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$N^*(1535)$ **electroproduction at high** Q^2

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Abstract. A covariant spectator quark model is applied to study the $\gamma N \to N^*(1535)$ reaction in the large Q^2 region. Starting from the relation between the nucleon and $N^*(1535)$ systems, the $N^*(1535)$ valence quark wave function is determined without the addition of any parameters. The model is then used to calculate the $\gamma N \to N^*(1535)$ transition form factors. A very interesting, useful relation between the $A_{1/2}$ and $S_{1/2}$ helicity amplitudes for $Q^2 > 2$ GeV^2, is also derived.

Keywords: Covariant quark model, $S_{11}(1535)$ electroproduction, Helicity amplitudes
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INTRODUCTION

Study of the meson-nucleon reactions is one of the most important research topics associated with modern accelerators like CEBAF at Jefferson Lab, and defines new challenges for theoretical models. Although the electroproduction of nucleon resonances ($\gamma N \to N^*$) is expected to be governed by the interaction of quarks and gluons (QCD) at very large momentum transfer squared Q^2, at present one has to rely on some effective and phenomenological approaches such as effective meson-baryon models [1] at low Q^2, and/or constituent quark models [2, 3, 4] at moderate and large Q^2, where meson cloud effects are attenuated.

The $N^*(1535)$ resonance, identified as an S_{11} state, is particularly interesting among the many experimentally observed nucleon resonances. It is the chiral partner ($J^P = \frac{1}{2}^-$) of the nucleon, and has strong decay channels for both πN and ηN. It has been suggested that $N^*(1535)$ can be dynamically generated as a $K\Sigma$ quasi-bound state [5, 6, 7]. But it was also argued that pure valence quark effects are important to explain its electromagnetic structure [6]. Furthermore, the $N^*(1535)$ resonance is also interesting due to the closeness in its mass with that of the other S_{11} state, $N^*(1650)$, where both states can be regarded as combinations of the quark core states of spin 1/2 and 3/2, and the mass splitting is due to the color hyperfine interactions between the quarks [4].

To describe the $\gamma N \to N^*(1535)$ transition, we use a covariant spectator quark model [8, 9, 10, 11]. The model has been successfully applied for studying the properties of nucleon [8, 10, 12], Δ [11, 13, 14, 15], higher resonances [2, 16, 17], and also the electromagnetic transitions in the lattice QCD regime [9, 14, 18]. In the covariant spectator quark model a baryon is described as a three-valence quark system with an on-shell quark-pair (diquark) with mass m_D, while the remaining quark is off-shell and free to interact with the electromagnetic fields. The quark-diquark vertex is represented by a baryon B wave function Ψ_B that effectively describes quark confinement [8]. To

represent the nucleon system, we adopt the simplest structure given by a symmetric and anti-symmetric combination of the diquark states, combined to a relative S-state with the remaining quark [8]:

$$\Psi_N(P,k) = \frac{1}{\sqrt{2}} \left[\Phi_I^0 \Phi_S^0 + \Phi_I^1 \Phi_S^1 \right] \psi_N(P,k), \tag{1}$$

where $\Phi_S^{0,1}$ [$\Phi_I^{0,1}$] is the spin [isospin] state which corresponds to the diquark with the quantum number 0 or 1. The function ψ_N is a scalar wave function which depends exclusively on $(P-k)^2$, where P (k) is the baryon (diquark) momentum. The $N^*(1535)$ state has the same isospin state but different spin state with that of the nucleon. The $N^*(1535)$ spin state can have P-states in the relative quark-diquark configuration and/or in the diquark system. Assuming that the core spin 1/2 state is dominant [4] and a point-like diquark (no internal P-states), one can represent the $N^*(1535)$ wave function as

$$\Psi_{S11}(P,k) = \frac{1}{\sqrt{2}} \gamma_5 \left[\Phi_I^0 X_\rho - \Phi_I^1 X_\lambda \right] \psi_{S11}(P,k), \tag{2}$$

where X_ρ and X_λ are respectively the anti-symmetric and symmetric spin states with respect to the exchange of the quarks 1 and 2, and ψ_{S11} is the $N^*(1535)$ radial wave function [2].

