$\gamma^* N \rightarrow \Delta$ at JLab: Exploring the High Q^2 Regime.

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Abstract. We report a new measurement of the exclusive electroproduction reaction $\gamma^* p \rightarrow \pi^0 p$ to explore the evolution from soft non-perturbative physics to hard processes via the Q^2 dependence of the magnetic (M_{1+}), electric (E_{1+}) and scalar (S_{1+}) multipoles in the $N \rightarrow \Delta$ transition. 9000 differential cross section data points cover W from threshold to 1.4 GeV/c², 4π center-of-mass solid angle, and Q^2 from 3 to 6 GeV²/c², the highest yet achieved. It is found that the magnetic form factor G_M^* decreases with Q^2 more steeply than the proton magnetic form factor, the ratio E_{1+}/M_{1+} is small and negative, indicating strong helicity non-conservation, and the ratio S_{1+}/M_{1+} is negative, while its magnitude increases with Q^2 .

Keywords: pi0; Delta; CLAS; Nucleon Resonances; Effective Lagrangian; Quadrupole Deformations

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INTRODUCTION

The $\Delta(1232)$ resonance is historically one of the most studied objects in nuclear and particle physics. It was first observed in 1950 [1], and interpreted as a spin 3/2 and isospin 3/2 state as early as 1951 [2]. For electromagnetic excitations in which the Δ decays into a pion and nucleon, the transition amplitudes are expressed in terms of multipoles, which for the $N \rightarrow \Delta$ transition are the magnetic M_{1+} , electric E_{1+} , and scalar S_{1+} [3]. Alternatively, the $N \rightarrow \Delta$ transition is expressed in terms of form factors G_M^* , G_E^* and G_C^* [4].

Soon after the discovery of the quark model, the $\Delta(1232)$ was successfully interpreted in the framework of a spherically symmetric quark potential model as a simple quark spin-flip excitation of the nucleon [5]. This implies that the transition amplitude is purely magnetic dipole M_{1+} , while the electric dipole E_{1+} and scalar S_{1+} are equal to zero. However, in order to explain the Δ 's energy splitting relative to the nucleon ground state, it was necessary to invoke a residual hyperfine interaction, which adds a small deformation to the wave function, with a small ($\sim$ few percent) E_{1+} and S_{1+} amplitude [6]. The coupling of the pion cloud to the quark core and two body exchange currents may also contribute to the small values of the E_{1+} and S_{1+} multipoles [7, 8].

The characterization of these amplitudes for photoproduction and electroproduction has been a goal of many previous experiments. As part of the Jefferson Lab (JLab) program to characterize the structure of the baryon resonance spectra, an in-depth study of the pion electroproduction of the Δ resonance as a function of momentum transfer Q^2 has been underway for several years in all three of its experimental halls. It is expected that with increasing Q^2 the reaction mechanism would evolve from a description in terms of the quark model to one where QCD variables are appropriate. At intermediate Q^2 , where soft QCD processes are expected to dominate, a description of the Δ 's magnetic form factor in terms of generalized parton distributions (GPD) has been applied with some success [9, 10]. In the asymptotic limit it is anticipated that hard perturbative processes (pQCD) dominate. As one passes through the range of applicability of the quark model, through processes involving soft QCD to hard pQCD, one should observe a characteristic evolution of the M_{1+} , E_{1+} and S_{1+} amplitudes. In particular, in the high Q^2 limit, in the absence of the role of orbital angular momentum, it is expected that the ratio E_{1+}/M_{1+} would dramatically increase and asymptotically approach unity. In addition the leading M_{1+} amplitude should begin to scale with Q^2 .

This Letter presents the results of a Jefferson Lab (JLab) experiment that extends the measurement of the electromagnetic $N \rightarrow \Delta$ transition to the highest momentum transfer yet achieved, in order to explore the transition region between these low and high Q^2 regimes. The unpolarized differential cross section for exclusive π^0 electroproduction has been obtained in the hadronic mass W from threshold to 1.4 GeV/c², in four-momentum transfer Q^2 from 3 to 6 GeV²/c², and solid angle 4π in the center of mass. The quantities G_M^* , $R_{EM} \equiv Re(E_{1+}/M_{1+})$ and $R_{SM} \equiv Re(S_{1+}/M_{1+})$, have been extracted from the measured cross sections using a unitary isobar model [11].

