Valence quark contributions for the $\gamma N \to P_{11}(1440)$ transition

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Abstract. A covariant spectator quark model is applied to estimate the valence quark contributions to the $F_1^+(Q^2)$ and $F_2^+(Q^2)$ transition form factors for the $\gamma N \to P_{11}(1440)$ reaction. The Roper resonance, $P_{11}(1440)$, is assumed to be the first radial excitation of the nucleon. The model requires no extra parameters except for those already fixed by the previous studies for the nucleon. The results are consistent with the experimental data in the high $Q^2$ region, and those from the lattice QCD. Finally the model is also applied to estimate the meson cloud contributions from the CLAS and MAID analysis.

Keywords: Covariant quark model, Roper electroproduction, Meson cloud

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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 laboratory, and defines new challenges for theoretical models. Although the electroproduction of nucleon resonances ($\gamma N \to N^*$) is expected to be governed by the short range interaction of quarks and gluons, i.e., perturbative QCD, at low and intermediate four-momentum transfer squared $Q^2$, one has to rely on some effective and phenomenological approaches such as constituent quark models.

The Roper [$P_{11}(1440)$] resonance is particularly interesting among the many experimentally observed nucleon resonances. Although usual quark models predict the Roper state as the first radial excitation of the nucleon, they usually result to give a much larger mass than the experimentally observed mass [1]. Experimentally the Roper has a large width which implies that it can be a molecular-like system, or alternatively, a system of a confined three-quark core surrounded by a large amount of meson clouds. The system can be studied using dynamical coupled channel models for the meson-nucleon reactions [2].

To describe the $\gamma N \to P_{11}(1440)$ transition, we use a covariant spectator model [3, 4, 5, 6, 7]. The model has been successfully applied to the nucleon [4, 6, 8, 9] and Δ systems [7, 10, 11, 12]. A particular interest of this work is the model for the nucleon [4]. In the covariant spectator quark model a baryon is described as a three-valence quark system with an on-shell quark-pair or 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 $\Psi_B$ that effectively describes quark confinement [4]. To represent the nucleon system, we adopt the simplest structure given by a symmetric and antisymmetric combination of the diquark states combined to a relative S-state with the remaining quark [4]:

$$\Psi_N = \frac{1}{\sqrt{2}} [\Phi_0^0 \Phi_0^0 + \Phi_1^0 \Phi_0^1] \psi_N(P,k)$$

(1)

where $\Phi_0^0, [\Phi_1^0]$ is the spin [isospin] state which corresponds to the diquark with the quantum number 0 or 1. The function $\psi_N$ is a scalar wave function which depends exclusively on $(P - k)^2$, where $P$ ($k$) is the baryon (diquark) momentum. As the Roper shares the same spin and isospin quantum numbers with the nucleon its wave function $\Psi_R$ can also be represented by Eq. (1) except for the scalar wave function $\psi_R$.

The constituent quark electromagnetic current in the model is described by

$$j^\mu_Q = \left( \frac{1}{2} f_{1+} + \frac{1}{2} f_{1-} \tau_3 \right) \left( \gamma^\mu - \frac{q q^\mu}{q^2} \right) + \left( \frac{1}{2} f_{2+} + \frac{1}{2} f_{2-} \tau_3 \right) j_2 \frac{i \sigma^{\mu \nu} q_\nu}{2M},$$

(2)
where $M$ is the nucleon mass and $\tau_3$ is the isospin 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 given by two vector meson poles: a light one corresponds to the $\rho$ or $\omega$ vector meson, and the heavier one corresponds to an effective heavy meson with mass $M_h = 2M$ to take accounts of the short range phenomenology. This parametrization allows us to extend the model for other regimes such as lattice QCD [5, 11, 13].

The $\gamma N \to P_{11}$ 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) on-mass-shell [14]:

$$\mathbf{J}^\mu = \sum_\Lambda \int d^3k \bar{\Psi}_R(P_-, k) f^\mu R \Psi_N(P_-, k),$$

$$= \bar{u}_R(P_+) \left( \gamma^\mu - \frac{q\gamma^\mu}{q^2} \right) F_1^+(Q^2) + \frac{i\sigma^\mu\nu q^\nu}{M_R + M} F^*_2(Q^2) u(P_+).$$

In the first line the sum is over the diquark states $\Lambda = \{s, \bar{s}, \lambda, \bar{\lambda}\}$, where $s$ and $\bar{s}$ stand for the scalar diquark and the vector diquark polarization, respectively, and the covariant integral is $\int_k \equiv \int d^3k/[2E_D(2\pi)^3]$, where $E_D$ is the diquark energy. 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 Roper $(u_R)$ and nucleon $(u)$ with the respective masses $M_R$ and $M$. For simplicity the spin projection indices are suppressed.

