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$\gamma^* N \to \Delta$ transition form factors: A new analysis of data on $p(e,e'p)\pi^0$ at $Q^2=2.8$ and 4.0 $(\mathrm{GeV}/c)^2$

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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 $(\mathrm{GeV}/c)^2$ 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 $Q^2=4.0$ $(\mathrm{GeV}/c)^2$, the extracted helicity amplitudes $A_{3/2}$ and $A_{/2}$ 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 bare helicity amplitude $A_{1/2}$ and $S_{1/2}$, but not $A_{3/2}$, starts exhibiting the scaling behavior at about $Q^2 \geqslant 2.5 (\mathrm{GeV}/c)^2$.

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In a recent experiment [1], electroexcitation of the Δ was studied at $Q^2=2.8$ and 4.0 $(\mathrm{GeV}/c)^2$ 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 $Q^2 \to \infty$, pQCD predicts the dominance of helicity-conserving amplitudes [2] and scaling results [3,4]. 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 $R_{SM}=S_{1+}^{(3/2)}/M_{1+}^{(3/2)} \to \mathrm{const}$. On the other hand, in symmetric $SU(6)$ quark models and with the inclusion of only one-body current contribution [5], 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 $E_{1+}=S_{1+}\equiv 0$. Recent experiments give nonvanishing ratios R_{EM} lying between -2.5% [6] and -3.0% [7] at $Q^2=0$. This has been widely taken as an indication of a deformed Δ, namely, an admixture of a D state in the Δ. 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. [1], 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 [8]. Another extraction of the resonance amplitudes was performed using the effective Lagrangian method [9]. 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. Both the ratios R_{EM} and R_{SM} extracted with these two methods are 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 [10] that the Q^2 dependence of the ratios R_{EM} and R_{SM} extracted in Ref. [1] could 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. [1] differ from each other by factors of 2 and 1.5 at $Q^2=2.8$ and 4.0 $(\mathrm{GeV}/c)^2$, respectively. In this Rapid Communication, we present the results of a new analysis of the data of Ref. [1], using a new version (hereafter called MAID) [11] of the unitary isobar model developed at Mainz (hereafter called MAID98) [12], and the dynamical model (DM) developed recently in Ref. [10], both give excellent descriptions of most of the existing pion photo- and electroproduction data [11]. Our analysis is similar to the second method used in [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 χ^2 per degree of freedom (d.o.f.)

In the dynamical approach to pion photo- and electroproduction [13], the t matrix can be expressed as

$$t_{\gamma\pi}(E)=v_{\gamma\pi}+v_{\gamma\pi}\, g_0(E)\, t_{\pi N}(E), \tag{1}$$

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and the physical multipoles in channel α are given by

$$t_{\gamma\pi}^{(\alpha)}(q_E,k)=\exp(i\delta^{(\alpha)})\cos\delta^{(\alpha)}\left[v_{\gamma\pi}^{(\alpha)}(q_E,k)+P\int_0^\infty dq'\frac{q'^2R_{\pi N}^{(\alpha)}(q_E,q')\,v_{\gamma\pi}^{(\alpha)}(q',k)}{E-E_{\pi N}(q')}\right], \quad (2)$$

where $v_{\gamma\pi}$ is the transition potential for $\gamma^*N\to\pi N$, and $t_{\pi N}$ and g_0 denote the πN t matrix and free propagator, respectively, with $E\equiv W$ the total energy in the c.m. frame. $\delta^{(\alpha)}$ and $R_{\pi N}^{(\alpha)}$ are the πN scattering phase shift and reaction matrix in channel α, respectively; q_E is the pion on-shell momentum and $k=|\mathbf{k}|$ 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

$$v_{\gamma\pi}(E)=v_{\gamma\pi}^B+v_{\gamma\pi}^\Delta(E), \quad (3)$$

where $v_{\gamma\pi}^B$ is the background transition potential and $v_{\gamma\pi}^\Delta(E)$ corresponds to the contribution of the bare Δ. The resulting t matrix can be decomposed into two terms [10]