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THE EXPERIMENT

For the present experiment, an electron beam of energy of 5.75 GeV was incident on a 5.0-cm-long liquid hydrogen target. The CEBAF Large Acceptance Spectrometer CLAS [12] was used to detect the scattered electrons and final state protons. Electrons were selected by a hardware trigger formed from the coincidence of signals from a threshold gas Čerenkov detector and an electromagnetic calorimeter. Multiwire drift chambers were used to reconstruct momenta by measuring particle tracks in the CLAS toroidal magnetic field. Plastic scintillators were used to record particle time of flight from the interaction point to the scintillators. From their known track length, particle velocities were computed and masses calculated using the measured momenta. Software analysis included geometrical and kinematic cuts to eliminate inefficient areas within the spectrometer. Backgrounds coming from π^-/e^- contamination were suppressed using the energy response in the calorimeter and the signal in the Čerenkov detector.

The $p\pi^0$ final state was identified using a cut on the reconstructed missing mass (M_X^2) of the detected electron and proton.

Figure 1 shows the (e, p) missing mass M_X^2 versus W distribution for the data analyzed. The elastic and Bethe Heitler (B.H.) events, illustrated in Figure 2, are clearly seen at $M_X^2 = 0$, with the characteristic increase of the cross section at high W . Also shown are the $S_{11}(1535)$ resonance decaying in η , the $P_{13}(1720)$ resonance decaying in ρ and the $\Delta_{33}(1232)$ resonance decaying in π^0 .

FIGURE 1. Missing mass M_X^2 versus W . Clearly visible are the elastic and B.H. events, the $S_{11} \rightarrow \eta$, the $P_{13} \rightarrow \rho$ and of course the $\Delta_{33} \rightarrow \pi^0$ events.

Figure 2 (left) shows the center-of-mass azimuthal angle of the proton ϕ_p^* versus M_X^2 in the $\Delta(1232)$ mass resonance region. The most prominent feature is the Bethe–Heitler radiative tail (BH) associated with elastic scattering. Since the BH events peak at $M_X^2 = 0$ and lie primarily in the electron scattering plane, they were suppressed by suitable cuts in the $M_X^2 - \phi_p^*$ plane. Figure 2 (right) shows the effects of the cuts on the M_X^2 distribution.

A Monte Carlo simulation based on GEANT3 [13] was used to determine the acceptance of CLAS and to evaluate the efficiency of the BH cuts. Inelastic radiative losses were corrected for using the program EXCLURAD [14], which provides a covariant treatment of both hard and soft photon radiation in exclusive electroproduction and does not rely

FIGURE 2. The Bethe-Heitler rejection. Left: ϕ_p^* vs M_x^2 for $W = 1.25 \text{ GeV}/c^2$. The cuts defined to reject the BH events are shown as solid curves and depend on W . Right: the resulting M_x^2 distribution in the W region considered. The dotted line shows the M_x^2 distribution prior to the cut, the solid line is what remains after the cut, and the dashed line represents the events eliminated by the cut.

on the peaking approximation.

Differential cross sections were obtained at 9000 kinematic points, binned as follows: 15 bins in W , 5 bins in Q^2 , 10 bins in $\cos \theta_{\pi^*}$, and 12 bins in ϕ_{π^*} . Cross sections are quoted at the center of each kinematic bin, and a correction was calculated to take into account non-linear dependencies of the cross section inside each bin. Experimental systematic errors were estimated by varying the kinematic cuts, such as M_x^2 , detector acceptance, particle identification and vertex reconstruction. Estimated uncertainties in the radiative and bin averaging corrections arising from their model dependence are also included. Figure 3 shows an example of the extracted cross sections as a function of ϕ_{π^*} for different $\cos \theta_{\pi^*}$ bins at $W = 1.25 \text{ GeV}/c^2$ and $Q^2 = 4.2 \text{ GeV}^2/c^2$.

