A covariant model for the $\gamma^* N \to N^*(1520)$ reaction

G. Ramalho[1,a] and M.T. Peña[2]

[1]International Institute of Physics, Federal University of Rio Grande do Norte, Av. Odilon Gomes de Lima 1722, Capim Macio, Natal-RN 59078-400, Brazil

[2]CFTP, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisboa, Portugal

Abstract. We apply the covariant spectator quark model to the study of the electromagnetic structure of the $N^*(1520)$ state ($J^P = \frac{3}{2}^-$), an important resonance from the second resonance region in both spacelike and timelike regimes. The contributions from the valence quark effects are calculated for the $\gamma^* N \to N^*(1520)$ helicity amplitudes. The results are used to parametrize the meson cloud dominant at low Q^2.

The electromagnetic structure of the nucleon (N) and the nucleon excitations (N^*) can be probed through the $\gamma^* N \to N^*$ reactions, with squared momentum transfer $q^2 < 0$ (spacelike region). Experimental facilities such as Thomas Jefferson Laboratory (Jlab), MIT-Bates and Mainz provide nowadays important information about those reactions for low and high Q^2, where $Q^2 = -q^2 > 0$ [1–3].

In order to interpret the data one has to rely on theoretical models based either on the fundamental QCD degrees of freedom, quarks and gluons, or effective ones. Although the microscopic dynamics refers to quarks and gluons, those degrees of freedom can be observed only at very high Q^2. At low and intermediate Q^2 more phenomenological descriptions with baryon and mesons or constituent quarks can be justified [1–4].

Among the constituent quark models the covariant spectator quark model (CSQM) [2, 5–8] was successfully applied to the nucleon [6], the $\Delta(1232)$ [9–11], to several others nucleon resonances such as the $N^*(1440)$ [12], the $N^*(1535)$ [13] and other baryons [14–17]. We apply now the CSQM to the $N^*(1520)$ state and $\gamma^* N \to N^*(1520)$ transition.

The state $N^*(1520)$ ($J^P = \frac{3}{2}^-$) is an important state, as it is the $N^*(1535)$ ($J^P = \frac{1}{2}^-$), from the second resonance region, and plays also an important role in the timelike region ($Q^2 < 0$). The extension of the CSQM to the timelike region was already made for the $\Delta(1232)$ [18]. The available data for the $\gamma^* N \to N^*(1520)$ transition, combined with model estimations suggest that valence quark effects dominate at high Q^2, while effects of the meson cloud dressing of the baryons can be significant at low Q^2 [1, 2, 19–21].

In the CSQM the wave function of the baryon B, Ψ_B, is determined by the baryon properties (flavor, spin, orbital angular momentum, etc.), and their symmetries, and the radial part represented by a scalar

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[a]e-mail: gilberto.ramalho2013@gmail.com

function ψ_B adjusted phenomenologically to the experimental electromagnetic form factor data, and lattice QCD data for some baryon systems [5, 7, 8]. According to the spectator theory, two of the quarks can be considered on-shell in the intermediate states and the third quark is free to interact with the electromagnetic probe. Integrating in the degrees of freedom of the quark-pair we can reduce the baryon to a quark-diquark system where the diquark is on-shell with effective mass m_D [6, 7, 22]. The quark electromagnetic current is described using vector meson dominance (VMD). The quark electromagnetic form factors are parametrized by some vector meson masses [6–8]. The vectors meson poles parametrize the *spatial extension* of the constituent quarks. VMD is very useful for the extrapolation of the model to other regimes such as the lattice regime [23] and the timelike regime [18]. Finally the electromagnetic current between two baryon states is obtained by taking the impulse approximation and summing in the individual quark currents [5–7, 22].