$$t_{\gamma\pi}(E)=t_{\gamma\pi}^B(E)+t_{\gamma\pi}^\Delta(E), \quad (4)$$

where

$$t_{\gamma\pi}^B(E)=v_{\gamma\pi}^B+v_{\gamma\pi}^B\,g_0(E)\,t_{\pi N}(E), \quad (5)$$

$$t_{\gamma\pi}^\Delta(E)=v_{\gamma\pi}^\Delta+v_{\gamma\pi}^\Delta\,g_0(E)t_{\pi N}(E). \quad (6)$$

Here $t_{\gamma\pi}^B$ 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 Δ are summed up in $t_{\gamma\pi}^\Delta$. Note that the multipole decomposition of both $t_{\gamma\pi}^B$ and $t_{\gamma\pi}^\Delta$ would take the same form as Eq. (2).

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 πNN coupling and t-channel vector meson exchanges, namely, $t_{\gamma\pi}^{B,\alpha}(\mathrm{MAID98})=v_{\gamma\pi}^{B,\alpha}(W,Q^2)$. 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,

$$t_{\gamma\pi}^{B,\alpha}(\mathrm{MAID})=\exp(i\delta^{(\alpha)})\cos\delta^{(\alpha)}v_{\gamma\pi}^{B,\alpha}(W,Q^2). \quad (7)$$

From Eqs. (2) and (7), 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 $\exp i(\delta^{(\alpha)})\cos\delta^{(\alpha)}=\frac{1}{2}[\exp(2i\delta^{(\alpha)})+1]$ in Eqs. (2) and (7) with $\frac{1}{2}[\eta_\alpha\exp(2i\delta^{(\alpha)})+1]$, where η_α is the inelasticity. In our actual calculations, both the πN phase shifts $\delta^{(\alpha)}$ and inelasticity parameters η_α are taken from the analysis of the GWU group [14]. Furthermore, the off-shell rescattering effects in the dynamical model are evaluated with the reaction matrix $R_{\pi N}^{(\alpha)}(q_E,q')$ as prescribed by a meson exchange model [15].

Following Ref. [12], we assume a Breit-Wigner form for the resonance contribution $t_{\gamma\pi}^{R,\alpha}(W,Q^2)$ to the total multipole amplitude,

$$t_{\gamma\pi}^{R,\alpha}(W,Q^2)=\overline{\mathcal{A}}_\alpha^R(Q^2)\frac{f_{\gamma R}(W)\Gamma_R\,M_R\,f_{\pi R}(W)}{M_R^2-W^2-iM_R\Gamma_R}e^{i\phi}, \quad (8)$$

where $f_{\pi R}$ 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 $f_{\gamma R}$, $f_{\pi R}$, and Γ_R are given in Ref. [12]. The phase $\phi(W)$ in Eq. (8) is introduced to adjust the phase of the total multipole to equal the corresponding πN phase shift $\delta^{(\alpha)}$. Because $\phi=0$ at resonance, $W=M_R$, this phase does not affect the Q^2 dependence of the γNR vertex.

We now concentrate on the $\Delta(1232)$. In this case the magnetic dipole ($\overline{\mathcal{A}}_M^\Delta$), the electric ($\overline{\mathcal{A}}_E^\Delta$), and Coulomb ($\overline{\mathcal{A}}_S^\Delta$) quadrupole form factors are related to the conventional electromagnetic helicity amplitudes $A_{1/2}^\Delta$, $A_{3/2}^\Delta$, and $S_{1/2}^\Delta$ by

$$\overline{\mathcal{A}}_M^\Delta(Q^2)=-\frac{1}{2}(A_{1/2}^\Delta+\sqrt{3}A_{3/2}^\Delta), \quad (9)$$

$$\overline{\mathcal{A}}_E^\Delta(Q^2)=\frac{1}{2}\left(-A_{1/2}^\Delta+\frac{1}{\sqrt{3}}A_{3/2}^\Delta\right), \quad (10)$$

$$\overline{\mathcal{A}}_S^\Delta(Q^2)=-\frac{S_{1/2}^\Delta}{\sqrt{2}}. \quad (11)$$

We stress that the physical meaning of these resonant amplitudes in different models is different [10,16]. 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 $t_{\gamma\pi}^{R,\alpha}$ and the electromagnetic vertex $\overline{\mathcal{A}}_\alpha^\Delta(Q^2)$ corresponds to the "bare" vertex.