To represent the scalar wave functions as functions of $(P - k)^2$, we can use a dimensionless variable

$$\chi_B = \frac{(M_B - m_D)^2 - (P - k)^2}{M_B m_D},$$

where $M_B$ is the baryon mass. With this form, the nucleon and the Roper scalar wave functions are given by [14]:

$$\psi_N(P, k) = \frac{N_0}{m_D(\beta_1 + \chi_B)(\beta_2 + \chi_B)}.$$

$$\psi_R(P, k) = \frac{N_1}{\beta_3 - \chi_B m_D(\beta_1 + \chi_B)(\beta_2 + \chi_B)}.$$

The nucleon scalar wave function is chosen to reproduce the asymptotic form predicted by pQCD for the nucleon form factors ($G_E, G_F \sim 1/Q^4$) and to describe the elastic nucleon form factor data [4]. The parameters $\beta_1$ and $\beta_2$ are associated with the momentum range. With $\beta_2 > \beta_1$, $\beta_1$ and $\beta_2$ are the long-range and short-range regulators, respectively. The expression for the Roper scalar wave function is inspired by the nonrelativistic wave functions in the spherical harmonic potentials [1, 18, 19], where the factor $\beta_3 - \chi_B$ (linear in the momentum variable $\chi_B$) characterizes the radial excitation. The factors $N_0$ and $N_1$ are normalization constants given by the condition $\int_k |\psi|_B^2 = 1$ at $Q^2 = 0$ for $B = N, R$. The new parameter $\beta_3$, associated with the Roper, is fixed by the orthogonality with the nucleon wave function.
RESULTS

The results for the $\gamma N \to P_{11}(1440)$ transition form factors are presented in Fig. 1. Recall that all parameters associated with the Roper have been determined by the relation with the nucleon. Therefore, the results are genuine predictions. The agreement with the data is excellent for $Q^2 > 2 \text{ GeV}^2$, in particular for $F_i^\gamma$. Our results are also consistent with other work for the intermediate and high $Q^2$ region. See Ref. [14] for more details. In dynamical coupled channel models [20] the Roper appears as a heavy bare system ($\approx 1.750 \text{ MeV}$) dressed by meson clouds that reduce the mass of the system to near the observed mass ($\approx 1.440 \text{ MeV}$). To explore further this reduction of mass due to the meson clouds, we replace the physical mass by the ‘bare’ mass. The result is indicated by the dotted line. As one can observe from the figure the effect due to the Roper bare mass is small although it approaches very slightly to the data.

The disagreement in the low $Q^2$ region in Fig. 1 can be interpreted as a limitation of the approach, since only valence quark effects have been included, but not the quark-antiquark, or meson cloud effects. The meson cloud effects are expected to be important in the low $Q^2$ region [1, 2, 15]. This argument is supported by the fact that when the model extended to a heavy pion mass lattice QCD regime, where the meson cloud effect is suppressed, since the result agrees well the heavy pion mass lattice data [14, 17]. The importance of the meson cloud contributions in inelastic reactions was also observed in the $\gamma N \to \Delta$ reaction [7, 10, 11]. Furthermore, it was shown that the covariant spectator quark model can describe both the lattice and physical data [11]. Based on the successes in describing the heavy pion mass lattice QCD data and the high $Q^2$ region data, we have some confidence that the model can describe well the valence quark contributions. Thus, we can use the spectator quark model to estimate the meson cloud contributions.

To estimate the meson cloud contributions, we decompose the form factors as,

$$F_i^\gamma(Q^2) = F_i^b(Q^2) + F_i^{mc}(Q^2) \quad (i = 1, 2),$$

where $F_i^b$ and $F_i^{mc}$ represent the valence quark (bare) and meson cloud contributions, respectively. This decomposition is justified if the meson is created by the overall baryon but not by a single quark in the baryon core. Replacing $F_i^b$ by the result of the spectator quark model, one can estimate the meson cloud contributions in the $\gamma N \to P_{11}(1440)$ transition. We estimate the meson cloud contributions in two different ways as presented in Fig. 2 (left panel). One is based on the MAID fit made for the whole $Q^2$ region, and estimates the bands associated with the meson cloud assuming the uncertainty of the CLAS data points (red region). The other estimate is from CLAS data for each data point by subtracting the valence quark contribution. The results are represented by circles.

Similarly, the meson cloud contributions can be determined for the helicity amplitudes, $A_{1/2}$ and $S_{1/2}$, associated with the photon polarizations of $+1$ and $0$ respectively. Representing the corresponding amplitudes by $\tilde{R} = A_{1/2}$ and $S_{1/2}$, respectively, one can obtain the meson cloud contributions:

$$R^{mc}(Q^2) = R(Q^2) - R^b(Q^2).$$

The results are also shown in Fig. 2 (right panel). Both methods suggest the significant meson cloud effects for low $Q^2$ region ($Q^2 < 1 \text{ GeV}^2$), and a fast falloff with increasing $Q^2$.

In conclusion, the spectator quark model can be effectively applied to study the nucleon resonances, particularly in the intermediate and high $Q^2$ region, where the valence quark effects are dominant, and both the relativity and covariance are essential. Another example of a successful application of the present approach can be found in Ref. [21].

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FIGURE 2. $\gamma N \to P_1^1(1440)$ transition form factors (left) and amplitudes (right) [14], compared with the CLAS data (squares) [15], and the meson cloud contributions estimated from CLAS data (circles). The dashed line is the MAID fit from Ref. [16]. The bands represent the limits of the meson cloud contributions estimated from the MAID fit [14].

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