\( \gamma^*N \rightarrow \Delta \) transition form factors: a new analysis of the JLab data on \( p(e,e'p)\pi^0 \) at \( Q^2=2.8 \) and \( 4.0 \) (GeV/c)\(^2\)

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Recent JLab data of the differential cross section for the reaction \( p(e,e'p)\pi^0 \) in the invariant mass region of \( 1.1 < W < 1.4 \) GeV at four-momentum transfer squared \( Q^2 = 2.8 \) and \( 4.0 \) (GeV/c)\(^2\) are analyzed with two models, both of which give an excellent description of most of the existing pion electroproduction data below \( W < 1.5 \) GeV. We find that at up to \( Q^2 = 4.0 \) (GeV/c)\(^2\), the extracted helicity amplitudes \( A_{3/2} \) and \( A_{1/2} \) remain comparable with each other, implying that hadronic helicity is not conserved at this range of \( Q^2 \). The ratios \( E_{1+}/M_{1+} \) obtained show, starting from a small and negative value at the real photon point, a clear tendency to cross zero, and to become positive with increasing \( Q^2 \). This is a possible indication of a very slow approach toward the pQCD region. Furthermore, we find that the helicity amplitude \( A_{1/2} \) and \( S_{1/2} \), but not \( A_{3/2} \), starts exhibiting the scaling behavior at about \( Q^2 \geq 2.5 \) (GeV/c)\(^2\).

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In a recent experiment [1], electro-excitation of the \( \Delta \) was studied at \( Q^2 = 2.8 \) and \( 4.0 \) (GeV/c)\(^2\) via the reaction \( p(e,e'p)\pi^0 \). It was motivated by the possibility of determining the range of momentum transfers where perturbative QCD (pQCD) would become applicable. In the limit of \( Q^2 \rightarrow \infty \), pQCD predicts the dominance of helicity-conserving amplitudes [2] and scaling results [3]. The hadronic helicity conservation should have the consequence that the ratio between magnetic dipole \( M_{1+}^{(3/2)} \) and electric quadrupole \( E_{1+}^{(3/2)} \) multipoles, \( R_{EM} = E_{1+}^{(3/2)}/M_{1+}^{(3/2)} \), approaches 1. The scaling behavior predicted by pQCD for the helicity amplitudes is \( A_{1/2}^{\Delta} \sim Q^{-3} \), \( A_{3/2}^{\Delta} \sim Q^{-5} \), and the Coulomb helicity amplitude \( S_{1/2}^{\Delta} \sim Q^{-3} \), resulting in \( R_{SM} = S_{1/2}^{(3/2)}/M_{1+}^{(3/2)} \rightarrow const. \). On the other hand, in symmetric SU(6) quark models, the \( \gamma N\Delta \) transition can proceed only via the flip of a single quark spin in the nucleon, leading to \( M_{1+} \) dominance and \( E_{1+} = S_{1+} = 0 \). Recent experiments give nonvanishing ratios \( R_{EM} \) lying between \(-2.5\%\) [4] and \(-3.0\%\) [5] at \( Q^2 = 0 \). This has been widely taken as an indication of a deformed \( \Delta \), namely, an admixture of a D state in the \( \Delta \). Accordingly, the question of how \( R_{EM} \) would evolve from a very small negative value at \( Q^2 = 0 \) to \( +100\% \) at sufficiently high \( Q^2 \), has attracted great interest both theoretically and experimentally.

In Ref. [6], the differential cross sections were measured in the invariant mass region of \( 1.1 < W < 1.4 \) GeV. Two methods were used to extract the contributing multipoles. The first one, which is model and energy independent, consisted of making approximate multipole fits to angular distributions independently at each \( W \), assuming \( M_{1+} \) dominance, and only \( S \) and \( P \) wave contributions [7]. Another extraction of the resonance amplitudes was performed using the effective Lagrangian method [8]. In this model-dependent analysis, the resonant multipoles are expressed as a sum of background and resonance amplitudes, both prescribed by an effective Lagrangian, and unitarized with the K-matrix method. The parameters in the model were fitted to data points with energy \( W \) only up to \( 1.31 \) GeV. The ratios \( R_{EM} \) and \( R_{SM} \) extracted with these two methods are both small, negative, and tending to more negative values with increasing \( Q^2 \), indicating that pQCD is not yet applicable in this region of \( Q^2 \). Recently, it was shown [9] that the \( Q^2 \)-dependence of the ratios \( R_{EM} \) and \( R_{SM} \) extracted in Ref. [6] can be explained in a dynamical model for electromagnetic production of pions, together with a simple scaling assumption for the bare \( \gamma^* N\Delta \) form factors.