THE UNITARY ISOBAR MODEL

The extraction of the Δ amplitudes is model dependent, since in addition to the Δ , the measured differential cross sections consist of non-resonant π^0 production, as well as tails of higher mass resonances. This is even more so at higher Q^2 since the Delta amplitude is decreasing relative to the non-resonant production. In the past, somewhat differing results for resonance amplitudes, especially the small amplitudes, have been obtained for fits to the world data for different specific physics analysis models [15, 16, 17].

In order to avoid specific models in the extraction of the Δ multipoles M_{1+} , E_{1+} and S_{1+} , the truncated multipoles expansion (TME) was commonly used at low Q^2 . In the TME, the structure functions are expanded up to p - or d -waves in Legendre polynomials, whose coefficients are related to the multipoles [18]. The magnetic dipole transition $|M_{1+}|^2$ is then assumed to dominate the π^0 production at the Δ pole, and only the terms interfering with M_{1+} are retained.

This was shown to be a good approximation at very low Q^2 where the Δ resonance is large compared to the underlying background. However, the Δ resonance contribution to the cross section has been shown to diminish smoothly with increasing Q^2 [24]. Thus the accuracy of the TME becomes poorer with increasing Q^2 , and it becomes necessary to utilize a reliable model for more realistically isolating the Δ amplitudes from the underlying backgrounds.

The predominantly used approaches have been based on the effective Lagrangian expansions, which model the reactions in terms of meson and baryon degrees of freedom. MAID [17], which is commonly used to characterize

FIGURE 3. The extracted virtual photon cross section as a function of ϕ_π^* for each $\cos(\theta_\pi^*)$ bin in the center-of-mass system at $W = 1.25 \text{ GeV}/c^2$ and $Q^2 = 4.2 \text{ GeV}^2/c^2$. The fit was carried out utilizing 9000 such data points, represent the fit using UIM [11]. Each Q^2 point was fitted separately. The error bars are statistical, and the gray band at the bottom of each panel corresponds to the estimated combined systematic error experimental cross section and the fit. The solid curves

resonance amplitudes, is an isobar model approach for photo- and electroproduction data. Other elaborations of the effective Lagrangian are the Dynamical [22], and DMT [15] models, which couple the baryon core and the pion cloud. SAID [16] is another approach often used to extract amplitudes from global data.

For the present case, the unitary isobar model (UIM) [11], developed at JLab, was used. This model incorporates the isobar approach as in Ref. [17]. The non-resonant background consists of the Born term and the t -channel ρ and ω contributions. To calculate the Born term the latest available measurements of the nucleon and pion form factors are used. Underlying tails from resonances such as the $P_{11}(1440)$, $D_{13}(1520)$ and $S_{11}(1535)$, which are modeled as Breit-Wigner shapes, are also incorporated. The contributions of these resonances are evaluated according to information known from world data and the latest CLAS measurements. The total amplitude is unitarized using the K-matrix approach. The results of the fit are given in Table 1. In this Table we have also included the systematic errors coming from the variation of all the form factors which determine non-resonant and higher resonances contributions within

FIGURE 4. The form factor $G_M^*/3G_D$. The filled squares are from the current CLAS experiment utilizing the UIM [11]. The errors shown are statistical, while estimated systematic errors are shown as gray bars at the bottom of the graph. Also shown are selected earlier published results. The filled black triangles correspond to a recent analysis of previous CLAS data [19, 20], and the filled blue circles are from an earlier JLab Hall C experiment [21, 15]. The curves are due to the following calculations. Green dashed: dynamical model of Ref [15]. Red dotted: dynamical model of Ref. [22] for the “bare” Δ (without the pion cloud). Black dotted: full dynamical model of Ref. [22]. Black dot-dot-dash: Light cone sum rule model of Ref. [23]. Magenta dot-dash: MAID-2003 [17]. Blue solid: GPD model of Ref [9].

their experimental uncertainties.

