Study of the Hadronic Properties of N*'s in Electroproduction Reactions off the Deuteron

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One of the key windows for studies of nonperturbative QCD is the investigation of baryonic resonance properties. We address this problem studying the electroproduction of N^*'s from a deuteron i.e. $d(e,e'N^*)N$ using kinematics in which the dominant contribution arises when a resonance produced on one of the nucleons undergoes a soft elastic rescattering off the other (spectator) nucleon. Such experiments then offer the possibility of determining the specific properties of the baryonic resonance that are not possible to ascertain by studying production off a single nucleon.

One such property is the hadronic radius of the resonance, a quantity that is crucial for understanding the dynamics governing its composite hadronic structure. Indeed, in a quantum mechanical potential picture, at least for certain types of potentials, excited states have larger radii than ground states. Moreover, knowing the dependence of the radius on the quantum number of the excitation may allow one to determine the interaction.

The issue of the radius of excited hadronic states also crucial for understanding the duality between the quark-gluon and the hadronic descriptions of the strongly interacting system. To saturate the sum rule for the distribution of the cross section, one should assume a significant probability for the cross section to be larger than average. One of the ideas for realizing such *large cross sections* is to adopt *larger sizes* for hadronic resonances.

Another property of interest is the compositeness of the produced state - whether it be a single baryonic resonance or the superposition of multichannel $meson - baryon$ components with a strong attraction that makes a resonance-like quasi-bound system. From the point of view of the production of excited hadronic states from an isolated nucleon, it is difficult to identify a signature to distinguish a single baryonic resonance from a multichannel $meson - baryon$ system when some of the channels contain a strong attraction, thus imitating the resonance-like mass distribution.

What follows we calculate the cross section of the $d(e,e'N^*)N$ reaction and demonstrate that choosing specific kinematics of *double scattering* allow us to make these reactions greatly sensitive to the hadronic structure of the produced N^*'s.

Kinematics

We are considering the situation for which the N^* is produced off a nucleon with small Fermi momentum. To fix such kinematics we choose $x \equiv \frac{Q^2}{2mq_0}$ to be

$$x = 1 - \frac{m_R^2 - m^2}{Q^2 + m_R^2 - m^2}. \qquad (1)$$

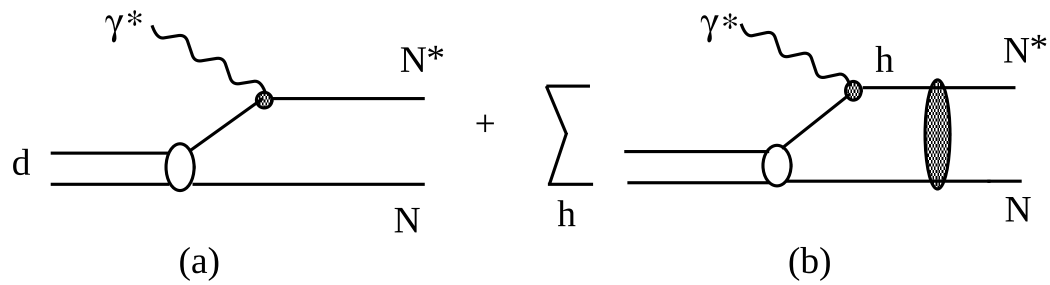

FIG. 1. Diagrams corresponding to the reaction $e + d \to e' + N^* + N$.

Here $-Q^2$ is the four-momentum squared of the virtual photon, and m and m_R are the masses of the nucleon and the resonance, respectively. $W^2 = (q + m_d - p_s)^2$ with $q \equiv (q_0, \mathbf{q})$ and $p_s \equiv (E_s, \mathbf{p}_s)$ being the four-momenta of virtual photon and spectator nucleon respectively. We also require that $\frac{E_s - p_{sz}}{m} \approx 1$, and $p_{st} \lesssim 0.4\ GeV/c$. The z axis is defined by the direction of virtual photon $\mathbf{q}$.

Cross Section of the Reaction

In general, the differential cross section of the $d(e, e'N^*)n$ can be represented as follows

$$\frac{d^6\sigma}{dE'_e d\Omega_e d^3p_s} = \frac{2\alpha}{Q^4}\frac{E'_e}{E_e}\eta_{\mu\nu}\bar{\sum_{s_i}}\sum_{s_f} F^{\mu}F^{\nu\dagger}, \tag{2}$$

where $\eta_{\mu\nu}$ is the leptonic tensor and $F^{\mu} = F^{\mu}_a + F^{\mu}_b$ is the electromagnetic transition amplitude of the deuteron [1].

Here, F^{μ}_a describes a transition amplitude within the impulse approximation (IA) when the resonance produced on one nucleon does not experience any further interaction (see Fig.1a):

$$F_a = (2\pi)^{\frac{3}{2}}\psi(p_s)A^{\mu}(Q^2), \tag{3}$$

where $A^{\mu}(Q^2)$ is the γNN^* transition amplitude and ψ is the deuteron wave function.