Because of the significance of the physics involved in the \( Q^2 \) evolution of \( R_{EM} \) and \( R_{SM} \), it is important to employ the best possible extraction method in the analysis of the data. In fact, the values of \( R_{EM} \) and \( R_{SM} \) extracted with the two methods used in Ref. [6] differ from each other by factors of 2 and \( 1.5 \) at \( Q^2 = 2.8 \) and \( 4.0 \) (GeV/c)\(^2\), respectively. In this letter, we present the results of a new analysis of the data of Ref. [6], using a new version (hereafter called MAID) [10] of the unitary isobar model developed at Mainz (hereafter called MAID98) [11], and the dynamical model developed recently in Ref. [9], which both give excellent descriptions of most of the existing pion photo- and electroproduction data [12]. Our analysis is similar to the second method
used in \[\text{1}\] in the sense that it also makes use of a model. However, we fit all the data points measured up to \(W = 1.4\) GeV and obtain smaller values of \(\chi^2\) per d.o.f.

In the dynamical approach to pion photo- and electroproduction \([\text{2,3}]\), the t-matrix can be expressed as \(t_{\gamma\pi}(E) = v_{\gamma\pi} + v_{\gamma\pi} g_0(E) t_{\pi N}(E)\) and the physical multipoles in channel \(\alpha\) are given by

\[
t^{(\alpha)}(q\kappa, k) = \exp(i\delta^{(\alpha)}) \cos\delta^{(\alpha)} \times \left[ v_{\gamma\pi}^{(\alpha)}(qE, k) + P \int_0^{\infty} dq' q'^2 R^{(\alpha)}_{\gamma\pi}(qE, q') v_{\gamma\pi}^{(\alpha)}(q', k) \frac{E - E_{\pi N}(q')}{E - E_{\pi N}(q')} \right],
\]

where \(v_{\gamma\pi}\) is the transition potential for \(\gamma^* N \rightarrow \pi N\), and \(t_{\pi N}\) and \(g_0\) denote the \(\pi N\) t-matrix and free propagator, respectively, with \(E \equiv W\) the total energy in the CM frame. \(\delta^{(\alpha)}\) and \(R^{(\alpha)}_{\gamma\pi}\) are the \(\pi N\) scattering phase shift and reaction matrix in channel \(\alpha\), respectively; \(qE\) is the pion on-shell momentum and \(k = |\kappa|\) is the photon momentum.

In a resonant channel like \((3,3)\) in which the \(\Delta(1232)\) plays a dominant role, the transition potential \(v_{\gamma\pi}\) consists of two terms, \(v_{\gamma\pi}(E) = v_{B,\pi}^{(\alpha)} + v_{\gamma\pi}^{(\alpha)}(E)\), where \(v_{B,\pi}^{(\alpha)}\) is the background transition potential and \(v_{\gamma\pi}^{(\alpha)}(E)\) corresponds to the contribution of the bare \(\Delta\). The resulting t-matrix can be decomposed into two terms \(\text{1} t_{\gamma\pi}(E) = t_{B,\pi}^{(\alpha)} + t_{\gamma\pi}^{(\alpha)}(E)\), where \(t_{B,\pi}^{(\alpha)}(E) = v_{B,\pi}^{(\alpha)} + v_{B,\pi}^{(\alpha)} g_0(E) t_{\pi N}(E)\), and \(t_{\gamma\pi}^{(\alpha)}(E) = v_{\gamma\pi}^{(\alpha)}(E) + v_{\gamma\pi}^{(\alpha)} g_0(E) t_{\pi N}(E)\). Here \(t_{B,\pi}^{(\alpha)}\) includes the contributions from the nonresonant background and renormalization of the vertex \(\gamma^* N\Delta\). The advantage of such a decomposition is that all the processes which start with the excitation of the bare \(\Delta\) are summed up in \(t_{\gamma\pi}^{(\alpha)}\). Note that the multipole decomposition of both \(t_{B,\pi}^{(\alpha)}\) and \(t_{\gamma\pi}^{(\alpha)}\) would take the same form as Eq. \((\text{1})\).