In the dynamical model of Ref. [10], a scaling assumption was made concerning the (bare) form factors $\overline{\mathcal{A}}_\alpha^\Delta(Q^2)$, 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,

$$\overline{\mathcal{A}}_\alpha^\Delta(Q^2)=X_\alpha^\Delta(Q^2)\overline{\mathcal{A}}_\alpha^\Delta(0)\frac{k}{k_W}F(Q^2), \quad (12)$$

where $k_W=(W^2-m_N^2)/2W$ and $k^2=Q^2+[(W^2-m_N^2-Q^2)/2W]^2$. The form factor F is taken to be $F(Q^2)=(1+\beta Q^2)\,e^{-\gamma Q^2}\,G_D(Q^2)$, where $G_D(Q^2)=1/(1+Q^2/0.71)^2$

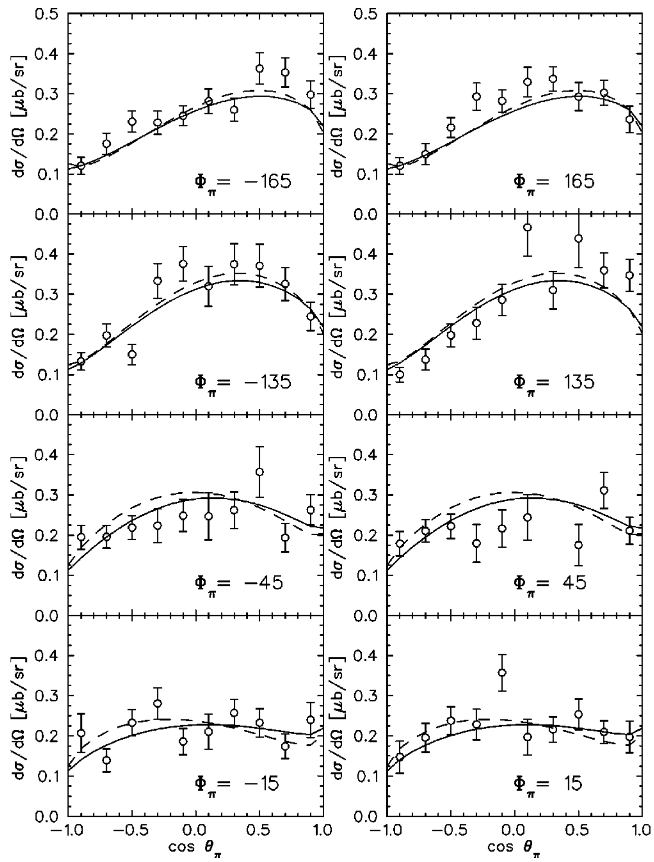

FIG. 1. The virtual photons differential cross sections at $Q^2 = 4.03\ (\mathrm{GeV}/c)^2$ and $W = 1232$ MeV. The full and dashed curves are the results from the MAID and DM analysis, respectively. Data are from Ref. [1].