RESULTS, DISCUSSIONS

Figure 4 shows the extracted $G_M^*/3G_D$ as a function of Q^2 in the Jones–Scadron convention [4]. We used the $M_{1+} \leftrightarrow G_M^*$ conversion factor

$$G_M^* = \frac{M_N}{\hbar c k_\gamma} \sqrt{\frac{8p_\pi \Gamma_\Delta}{3\alpha}} \left(1 + \frac{Q^2}{(M_\Delta + M_N)^2}\right) M_{1+}(M_\Delta),$$

where k_γ and p_π are the center-of-mass momenta of the virtual photon and pion respectively, $M_\Delta = 1.23 \text{ GeV}/c^2$, the resonance width $\Gamma_\Delta = 120 \text{ MeV}$, and $G_D = (1 + Q^2/0.71)^{-2}$. Also shown are selected earlier published results. The most notable feature is that G_M^* continues to decrease with Q^2 faster than the elastic magnetic form factor. This is consistent with Ref. [30], which pointed out that, through the application of chiral symmetry, G_M^* can be directly related to the isovector part of the nucleon elastic form factors. This idea was applied in the framework of Generalized

TABLE 1. Results for $G_M^*/3G_D$, R_{EM} and R_{SM} . The first of the quoted errors is statistical, and the second represents our calculation of the systematic uncertainties. The quoted form factor G_M^* is defined according to the Jones–Seadron convention of Ref. [4].

Q^2 GeV ² /c ²	$100 \cdot G_M^*/3G_D$	R_{EM} (%)	R_{SM} (%)
3.0	$63.4 \pm 0.2 \pm 0.9$	$-1.61 \pm 0.39 \pm 0.22$	$-11.5 \pm 0.5 \pm 2.01$
3.5	$61.4 \pm 0.4 \pm 1.2$	$-1.07 \pm 0.47 \pm 0.10$	$-13.0 \pm 0.7 \pm 1.13$
4.2	$55.2 \pm 0.5 \pm 1.9$	$-3.15 \pm 0.70 \pm 0.20$	$-16.4 \pm 1.2 \pm 1.38$
5.0	$52.2 \pm 1.0 \pm 2.8$	$-3.23 \pm 1.51 \pm 0.33$	$-24.8 \pm 2.7 \pm 2.8$
6.0	$39.9 \pm 1.5 \pm 4.0$	$-3.84 \pm 2.69 \pm 1.40$	$-24.8 \pm 5.3 \pm 3.0$

Parton Distributions (GPDs) by Ref. [9], and later by Ref. [10], to suggest that the falloff of G_M^* is related to the falloff of G_E^p [31] through their mutual isovector form factor.

A recent calculation uses the light-cone sum-rules (LCSR) [23]. In this approach, the form factor is effectively governed by the overlap of the initial and final QCD wave functions. As shown in Fig. 4, there is modest agreement with experiment for Q^2 greater than a few GeV²/c².

Figure 5 shows the extracted ratios R_{EM} and R_{SM} . R_{EM} is small and negative over the entire Q^2 range, indicating strong helicity non-conservation. R_{SM} is negative and its magnitude increases as a function of Q^2 . Our results suggest that the region of Q^2 where pQCD processes would be expected to be valid is higher than currently accessible. Adding to the controversy, Ref. [29] has suggested that pQCD can possibly be invoked without strict helicity conservation if orbital angular momentum flips are included into the perturbative reaction mechanism. The prediction for R_{SM} of Ref. [29] is shown in Fig. 5 (lower panel).

Progress is being made in describing the $\gamma^* p \rightarrow \Delta$ transition at low Q^2 using the methods of lattice QCD (LQCD), where calculations of the magnetic form factor of this transition are being carried out up to $Q^2 \sim 1.5$ GeV²/c². The results appear encouraging [32], however, at the Q^2 values of the present experiment, the application of LQCD is not yet feasible.

Meanwhile studies continue in the framework of quark models, where it is found that relativistic effects and d-wave mixing give significant effects on the R_{EM} and R_{SM} ratios [33].

Included in Figs. 4 and 5 are the results of calculations using effective Lagrangian based models whose ingredients were tuned to fit earlier data at lower Q^2 . Until a reliable treatment in terms of QCD degrees of freedom becomes fully developed, these models give unique insights into the baryon structures and their manifestations in terms of the traditional hadronic degrees of freedom. A review of some of these models and the physical interpretations may be found in Ref. [34].