For a correct description of the resonance contributions we need, first of all, a reliable description of the nonresonant part of the amplitude. In MAID98, the background contribution was described by Born terms obtained with an energy dependent mixing of pseudovector-pseudoscalar \(\pi N\) coupling and t-channel vector meson exchanges, namely, \(t^{B,\alpha}_{\gamma\pi}\) (MAID98) = \(v_{B,\pi}^{(\alpha)}(W, Q^2)\). The mixing parameters and coupling constants were determined from an analysis of nonresonant multipoles in the appropriate energy regions. In the new version of MAID, the \(S\), \(P\), \(D\) and \(F\) waves of the background contributions are complex numbers defined in accordance with the K-matrix approximation,

\[
t^{B,\alpha}_{\gamma\pi}(\text{MAID}) = \exp(i\delta^{(\alpha)}) \cos\delta^{(\alpha)} v^{B,\alpha}_{\gamma\pi}(W, Q^2). \tag{2}
\]

From Eqs. \((\text{1})\) and \((\text{2})\), one finds that the difference between the background terms of MAID and of the dynamical model is that off-shell rescattering contributions (principal value integral) are not included in MAID. To take account of the inelastic effects at the higher energies, we replace \(\cos\delta^{(\alpha)}\) \(\cos\delta^{(\alpha)} = \frac{1}{2} [\exp(2i\delta^{(\alpha)}) + 1]\)

in Eqs. \((\text{1})\) and \((\text{2})\) by \(\frac{1}{2} \eta_\alpha \exp(2i\delta^{(\alpha)}) + 1\), where \(\eta_\alpha\) is the inelasticity. In our actual calculations, both the \(\pi N\) phase shifts \(\delta^{(\alpha)}\) and inelasticity parameters \(\eta_\alpha\) are taken from the analysis of the GWU group \([\text{4}]\). Furthermore, the off-shell rescattering effects in the dynamical model are evaluated with the reaction matrix \(R^{(\alpha)}_{\gamma\pi}(qE, q')\) as prescribed by a meson exchange model \([\text{4}]\).

Following Ref. \([\text{2}]\), we assume a Breit-Wigner form for the resonance contribution \(A_R^\alpha(W, Q^2)\) to the total multipole amplitude,

\[
A_R^\alpha(W, Q^2) = \frac{f_{R}(W)\Gamma_R M_R f_{R}(W)}{M_R^2 - W^2 - iM_R\Gamma_R} e^{i\phi}, \tag{3}
\]

where \(f_{R}\) is the usual Breit-Wigner factor describing the decay of a resonance \(R\) with total width \(\Gamma_R(W)\) and physical mass \(M_R\). The expressions for \(f_{R}\), \(f_{R}(W)\) and \(\Gamma_R\) are given in Ref. \([\text{2}]\). The phase \(\phi(W)\) in Eq. \((\text{3})\) is introduced to adjust the phase of the total multipole to equal the corresponding \(\pi N\) phase shift \(\delta^{(\alpha)}\). Because \(\phi = 0\) at resonance, \(W = M_R\), this phase does not affect the \(Q^2\) dependence of the \(\gamma NR\) vertex.

We now concentrate on the \(\Delta(1232)\). In this case the magnetic dipole \((A_M^\alpha)\) and the electric quadrupole \((A_E^\alpha)\) form factors are related to the conventional electromagnetic helicity amplitudes \(A_{1/2}^\alpha, A_{3/2}^\alpha\) of the resonance and \(S_{1/2}^\alpha\) by

\[
A_{1/2}^\alpha(Q^2) = -\frac{1}{2} (A_{1/2}^\alpha + \sqrt{3}A_{3/2}^\alpha), \tag{4}
\]

\[
A_{3/2}^\alpha(Q^2) = \frac{1}{2} (A_{1/2}^\alpha + \frac{1}{\sqrt{3}}A_{3/2}^\alpha), \tag{5}
\]

\[
A_{S}^\alpha(Q^2) = -\frac{1}{\sqrt{2}} S_{1/2}^\alpha. \tag{6}
\]

where \(k^2 = Q^2 + [(W^2 - m_{\Delta}^2 - Q^2) / 2W]^2\). We stress that the physical meaning of these resonant amplitudes in different models is different \([\text{2,4,5}]\). In MAID, they contain contributions from the background excitation and describe the so called "dressed" \(\gamma N\Delta\) vertex. However, in the dynamical model the background excitation is included in \(A_B^\alpha\) and the electromagnetic vertex \(A_E^\alpha(Q^2)\) corresponds to the "bare" vertex.