is the usual dipole form factor. The parameters β and γ were determined by setting $X_M^\Delta = 1$ and fitting $\overline{\mathcal{A}}_M^\Delta(Q^2)$ to the data for G_M^* as defined in [10,12,18]. The values of $\overline{\mathcal{A}}_M^\Delta(0)$ and $\overline{\mathcal{A}}_E^\Delta(0)$ were determined by fitting to the multipoles obtained in the recent analyses of the Mainz [17] and GWU [14] groups. Both X_E and X_S are to be determined by the experiment with $X_\alpha^\Delta(0) = 1$. Note that deviations from $X_\alpha^\Delta = 1$ value will indicate a violation of the scaling law. Similar treatment is also applied to the $N^*(1440)$ resonance with two additional parameters X_M^{P11} and X_S^{P11} corresponding 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 $Q^2 = 4.0\ (\mathrm{GeV}/c)^2$ 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. As an example, we show in Fig. 1 results of our global fit at $W = 1232$ MeV and $Q^2 = 4.0\ (\mathrm{GeV}/c)^2$. In fact, the values of χ^2/d.o.f. for our two models are smaller than those obtained in Ref. [1] (see Table I). Our results for the G_M^* form factor are shown in Fig. 2. Here the best fit is obtained with $\gamma = 0.21\ (\mathrm{GeV}/c)^{-2}$ and $\beta = 0$ in the case of MAID, and $\gamma = 0.42\ (\mathrm{GeV}/c)^{-2}$ and $\beta = 0.61\ (\mathrm{GeV}/c)^{-2}$ in the case of DM.

TABLE I. Our results for the ratios R_{EM} and R_{SM}, at $Q^2 = 2.8$ (upper row) and 4.0 (lower row) $(\mathrm{GeV}/c)^2$, extracted from a global fit to the data with MAID and DM as discussed in the text. Results from Ref. [1] are listed for comparison. Ratios are given in percents.

Models	MAID	DM	Ref. [1]
$R_{EM}^{(p\pi^0)}$	-0.56 ± 0.33	-1.28 ± 0.32	-2.00 ± 1.7
	0.09 ± 0.50	-0.84 ± 0.46	-3.1 ± 1.7
$R_{SM}^{(p\pi^0)}$	-9.14 ± 0.54	-11.65 ± 0.52	-11.2 ± 2.3
	-13.37 ± 0.95	-17.70 ± 1.0	-14.8 ± 2.3
$G_M^* \times 100$	6.78 ± 0.05	7.00 ± 0.04	6.9 ± 0.4
$\times 100$	2.86 ± 0.02	3.04 ± 0.02	2.9 ± 0.2
χ^2	1.02	1.46	1.60
	1.14	1.28	1.45

With the resonance parameters $X_\alpha^\Delta(Q^2)$ determined from the fit, the ratios $R_{EM} = \mathrm{Im}E_{1+}/\mathrm{Im}M_{1+}$ and $R_{SM} = \mathrm{Im}S_{1+}/\mathrm{Im}M_{1+}$ 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 $(p\pi^0)$ and isospin 3/2 channels and find them to agree with each other. The extracted Q^2 dependence of the X_α^Δ parameters is $X_E^\Delta(\mathrm{MAID}) = 1 - Q^2/3.7$, $X_E^\Delta(\mathrm{DM}) = 1 + Q^4/2.4$, $X_S^\Delta(\mathrm{MAID}) = 1 + Q^6/61$, $X_S^\Delta(\mathrm{DM}) = 1 - 10Q^2$, with Q^2 in units of $(\mathrm{GeV}/c)^2$.

Our extracted values for R_{EM} and R_{SM} and a comparison with the results of Ref. [1] are presented in Table I and shown in Fig. 3. 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