As Q^2 increases, the $N \rightarrow \Delta$ amplitudes are decreasing more rapidly with Q^2 than the non-resonant background, as well as some of the more important resonances, whose tails also contribute under the peak of the Δ . The most important contributions from the higher resonances come from the Roper resonance - $P_{11}(1440)$, and the $S_{11}(1535)$. Regarding the $S_{11}(1535)$, it is well known that the cross section remains strong with increasing Q^2 [24, 35], becoming significantly greater than that of the Δ at a few GeV²/c². Of even greater importance is the $P_{11}(1440)$. At lower Q^2 the $P_{11}(1440)$'s contribution to the overall electroproduction cross section is small. However, π^+ electroproduction data taken at CLAS [36] in parallel with the new CLAS π^0 data presented here, shows that the $P_{11}(1440)$'s leading M_{1-} amplitude crosses zero at low Q^2 and then increases with Q^2 compared with other resonances. Given the large $P_{11}(1440)$ width, the results of the fit [20, 17] to the differential cross sections at the Q^2 values of new CLAS π^0 data presented here, is that the $P_{11}(1440)$ contribution at the peak of the Δ is rather comparable to the contribution of the Δ itself. An example, at $Q^2 = 6.3$ GeV²/c², from Aznaurian using the JANR model [20, 11], is Fig. 6. Although the Δ 's leading M_{1+} partial wave can still be extracted from the various background partial waves, the large and relatively less certain known contributions of background tails lead to a significant systematic error.

The model uncertainties affect not only the extraction of multipoles amplitudes but also the experimental calculation of the cross section: the acceptance, radiative and bin averaging corrections depend quite strongly on the theoretical

FIGURE 5. The ratios R_{EM} (upper panel) and R_{SM} (lower panel). The filled red squares are from the UIM [11] fit to the current CLAS experiment. The errors shown are statistical, while estimated systematic errors are shown as gray bars at the bottom of the graph. The filled black triangles at lower Q^2 are the previously reported CLAS results [19]. The filled blue circles are from an earlier JLab Hall C experiment [21, 15]. The open triangles: JLab Hall-A [25]. Additional symbols at lower Q^2 are results of measurements by other laboratories as follows. Open blue squares: Bates [26]. Open trapezoids: Mainz [27]. The open circle: Bonn [28]. The curves are as follows. Black dotted: full dynamical model of Ref. [22]. Green dashed: dynamical model of Ref [15]. Magenta dot-dash: MAID-2003 [17]. Black solid: pQCD with orbital angular momentum effects of Ref [29].

model used to compute them. The contributions of the other resonance and background to the Δ signal can be not only large, but quite unknown as shown in Fig. 7, where the cross section prediction for different models is plotted for $Q^2 = 3.5 \text{ GeV}^2/c^2$ and $W = 1.35 \text{ GeV}/c^2$. One can notice the large variation of both the magnitude and shape of the cross section.

CONCLUSIONS

In summary, complete angular distributions for single π^0 electroproduction from protons are reported for a range of Q^2 from 3 to 6 GeV^2/c^2 and a range of W from π^0 threshold to 1.4 GeV/c^2 . The quantities G_M^* , R_{EM_2} and R_{SM} were extracted utilizing the isobar model [11]. The results indicate that the form factor G_M^* decreases with Q^2 faster than the

FIGURE 6. The non resonant and higher resonances contributions to the Δ signal at $W = 1.23 \text{ GeV}/c^2$ and $Q^2 = 6.3 \text{ GeV}^2/c^2$ according to the UIM model [11]. In Black: the total cross section. In red: the cross section without the P_{11} and S_{11} contributions. In blue: the non resonant contribution.

elastic magnetic form factor. R_{EM} is small and negative, while R_{SM} remains negative and increases in magnitude. These results confirm the absence of pQCD scaling at these kinematics and suggest large helicity non-conservation. They provide strong constraints on isobar-based effective Lagrangian models, or on approaches employing fundamental partonic degrees of freedom such as LQCD, GPDs, LCSR and eventually pQCD. However, greater theoretical progress will be necessary before good quantitative agreement with the experimental high- Q^2 data is obtained.

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CROSS SECTION ϕ^* for different $\cos\theta$ $W=1.350$ $Q^2=3.50$

FIGURE 7. The cross section predictions for different models at $W = 1.35 \text{ GeV}/c^2$, and $Q^2 = 3.5 \text{ GeV}/c^2$. The color codes are as follow: blue: maid2003; red: maid2003 with no Roper resonance. Green: dmt2001. Black: maid2002.

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