In the dynamical model of Ref. \([\text{3}]\), a scaling assumption was made concerning the ("bare") form factors \(A_E^\alpha(Q^2)\), namely, that all of them have the same \(Q^2\) dependence. In the present analysis, we do not impose the scaling assumption and write, for electric (\(\alpha = E\)), magnetic (\(\alpha = M\)) and Coulomb (\(\alpha = S\)) multipoles,

\[
A_{E}^\alpha(Q^2) = X_{E}^\alpha(Q^2) A_{E}^\alpha(0) \frac{k}{k_W} F(Q^2), \tag{7}
\]

where \(k_W = (W^2 - m_{\Delta}^2) / 2W\). The form factor \(F\) is taken to be \(F(Q^2) = (1 + \beta Q^2) e^{-\gamma Q^2} G_D(Q^2)\), where \(G_D(Q^2) = 1/(1 + Q^2 / 0.71)^2\) is the usual dipole form factor. The parameters \(\beta\) and \(\gamma\) were determined by setting
\[ X_M^\Delta = 1 \] and fitting \( \hat{A}_M^\Delta (Q^2) \) to the data for \( G_m^* \) as defined in \[ {[1,3,7]}. \] The values of \( \hat{A}_M^\Delta (0) \) and \( \hat{A}_\Delta^\Delta (0) \) were determined by fitting to the data with \( X^\Delta (0) = 1. \) Note that deviations from \( X^\Delta = 1 \) value will indicate a violation of the scaling law. Similar treatment is also applied to the \( N^*(1440) \) resonance with two additional parameters \( X^P_{11} \) and \( X^P_{11} \) to the transverse and longitudinal resonance transitions in the isospin 1/2 channel.

The dynamical model and MAID are used to analyze the recent JLab differential cross section data on \( p(e,e'p)\pi^0 \) at high \( Q^2 \). All measured data, 751 points at \( Q^2=2.8 \) and 867 points at \( Q^2=4.0 \) \((\text{GeV}/c)^2\) covering the entire energy range \( 1.1 < W < 1.4 \) GeV, are included in our global fitting procedure. We obtain a very good fit to the measured differential cross sections. In fact, the values of \( \chi^2/\text{d.o.f.} \) for our two models are smaller than those obtained in Ref. \[ {[1]} \] (see Table 1). Our results for the \( G_m^* \) form factor are shown in Fig. 1. Here the best fit is obtained with \( \gamma = 0.21 \) \((\text{GeV}/c)^{-2} \) and \( \beta = 0 \) in the case of MAID, and \( \gamma = 0.40 \) \((\text{GeV}/c)^{-2} \) and \( \beta = 0.52 \) \((\text{GeV}/c)^{-2} \) in the case of the dynamical model.

With the resonance parameters \( X^\Delta (Q^2) \) determined from the fit, the ratios \( R_{EM} = ImE_{1+}/ImM_{1+} \) and \( R_{SM} = ImS_{1+}/ImM_{1+} \) of the total multipoles and the helicity amplitudes \( A_{1/2} \) and \( A_{3/2} \) can then be calculated at resonance. We perform the calculations for both physical \((\pi^0)^3 \) and isospin 3/2 channels and find them to agree with each other. The extracted \( Q^2 \) dependence of the \( X^\Delta \) parameters is: \( X^\Delta (\text{MAID}) = 1 - Q^2 /3.7 \), \( X^\Delta (\text{DM}) = 1 + Q^4 /2.4 \), \( X^\Delta (\text{DM}) = 1 + Q^6 /61 \), \( X^\Delta (\text{DM}) = 1 - 10Q^2 \), with \( Q^2 \) in units \((\text{GeV}/c)^2 \).

Our extracted values for \( R_{EM} \) and \( R_{SM} \) and a comparison with the results of Ref. \[ {[1]} \] are presented in Table 1 and shown in Fig. 2. The main difference between our results and those of Ref. \[ {[1]} \] is that our values of \( R_{EM} \) show a clear tendency to cross zero and change sign as \( Q^2 \) increases. This is in contrast with the results obtained in the original analysis \[ {[1]} \] of the data which concluded that \( R_{EM} \) would stay negative and tend toward more negative values with increasing \( Q^2 \). Furthermore, we find that the absolute value of \( R_{SM} \) is strongly increasing. In terms of helicity amplitudes, our results for a small \( R_{EM} \) can be understood in that the extracted \( A_{3/2} \) remains as large as the helicity conserving \( A_{1/2} \) up to \( Q^2 = 4.0(\text{GeV}/c)^2 \), resulting in a small \( E_{1+} \).