For the transition between the nucleon and the $N^*(1520)$ state, here labeled as R (for resonance), we need to construct the nucleon and the R wave functions. For the nucleon, we use the wave function derived in a work where the nucleon is described as a S-wave quark-diquark system [6]. For the R wave function we took a covariant generalization of the non relativistic form [4, 24]. The non relativistic form couples angular momentum states Y_{1m} ($m = 0, \pm 1$) in the diquark momentum k and in the relative quark-pair momentum r to three-spin states with different symmetries (mixed-symmetric, mixed-antisymmetric and totally symmetric). In principle the $N^*(1520)$ wave function is a combination of states with core spin (sum of the quark spins) 1/2 and 3/2, but hadronic decays suggests that the spin-3/2 admixture is small ($\sin \theta_D \approx 0.1 \ll 1$) [4].

In the transition between a $J^P = \frac{1}{2}^+$ (nucleon) and a $J^P = \frac{3}{2}^-$, like the $N^*(1520)$ state, one defines three independent electromagnetic form factors. In particular one can consider G_M, the magnetic dipole form factor, the function $G_4' = -(G_M + G_E)$, where G_E is the electric quadrupole form factor, and G_C, the Coulomb quadrupole form factor. Alternatively, one can use the *classic* helicity amplitudes, $A_{1/2}$, $A_{3/2}$ and $S_{1/2}$, in the R rest frame. One has then [24]

$$A_{1/2} \propto G_M + \frac{1}{4}G_4', \qquad A_{3/2} \propto G_4', \qquad S_{1/2} \propto G_C. \tag{1}$$

The form factors and the helicity amplitudes are functions of Q^2 only.

In the CSQM the transition form factors are written as a combination of quark electromagnetic form factors and the radial wave functions. The dependence on the radial wave functions is codified in a covariant function $I_z(Q^2)$, which is an *overlap integral*. In the R rest frame one has

$$I_z(Q^2) = \int_k \frac{k_z}{|\mathbf{k}|} \psi_R(P_R, k)\psi_N(P_N, k), \tag{2}$$

where P_R (P_N) are the R (nucleon) momentum and k the diquark momentum at the R rest frame. The integration symbol is a short notation for the covariant integration in k. A covariant generalization of the equation (2) can be derived in an arbitrary frame [24].

The orthogonality between the nucleon and the R state is expressed by the condition $I_z(0) = 0$. Based on this condition it is possible to construct a function $\psi_R(P_R, k)$ with one adjustable parameter that can be fitted to the data. The calculations using the spin-1/2 component of the R wave function lead to

$$A_{1/2} \propto I_z(Q^2), \qquad A_{3/2} \equiv 0, \quad S_{1/2} \propto \frac{I_z(Q^2)}{Q^2}. \tag{3}$$

According to equation (1) these results are a consequence of $G_4' \equiv 0$. The results for the valence quark contributions to the helicity amplitudes are presented in the Fig. 1 (dash-lines). Our fit of the function ψ_R was made for $Q^2 > 1.5$ GeV^2, a regime where we expect small meson cloud effects.