The scalar wave functions $\psi_B(B = N, S_{11})$ are represented using the dimensionless variable χ_B:

$$\chi_B = \frac{(M_B - m_D)^2 - (P-k)^2}{M_B m_D}, \qquad \psi_B(P,k) = \frac{N_B}{m_D(\beta_1 + \chi_B)(\beta_2 + \chi_B)}. \tag{3}$$

Note that, χ_B contains a dependence on the baryon mass M_B that can be M for the nucleon and M_S for the $N^*(1535)$. In the above equation, N_B are the normalization constants, and β_1 and β_2 are momentum range parameters that regulate the short and long range behavior in position space. As we represent both the wave functions with the same parameters for N and $N^*(1535)$, they have the same form in the respective rest frames, apart from the orbital angular momenta. This means that no extra parameters are required to represent the $N^*(1535)$ state. The analytic form (3), was chosen to reproduce the asymptotic form predicted by pQCD for the nucleon form factors ($G_E, G_M \sim 1/Q^4$), but also assures the expected pQCD behavior for the $\gamma N \to N^*(1535)$ transition form factors [2].

The constituent quark electromagnetic current in the model is described by

$$j_I^\mu = \left(\tfrac{1}{6} f_{1+} + \tfrac{1}{2} f_{1-} \tau_3 \right) \left(\gamma^\mu - \frac{\slashed{q} q^\mu}{q^2} \right) + \left(\tfrac{1}{6} f_{2+} + \tfrac{1}{2} f_{2-} \tau_3 \right) \frac{i\sigma^{\mu\nu} q_\nu}{2M}, \tag{4}$$

where τ_3 is the isospin projection operator. To parameterize the electromagnetic structure of the constituent quark in terms of the quark form factors $f_{1\pm}$ and $f_{2\pm}$, we adopt a vector meson dominance-based parametrization [8, 9].

The $\gamma N \to S_{11}$ transition in the model is described by a relativistic impulse approximation in terms of the initial P_- and final P_+ baryon momenta with the diquark (spectator)
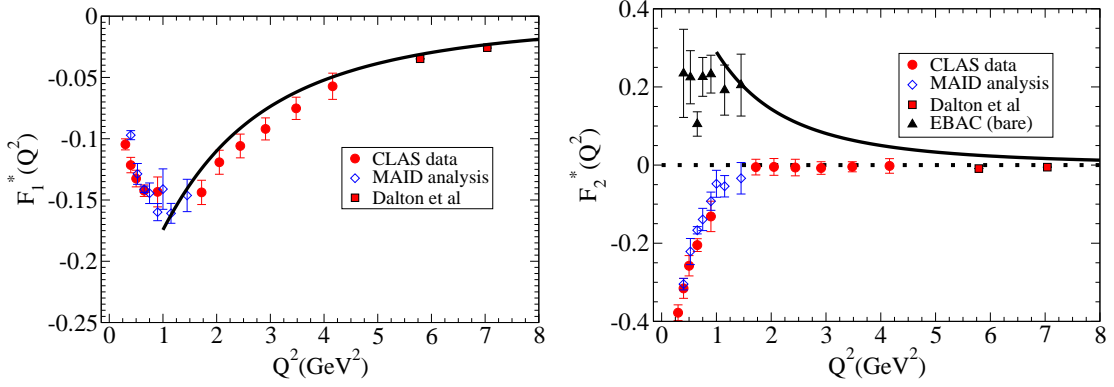
FIGURE 1. Model predictions for the $\gamma N \rightarrow S_{11}(1525)$ transition form factors (solid line) [2]. Left panel: model for F_1^* compared with the data. Right panel: model for F_2^* compared with the data and an estimate for the quark core contributions from EBAC [7]. The dotted line indicate the zero line. Data are from Refs. [19, 20, 21].

on-mass-shell [2, 3]:

$$
\begin{aligned}
J^\mu &= 3\sum_\Lambda \int_k \bar{\Psi}_R(P_-,k) j_I^\mu \Psi_N(P_-,k), \\
&= \bar{u}_S(P_+)\left[\left(\gamma^\mu - \frac{\not{q}q^\mu}{q^2}\right)F_1^*(Q^2) + \frac{i\sigma^{\mu\nu}q_\nu}{M_S+M}F_2^*(Q^2)\right]\gamma_5 u(P_-). \quad (5)
\end{aligned}
$$

In the first line the sum is over the diquark states $\Lambda = \{s,\lambda\}$, where s and $\lambda = 0,\pm 1$ stand for the scalar diquark and the vector diquark polarizations, respectively, and $\int_k$ is a covariant integral in the diquark momentum. The factor 3 is due to the flavor symmetry. In the second line the transition form factors F_1^* and F_2^* are defined independent of the frame using the Dirac spinors of the S_{11} state (u_S) and nucleon (u). The spin projection indices are suppressed for simplicity.