F^{μ}_b describes the amplitude where additional rescattering of the electromagnetically produced hadronic system is taking place (see Fig.1b). Our results is

$$F^{\mu}_b = -\frac{(2\pi)^{\frac{3}{2}}}{2}\sum_h \int \psi_d(p_s - k)A^{\mu}_h(Q^2)\frac{f^{hN\to N^*N}(k)}{[-k_z + \Delta + i\epsilon]}\frac{d^3k}{(2\pi)^3}, \tag{4}$$

where $\Delta = (E_s - m)\frac{E_f}{p_{fz}} - (p_{st} - p'_{st})\frac{p_{ft}}{p_{fz}} + \frac{W^2 - m_h^2}{2p_{fz}}$ [1].

In eq.(4), the only quantities to be specified are the electromagnetic transition amplitude $A^{\mu}_h(Q^2)$ and the soft rescattering amplitude $f^{hN\to N^*N}(p_s - p'_s)$.

Structure of $S_{11}(1535)$ resonance

Specifically we are considering the electroproduction of the $S_{11}(1535)$ resonance in the $d(e, e'S_{11})n$ reaction, where the neutron will be detected as a spectator. The choice of the $S_{11}(1535)$ is suggested by two important characteristics of this resonance: first, the $S_{11}(1535)$ has a large cross section for the electromagnetic NN^* transition and a weak $NN \to NN^*$ transition; and, second, the $S_{11}(1535)$ has a large $N\eta$ branching ratio (up to 55%), which makes it experimentally easily detectable.

To demonstrate how much the considered reactions are sensitive to the hadronic structure of the $S_{11}(1535)$ we apply two alternative frameworks in describing the $S_{11}(1535)$.

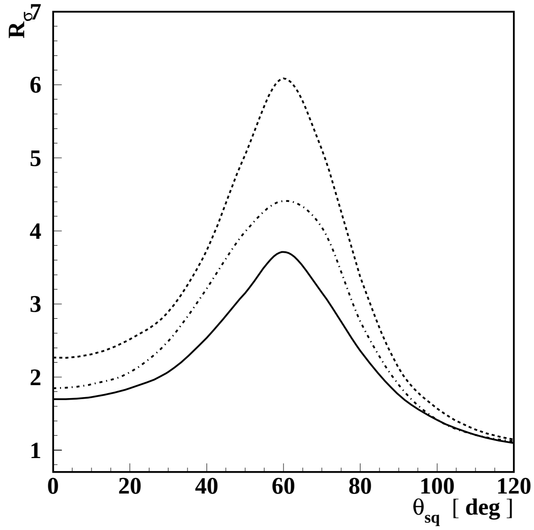

FIG 2: *Dependence of R_σ on the angle of the spectator nucleon with respect to* $\mathbf{q}$. *Solid line - f^{N^*N} taken as a NN elastic amplitude, dashed line - CQM prediction, dash-doted line - ECL predictin.*

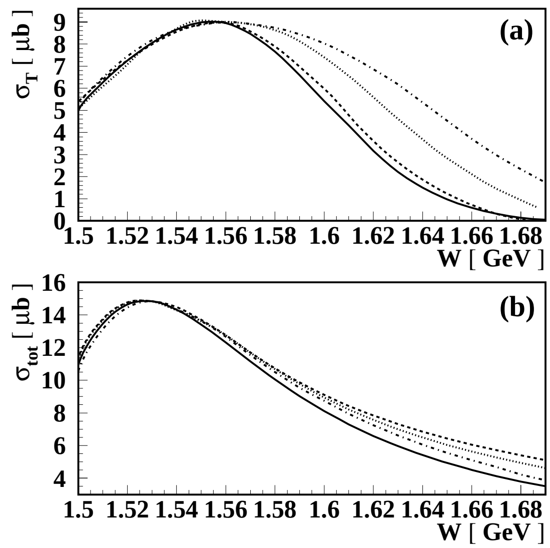

FIG 3: *(a): W dependence of σ_T calculated according to ECL. (b): W dependence of σ_{tot} calculated by CQM. Solid, dashed dotted and dash-doted curves corresponds to $p_{st} = 0, 200, 300, 400$ Mev/c respectively.*

CQM approach: One approach is based on the constituent quark model (CQM) [2], according to which the $S_{11}(1535)$ belongs to the $[70, 1^-]_1$ supermultiplet and represents an $L = 1$ radial excitation of the nucleon. In a typical constituent-quark model with a harmonic oscillator ansatz for the interacting potential (e.g, [2]), the larger radial extension of the $L = 1$ wave function means that the distribution of quarks in the S_{11} should be more spread out than the one for the nucleon. One can estimate the spatial distribution of quarks based on zero-order quark shell model of Ref. [2]:

$$< r^2 >= [(2N_\lambda + L_\lambda + 3/2) + (2N_\rho + L_\rho + 3/2)]b^2_{hosc}. \quad (5)$$

where b^2_{hosc} is the slope factor of the Harmonic Oscillator wave function of constituent quark. For the S_{11} one set of $(N, L) = (0, 0)$ and the other is $(0, 1)$. *This gives* $< r^2_{s11} >= 4b^2_{hosc}$.

