definition of σ_{E2} clearly shows that its experimental determination is complex and difficult, requiring several cross section measurements. As a result, the systematic error with which σ_{E2} is extracted could very easily grow to unacceptable levels unless careful planning and precise instrumentation is used.

The H$(e, e'p)$ measurements were performed using the out-of-plane spectrometer (OOPS) system [27,28] of the

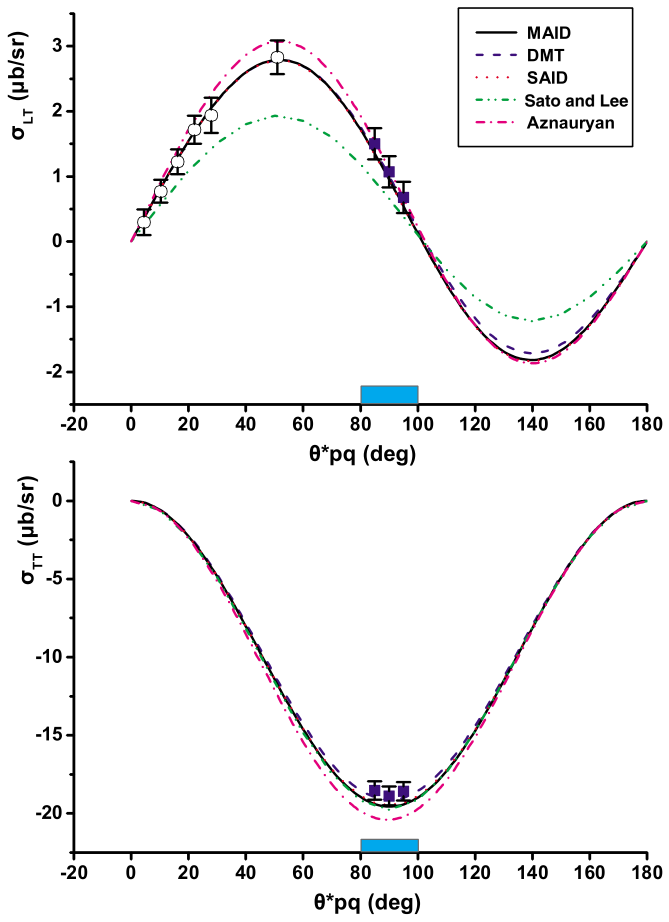

FIG. 1 (color online). The measured σ_{LT}, σ_{TT}, $\sigma_0 = \sigma_T + \epsilon\sigma_L$, and σ_{E2} partial cross sections as a function of θ^*_{pq}. The solid square points depict this experiment's results while the open circle points correspond to the results from the previous Bates experiments [9,10]. The shaded bands depict the corresponding systematic uncertainty.

MIT-Bates Laboratory. Electrons were detected with the OHIPS spectrometer [29] which employed two vertical drift chambers for the track reconstruction and three scintillator detectors for timing information. A Cherenkov detector and two layers of 18 Pb-glass detectors identified the π^- background. Protons were detected with the OOPS spectrometers which were instrumented with three horizontal drift chambers for the track reconstruction followed by three scintillator detectors for timing and for the separation of the strong π^+ background coming from the $\gamma^* p \to \pi^+ n$ process. Three identical OOPS modules were placed symmetrically at azimuthal angles $\phi_{pq} = 60°, 90°$, and 180° with respect to the momentum transfer direction for the measurement at central kinematics of $\theta^*_{pq} = 90°$; thus we were able to isolate $\sigma_{\rm TT}$, $\sigma_{\rm LT}$, and $\sigma_0 = \sigma_T + \epsilon\sigma_L$. An OOPS spectrometer was positioned along the momentum transfer direction thus directly measuring the parallel cross section $\sigma_0(\theta^*_{pq} = 0°)$.

A high duty factor 950 MeV electron beam of 7 μA average current was scattered from a cryogenic liquid-hydrogen target. Measurements were taken at $W = 1232$ MeV and $Q^2 = 0.127$ GeV$^2/c^2$ and central proton angles of $\theta^*_{pq} = 0°$ and 90°; the extensive phase space coverage of the spectrometers allowed the extraction of the responses at $\theta^*_{pq} = 85°$, 90°, and 95°. 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 allowed the determination of the optical matrix elements for all spectrometers and their absolute efficiency. An OOPS spectrometer was used throughout the experiment as a luminosity monitor detecting elastically scattered protons. 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. A detailed description of all experimental uncertainties and their resulting effects in the measured responses is presented in [30].