Finally, we show our results for \( Q^2A_{1/2}^\Delta, Q^2A_{3/2}^\Delta \), and \( Q^2S_{1/2}^\Delta \) in Fig. 3. The bare form factors obtained with DM is used since the scaling behavior predicted by

| models | MAID | DM | Ref. [1] |
|--------|------|----|----------|
| \( R_{EM}^{(p\pi^0)} \) | -0.56 ± 0.33 | -1.28 ± 0.32 | -2.00 ± 1.7 |
| \( R_{SM}^{(p\pi^0)} \) | 0.09 ± 0.50 | -0.84 ± 0.46 | -3.1 ± 1.7 |
| \( G^\Delta_M \times 100 \) | 6.78 ± 0.05 | 7.00 ± 0.04 | 6.9 ± 0.4 |
| \( \chi^2 \) | 1.02 | 1.46 | 1.60 |
| \( \chi^2/\text{d.o.f.} \) | 1.14 | 1.28 | 1.45 |

FIG. 1. The \( Q^2 \) dependence of the \( G_m^* \) form factor. The solid and dashed curves are the results of the MAID and dynamical model analyses, respectively. The data at \( Q^2=2.8 \) and 4.0 \((\text{GeV}/c)^2 \) are from Ref. [1], other data from Refs. [5].

FIG. 2. The \( Q^2 \) dependence of the ratios \( R_{EM}^{(p\pi^0)} \) and \( R_{SM}^{(p\pi^0)} \) at \( W = 1232 \) MeV. The solid and dashed curves are the MAID and dynamical model results, respectively, obtained with a violation of the scaling assumption. Results of previous data analysis at \( Q^2 = 0 \) from Ref. [1], data at \( Q^2=2.8 \) and 4.0 \((\text{GeV}/c)^2 \) from Ref. [1] (stars). Results of our analysis at \( Q^2=2.8 \) and 4.0 \((\text{GeV}/c)^2 \) are obtained using MAID (•) and the dynamical models (△). Other data from Ref. [1].
pQCD arises from the 3q Fock states in the nucleon and $\Delta$. It is interesting to see that $S_{1/2}^\Delta$ and $A_{1/2}^\Delta$ clearly starts exhibiting the pQCD scaling behavior at about $Q^2 \geq 2.5(\text{GeV}/c)^2$. The maximal value for the $Q^2 A_{1/2}^\Delta$ which we obtained in this region is about -0.11 GeV$^5/2$.

This is in between of the asymptotic behavior of $S_{1/2}^\Delta$ and $A_{1/2}^\Delta$, which suggests that hadronic helicity conservation is not yet observed in this region of $(\text{GeV}/c)^2$.

It appears likely that the onset of scaling behavior might take place at a lower momentum transfer than that of electroproduction.

In summary, we have re-analyzed the recent JLab data for electroproduction of the $\Delta(1232)$ resonance via $p(e,e'p)\pi^0$ with two models for pion electroproduction, both of which give excellent descriptions of the existing data. We find that $A_{3/2}^\Delta$ is still as large as $A_{1/2}^\Delta$ at $Q^2 = 4\text{ (GeV}/c)^2$, which implies that hadronic helicity conservation is not yet observed in this region of $Q^2$. Accordingly, our extracted values for $R_{EM}$ are still far from the pQCD predicted value of +100%. However, in contrast to previous results we find that $R_{EM}$, starting from a small and negative value at the real photon point, actually exhibits a clear tendency to cross zero and change sign as $Q^2$ increases, while the absolute value of $R_{SM}$ is strongly increasing.

In regard to the scaling, our analysis indicates that $S_{1/2}^\Delta$ and $A_{1/2}^\Delta$, but not $A_{3/2}^\Delta$, starts exhibiting the pQCD scaling behavior at about $Q^2 \geq 2.5(\text{GeV}/c)^2$. It appears likely that the onset of scaling behavior might take place at a lower momentum transfer than that of hadron helicity conservation.

It will be most interesting to have data at yet higher momentum transfer in order to see the region where the helicity amplitude $A_{1/2}^\Delta$ finally dominates over $A_{3/2}^\Delta$. It is only there that we could expect to see the onset of the asymptotic behavior of $R_{EM} \to +100\%$ and $R_{SM} \to \text{const}$.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig3.png}
\caption{The $Q^2$ dependence of the $Q^2 A_{1/2}^\Delta$ (solid curve) $Q^2 A_{3/2}^\Delta$ (dashed curve) and $Q^2 S_{1/2}^\Delta$ (dotted curve) amplitudes (in units $10^{-3}$ GeV$^{\nu/2}$) obtained with DM.}
\end{figure}

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