RESULTS

The results for the $\gamma N \rightarrow N^*(1535)$ transition form factors are [2]:

$$
F_1^*(Q^2) = \frac{1}{2}(3j_1 + j_3)\mathscr{I}_0(Q^2), \qquad F_2^*(Q^2) = -\frac{1}{2}(3j_2 - j_4)\frac{M_S+M}{2M}\mathscr{I}_0(Q^2), \quad (6)
$$

where $j_i = \frac{1}{6}f_{i+} + \frac{1}{2}f_{i-}\tau_3$ and $j_{(i+2)} = \frac{1}{6}f_{i+} - \frac{1}{6}f_{i-}\tau_3$ ($i = 1,2$), and $\mathscr{I}_0(Q^2)$ the overlap integral between the scalar wave functions that can be written in the $N^*(1535)$ rest frame as

$$
\mathscr{I}_0(Q^2) = \int_k \frac{k_z}{|\mathbf{k}|}\psi_{S11}(P_{S11},k)\psi_N(P_N,k), \quad (7)
$$

where the factor k_z is due to the $N^*(1535)$ P-state. The expression for $\mathscr{I}_0$ can be used to define the applicable range of the model. In the $Q^2 \rightarrow 0$ limit we can write $\mathscr{I}_0(Q^2) \propto |\mathbf{q}|$,

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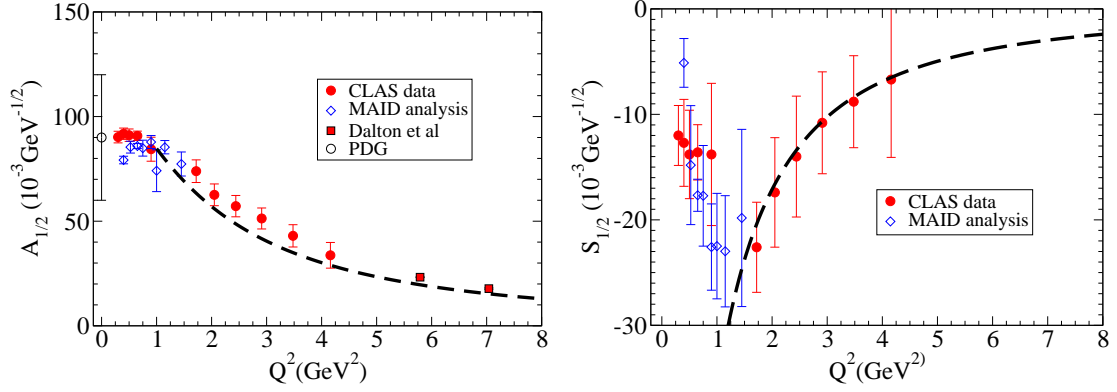
FIGURE 2. $\gamma N \to S_{11}(1525)$ helicity amplitudes [2] determined from the model for the form factors with $F_2^* = 0$ (dashed line). Data are from Refs. [19, 20, 21].

where $|\mathbf{q}|$ is the photon 3-momentum in the $N^*(1535)$ rest frame, which is $|\mathbf{q}| = \frac{M_S^2 - M^2}{2M_S}$, when $Q^2 = 0$. As a consequence $\mathscr{I}_0(0) \neq 0$, if $M_S \neq M$, meaning that nucleon and $N^*(1535)$ states are not orthogonal [2]. In a regime where $|\mathbf{q}| = \frac{M_S^2 - M^2}{2M_S}$ is very small, one can regard that $\mathscr{I}_0(0) \approx 0$, and the model is valid. Taking $Q^2 \gg |\mathbf{q}|^2 = 0.23$ GeV^2 one may assume that the states are orthogonal in the region $Q^2 > 2.3$ GeV^2. In figures we will present our results for the region $Q^2 > 1$ GeV^2.