In Fig. 1 we present the experimental results for $\sigma_{\rm TT}$, $\sigma_{\rm LT}$, $\sigma_T + \epsilon\sigma_L$, and σ_{E2} along with those of earlier Bates experiments [9,10]. The consistency of the new and the previous measurements [9] is confirmed through their excellent agreement in the parallel cross section $\sigma_0(\theta^*_{pq} = 0°)$. They are compared with the SAID multipole analysis [22], the phenomenological model MAID 2000 [17,18], the Aznauryan dispersion analysis [21], the dynamical models of Sato and Lee (SL) [16], and of DMT (Dubna, Mainz, and Taipei) [19]. Results from these models have been widely used in comparisons with recent experimental results [3–8]; a description of their physical content is presented in the original papers.

The SAID multipole analysis [22,31] successfully describes the new data, as can be seen in Fig. 1; however, the same solution fails to describe the corresponding recoil polarization data [8,12]. The database at $Q^2 = 0.127$ GeV$^2/c^2$ is found [31] to be insufficient to provide a stable solution. It is hoped [31] that the addition of the H$(e, e'\pi^+)$ data (same Q^2) which are now being analyzed will provide a sufficiently strong constraint to yield an independent stable solution (fit).

The MAID model [17,18], which offers a flexible phenomenology, also provides a successful description of the new data especially when its parameters are readjusted. In addition it offers a consistently good description of all available measurements [9,10,12] at this Q^2; it is the only model that succeeds in this very demanding task.

The fixed t dispersion analysis of Aznauryan [21] provides an alternative phenomenological approach to describing the data and extracting the multipoles of interest. Aznauryan is able to fit the gross features of the new data adequately; in the case of our earlier published measurements at the same Q^2 the fixed t dispersion analysis accounts for the data rather well with the exception of the $\sigma_{\rm LT}$ at $W = 1170$ MeV [10].

The SL [16] and DMT [19] dynamical models provide a nucleon description which incorporates the 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 find that a large fraction of the $E2$ and $C2$ multipole strength arises 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 $\sigma_{\rm LT}$ measurements but also with our earlier $\sigma_{\rm LT'}$ and polarization results [10]. DMT agree with our data at resonance but fail to describe σ_0 and $\sigma_{\rm LT}$ below resonance as well as the W dependence of the parallel cross section [10,13]. The comparison with SL and DMT indicates that the dynamical models offer a promising phenomenology for exploring the role of the pionic cloud to the conjectured deformation of the nucleon. However, these models have not yet achieved a satisfactory detailed description of the data in the region where the pionic cloud effect is expected to be maximal.

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.

	CMR (%)	EMR (%)	$M^{3/2}_{1+}(10^{-3}/m_{\pi^+})$
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

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 particular version of TME fit, as in [9], it is assumed that only the resonant amplitudes ($M^{3/2}_{1+}$, $E^{3/2}_{1+}$, and $S^{3/2}_{1+}$) contribute. Table I shows that for the resonant amplitudes an overall consistency in terms of 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 database of our results at this momentum transfer. For this reason, and in accordance with earlier publications [8,9], we adopt the values derived from the MAID fit [32] to our data: $M^{3/2}_{1+} = (41.4 \pm 0.3_{\text{stat+syst}} \pm 0.4_{\text{model}})(10^{-3}/m_{\pi^+})$, $\text{EMR} = (-2.3 \pm 0.3_{\text{stat+syst}} \pm 0.6_{\text{model}})\%$, and $\text{CMR} = (-6.1 \pm 0.2_{\text{stat+syst}} \pm 0.5_{\text{model}})\%$. The quoted model error is an estimate of the uncertainty arising from the employment of multipoles in MAID not constrained by our measurements [30]. The results of the TME are compatible with those of MAID if the truncation (model) error due to the omission of the nonresonant amplitudes is taken into account [9,30]. The new results are consistent with our earlier results [9,10], but they are significantly more accurate. They are the most accurately known CMR and EMR at any finite Q^2 value.

Particularly interesting are recent results from lattice QCD [15] which are accurate enough to allow a meaningful comparison to experiment. The chirally extrapolated values of CMR and EMR are found to be nonzero and negative, in qualitative agreement with our experiment thus linking for the first time experimental evidence for deformation directly to QCD.

In summary, 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 $Q^2 = 0.127\ (\text{GeV}/c)^2$. Both ratios are dramatically bigger (by an order of magnitude) than the values predicted by quark models on account of the noncentral color-hyperfine interaction [14]. They are consistent in magnitude, but not in detail, with the values predicted by models [16,19] 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 [24]. Recent lattice calculations [15] of EMR and CMR find them in qualitative agreement with our measurements thus providing a direct link to QCD. We conclude by observing that the nonzero 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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