Having estimated the rms of the S_{11} one can calculate the rescattering amplitude

$$f_{N^*N\to N^*N}(t) \approx i\sigma^{tot}_{N^*N}(1 + \alpha)e^{\frac{b}{2}t}, \quad (6)$$

where $\sigma^{tot}_{N^*N}$ is the total N^*N scattering cross section, b defines the slope factor of the elastic differential cross section, and α accounts for the real part of the amplitude. From phenomenology of soft hadronic interactions (see e.g. Ref.[3]): $\sigma^{tot}_{hN} = \sigma^{tot}_{NN}\frac{<r^2_h>}{<r^2_N>}$ and $b \approx \frac{1}{3}(< r^2_h > + < r^2_N >)$. Thus within CQM we where able to estimate the rescattering amplitude which enters into the eq.(4).

ECL approach: Second approach is based on the framework developed in Refs.[4,5], where effective potentials for the interaction of pseudoscalar Goldstone bosons (π, K, η) with octet baryons (N, Λ, Σ, Ξ) have been derived from an $SU(3)$ effective chiral Lagrangian (ECL). While solving a coupled-channel Schrödinger equation with the above mentioned potentials for the four-channel system of πN, ηN, $K\Lambda$, and $K\Sigma$ states with total isospin $\frac{1}{2}$, it was found in Refs.[4,5] that the properties of the $S_{11}(1535)$ can be well-described as an S-wave superposition of these four states. This approach naturally solves the problem of the large branching ratio of $S_{11}(1535)$ decay to ηN, showing it to be a consequence of the strong coupling of the πN and ηN channels to the $K\Sigma$ channel [4,5].

Within ECL one can describe the intermediate state of Fig. 1b by four $meson-baryon$ states, which then interact with the spectator nucleon. Such a picture will correspond to the Eq.(4) where sum goes over four intermediate states and rescattering amplitudes depends effective form-factors of the meson-baryon systems [1].

To assess the sensitivity of the reaction on the structure of S_{11} within CQM and ECL approaches we have calculated the following ratio

$$R_\sigma(p_{s1},p_{s2}) = \frac{\sigma(p_s \approx 400MeV/c)}{\sigma(p_s \approx 200MeV/c)}. \tag{7}$$

where $\sigma(p_s \approx 400MeV/c)$ and $\sigma(p_s \approx 200MeV/c)$ are the cross sections of $d(e,e'N^*)n$ with spectator momentum fixed 400 Mev/c and 200 Mev/c respectively. The choice of such kinematics is based on observation [6] that at $p_s \leq 200$ Mev/c the rescattering (4) screens the overall cross section while at $p_s \geq 400$ Mev/c it increases the cross section compared to the IA approximation. As a result the any change of the rescattering amplitude (4) because of the structure of the produced resonance will have the opposite contribution to the numerator and denominator of (7), making later very sensitive to the properties of the S_{11} interaction with the spectator nucleon.

In Figure 2 we represent the angular dependence of $R_\sigma(p_{s1},p_{s2})$ normalized by $R_{\sigma(IA)}$ calculated for $p_{s1} = 400$ and $p_{s2} = 200$ MeV/c. As follows from this figure, the CQM predictions corresponding to the larger resonance radius differ by a factor of 2 from those corresponding to an S_{11} whose radius has been taken equal to the nucleon radius (solid line).

Next we consider the mass (W) distribution of the produced resonance. Within ECL one expects that at larger W the contribution of larger mass intermediate states will increase, thus increasing the rescattering in the overall cross section. With CQM larger final masses corresponds to larger longitudinal momentum transfer and therefore less final state interaction on the tails of the W distribution. In Fig.3 we present the calculation of the W distribution of σ_t within ECL and calculation of $\sigma_{tot} = \sigma_t + \epsilon\sigma_l$ ($\epsilon = [1 + 2tan^2(\frac{\theta_e}{2})\frac{q^2}{Q^2}]^{-1}$) according to the CQM (in the later case we used the experimental parameterization for σ_{tot}^{proton}). The figures show different (opposite) patterns of broadening of the mass distribution due to final state interactions, calculated within ECL or CQM approaches.

Note that it will be very interesting to proceed with similar study to the region of the baryonic resonances with higher quantum excitation number. In this case one should expect to observe characteristic scaling relations between the rescattering contribution and the quantum numbers of the produced resonances.

References

1. L. Frankfurt, M. Johnson, M. Sargsian, M. Strikman, W. Weise, TUM/T39-98-13.
2. N. Isgur and G. Karl, Phys. Rev. **D28**, 4187 (1978); Phys. Rev. **D19**, 2653 (1979).
3. B. Povh and J. Hüfner, Phys. Rev. Lett. **58**, 1612 (1987).
4. N. Kaiser, P. Siegel, W. Weise, Phys.Lett.**B362**, 23 (1995); Nucl.Phys.**A594**,325 (1995).
5. N. Kaiser, T. Waas, W. Weise, Nucl. Phys. **A612**, 297 (1997).
6. L. Frankfurt, et al. Z.Phys **A352** 1995; Phys. Lett. **B369**, 201 (1996).