The results corresponding to the model are presented in Fig. 1, and compared with the CLAS and MAID data [19, 20], and also with an estimate for the valence quark core contributions from EBAC [7]. The results of the experimental data $F_2^* \simeq 0$, for $Q^2 > 1.5$ GeV^2, are in contradiction with the results of the model. The simplest interpretation of this discrepancy is that the valence quark effects are canceled by the meson cloud contributions [2]. This interpretation is supported by EBAC [7] and effective chiral meson-baryon models [6, 22]. We use then the result $F_2^* = 0$ in the calculation of the helicity amplitudes $A_{1/2}$ and $S_{1/2}$. The results are presented in Fig. 2.

The direct consequence of the result $F_2^* = 0$ is the relation [3]

$$S_{1/2} = -\frac{\sqrt{1+\tau}}{\sqrt{2}} \frac{M_S^2 - M^2}{2M_S Q} A_{1/2}, \qquad (8)$$

where $\tau = \frac{Q^2}{(M_S + M)^2}$, which holds for $Q^2 > 1.8$ GeV^2 [when $|\mathbf{q}| \simeq Q\sqrt{1+\tau}$]. We can see that the relation (8) is consistent with the data using our result for $A_{1/2}$, and it is also valid for the MAID parametrization [20] for $A_{1/2}$ and $S_{1/2}$ amplitudes [3]. The test for MAID is presented in the left panel of Fig. 3. Finally, we look the asymptotic behavior in Q^2 for $A_{1/2}$ and compare with the data. Our result and the data are consistent with the $1/Q^3$ behavior, apart from a small logarithmic correction (see the right panel of Fig. 3).

In conclusion the $\gamma N \to N^*(1535)$ reaction is a very interesting reaction from the constituent quark model perspective. The quark degrees of freedom are sufficient to explain the F_1^* data, but insufficient to explain the F_2^* data for large Q^2. Extracted data $F_2^* = 0$ for large Q^2, leads to a very interesting relation between the $S_{1/2}$ and $A_{1/2}$ helicity

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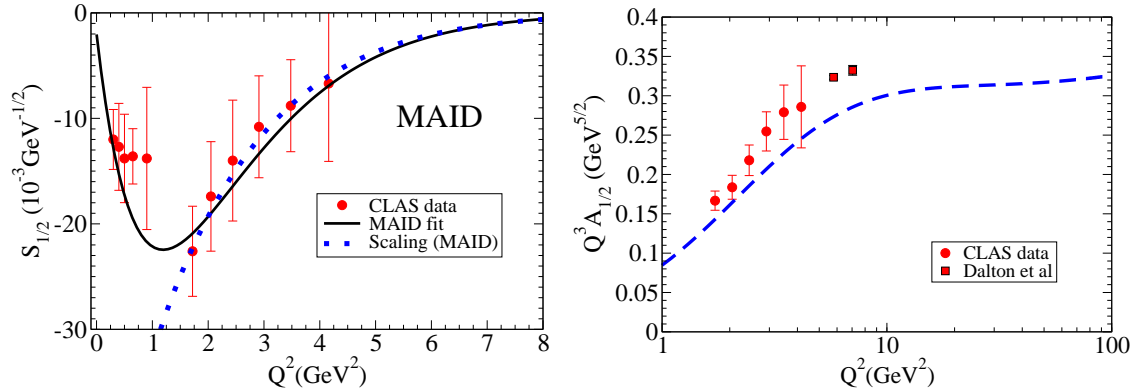
FIGURE 3. Left panel: Test of the relation (8) using the MAID parametrization for $A_{1/2}$ (dotted line) compared with the $S_{1/2}$ parametrization (solid line). Right panel: Comparison of the asymptotic behavior of the model for $A_{1/2}$ (dashed line) compared with the data [19, 21].

amplitudes given by Eq. (8). When interpreted in terms of the valence quark and the meson cloud excitation effects, Eq. (8) is the consequence of the cancellation between the two effects. Accurate data for $A_{1/2}$ and $S_{1/2}$ for $Q^2 > 2$ GeV^2, are necessary to test the relation (8) and clarify this point. Efforts from quark models, dynamical coupled-channel models, chiral effective models, QCD sum rules [23], and lattice QCD, are welcome in order to interpret the $\gamma N \rightarrow N^*(1535)$ reaction data.

ACKNOWLEDGMENTS

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