Although in the CSQM the quarks have structure, there are processes such as meson exchange between two different quarks inside the baryon, that cannot be interpreted just as quark dressing and have
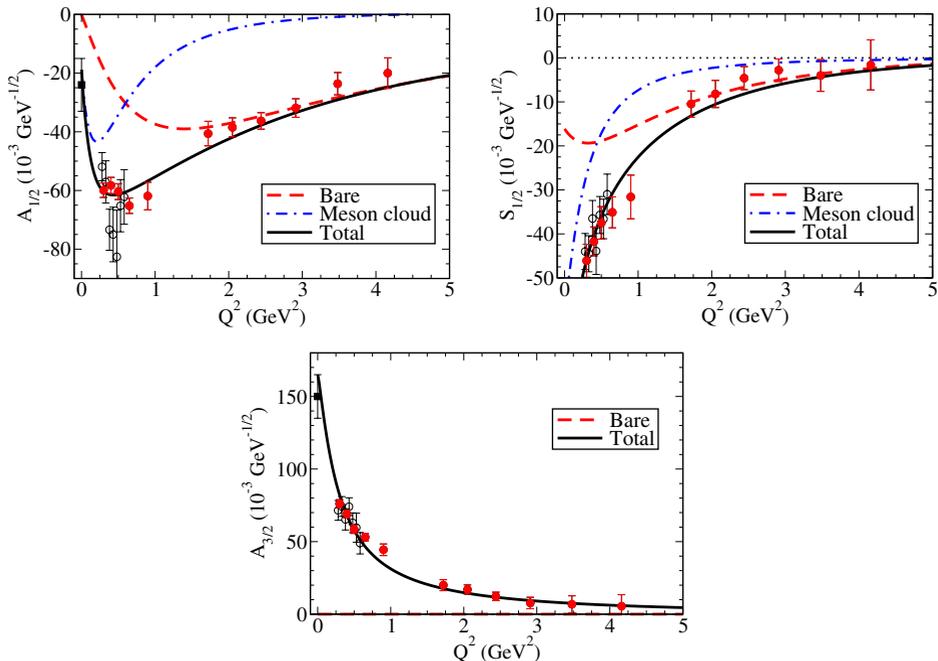
Figure 1. Helicity amplitudes for the $\gamma^* N \to N^*(1520)$ at the resonance rest frame. Valence quark (dash-line), meson cloud effects (dot-dashed line) and total (solid line). Data from CLAS/Jlab [19, 20]. Not included are the results from the MAID analysis [25].
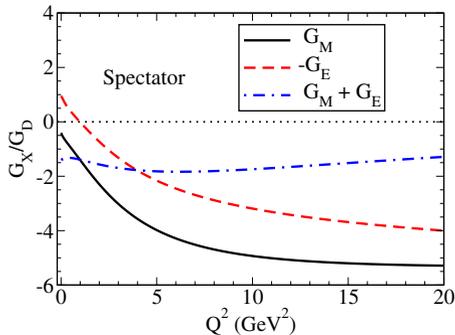

Figure 2. Results of the form factors G_M, $-G_E$ for very high Q^2. Scale extended to 20 GeV^2 (prediction to the Jlab-20 GeV update regime). Form factors normalized with $G_D = (1 + \frac{Q^2}{0.71})^{-2}$, where Q^2 is in GeV^2. Note the slow falloff of $G_M + G_E$ with Q^2.

to be classified at hadronic level as meson cloud [8, 14]. Assuming then that the CSQM gives a good description of the valence quark effects only, we used the model to extract the meson cloud contributions from the data. Since the pion is the dominant decay, we assumed a parametrization regulated by the pion with some effective momentum ranges (cutoffs) adjusted to the global data. The results of the fit are presented also in the Fig. 1 (dot-dashed lines). The solid line gives the final result (total).

From Fig. 1, one concludes that valence quark effects dominate the high Q^2 regime ($Q^2 > 1.5$ GeV^2) for the amplitudes $A_{1/2}$, $S_{1/2}$, although meson cloud effects are significant at low Q^2. As for $A_{3/2}$, only

the meson cloud contributes. This result differs from other quark model estimates, but it is consistent with the large meson cloud estimate from the EBAC group [21].

Finally we look at the results for the multipole form factors at very high Q^2, extending the model to the region of the Jlab 12-GeV upgrade. In the Fig. 2, we plot G_M, $-G_E$ and $G_M + G_E$, normalized by the dipole form factor G_D, for a better observation of the falloff of those form factors. Note the scaling of G_M, $-G_E$, and also the very slow falloff of $G_M + G_E$, that is negligible for very high Q^2, according to pQCD [26, 27] and also to the CSQM. Those results suggest that $G_M + G_E \simeq 0$ (or $G_E \simeq -G_M$), equivalent to $A_{3/2} \simeq 0$, happens only for very large Q^2.

The present parametrization of the $\gamma^* N \to N^*(1520)$ transition form factors in the spacelike regime can be extended to the timelike regime [28].

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