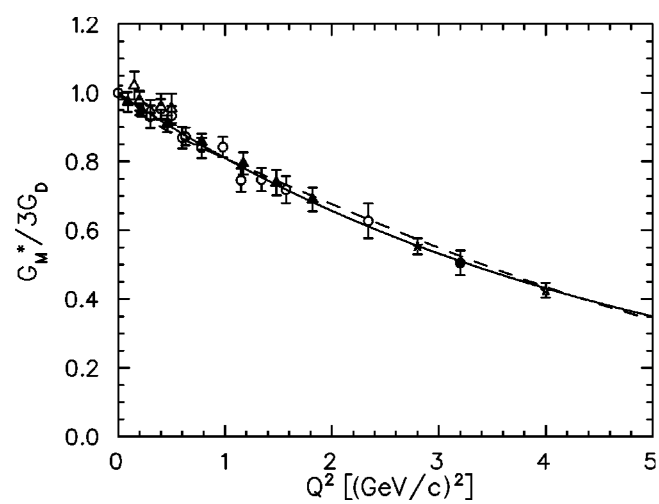

FIG. 2. The Q^2 dependence of the G_M^* form factor. The solid and dashed curves are the results of the MAID and DM analyses, respectively. The data at $Q^2 = 2.8$ and 4.0 $(\mathrm{GeV}/c)^2$ are from Ref. [1], other data from Ref. [19].

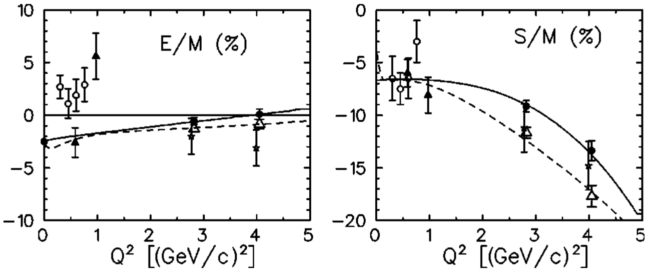

FIG. 3. The Q^2 dependence of the ratios $R_{EM}^{(p\pi^0)}$ and $R_{SM}^{(p\pi^0)}$ at $W=1232$ MeV. The solid and dashed curves are the MAID and dynamical model results, respectively, obtained with a violation of the scaling assumption. Results of previous data analysis at $Q^2=0$ from Ref. [6], data at $Q^2=2.8$ and 4.0 (GeV/c)^2 from Ref. [1] (stars). Results of our analysis at $Q^2=2.8$ and 4.0 (GeV/c)^2 are obtained using MAID (●) and the dynamical models (△). Other data from Ref. [20].

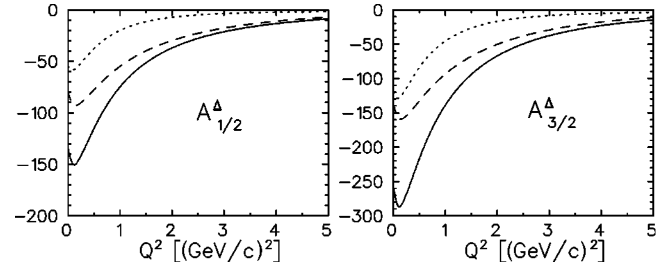

FIG. 4. The Q^2 dependence of the bare (dashed curves) and dressed (solid curves) helicity amplitudes $A_{1/2}$ and $A_{3/2}$ (in units of 10^{-3} GeV$^{-1/2}$) extracted with DM. The dotted curves are the pion cloud contributions.

Q^2. Furthermore, we find that the absolute value of R_{SM} is strongly increasing. Our results also differ from those obatined with fixed-t dispersion relation analysis of Ref. [21] wherein it was concluded that the ratio R_{EM} is definitely positive at $Q^2=2.8-4.0$ (GeV/c)^2. In addition, the extracted values of R_{SM} in [21] are far less negative and show a less rapid rate of change with increasing Q^2 than ours.

At low Q^2, the Q^2 evolution of both R_{EM} and R_{SM} obtained with DM and MAID exhibits some marked difference, as can be seen in Fig. 3. In particular, the value of R_{SM} at $Q^2=0$ extracted with these two models even differ by a factor of 2. This is due to the fact that within MAID, the background contribution of Eq. (7) vanishes at the resonance so that R_{EM} and R_{SM} become the ratios of the dressed form factors $\bar{\mathcal{A}}_{\alpha}^{\Delta}$. Therefore, if we neglect the small influence of the $X_{\alpha}^{\Delta}(Q^2)$ factor at small Q^2, the scaling assumption leads to a rather smooth Q^2 dependence for the R_{EM} and R_{SM}. In the dynamical model, both $E_{1^+}^{(3/2)}$ and $S_{1^+}^{(3/2)}$ are dominated by the contribution from pion cloud [10,22], namely, the principal value integral term in Eq. (2). Our results indicate that the Q^2 dependence of the pion cloud contribution deviates strongly from the scaling assumption. It is interesting to observe that the recent calculation of the two-body current contribution, which in part includes the pion cloud effect, to the R_{SM} within a constituent quark model [5] also gives results for R_{SM} similar to our DM values at small Q^2.

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 $Q^2=4.0$ (GeV/c)^2, as seen in Fig. 4, resulting in a small E_{1^+}. The contributions from the bare Δ and pion cloud obtained with DM are also shown by the dashed and dotted curves, respectively. Note that the latter drop faster than the bare Δ contribution. The sum gives the dressed helicity amplitudes which are practically identical to those of MAID.

Finally, we present in Fig. 5 our DM results for $Q^3A_{1/2}^{\Delta}$, $Q^5A_{3/2}^{\Delta}$, and $Q^3S_{1/2}^{\Delta}$, to check the scaling behavior of the bare and dressed helicity amplitudes. Note that the scaling behavior predicted by pQCD arises from the three quark (3q) Fock states in the nucleon and Δ, and should apply primarily to the bare amplitudes. We find that the bare $S_{1/2}^{\Delta}$ and $A_{1/2}^{\Delta}$ clearly starts exhibiting the pQCD scaling behavior at about $Q^2\geqslant 2.5$ (GeV/c)^2. However, it is difficult to draw any definite conclusion for $Q^5A_{3/2}^{\Delta}$. The dressed Coulomb form factor $S_{1/2}^{\Delta}$ does not exhibit pQCD scaling behavior in the considered Q^2 range. This is due to the fact that in this case the dominant pion cloud contribution does not drop as fast as in the transverse amplitudes. From these results, it appears likely that scaling will set in earlier than the helicity conservation. This is not surprising in the sense that the pQCD scaling behavior is predicted based on the argument that, in exclusive reactions, when the photon finds the nucleon in a small 3q Fock substate, with dimensions comparable to the photon wavelength, then processes with only two hard gluon exchanges dominate [4]. On the other hand, hadron helicity would be conserved only if this small 3q Fock state would further have a spherically symmetric distribution amplitude such that $L_z=0$ and the hadron helicity is the sum of individual quark helicities.

In summary, we have reanalyzed 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 $Q^2=4$ (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

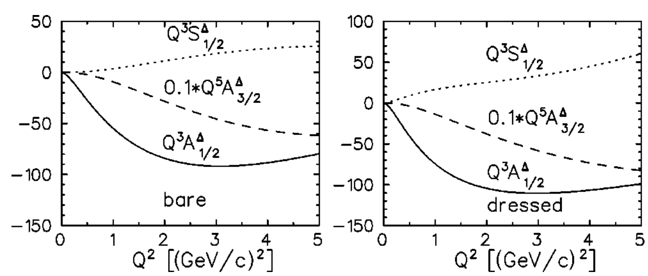

FIG. 5. The Q^2 dependence of the $Q^3A_{1/2}^{\Delta}$ (solid curve), $Q^5A_{3/2}^{\Delta}$ (dashed curve), and $Q^3S_{1/2}^{\Delta}$ (dotted curve) amplitudes (in units of 10^{-3} GeV$^{n/2}$) obtained with DM.

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 bare $S^{\Delta}_{1/2}$ and $A^{\Delta}_{1/2}$, but not $A^{\Delta}_{3/2}$, starts exhibiting the pQCD scaling behavior at about $Q^2 \geqslant 2.5\ (\mathrm{GeV}/c)^2$. 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 $A^{\Delta}_{1/2}$ finally dominates over $A^{\Delta}_{3/2}$. It is only there that we could expect to see the onset of the asymptotic behavior of $R_{EM} \rightarrow +100\%$ and $R_{SM} \rightarrow \mathrm{const}$.

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