Nuclear response functions for the N-N*(1440) transition

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Abstract. We have obtained the response functions for the inclusive electroexcitation of the Roper resonance in nuclear matter, modeled as a relativistic Fermi gas, using various theoretical models of the $N-N^*(1440)$ transition form factors. The contributions of the Roper resonance to the Coulomb sum rule and to the asymmetry are also explored.

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Parity-conserving (PC) inclusive electron scattering from nuclei is a relevant source of information about many important aspects of the nuclear many-body problem. Parity-violating (PV) electron scattering goes further by opening the possibility of obtaining new information on nucleon structure. A basic motivation for studying PV asymmetries in nuclei is that a proton alone is insufficient when attempting to disentangle all of nucleon's form factors (FF).

The regions of the quasielastic (QE) and the $\Delta(1232)$ peaks have been extensively studied. However, there is increasing interest in the so called second resonance region, where the $N^*(1440)$ (Roper), $N^*(1520)$ and $N^*(1535)$ resonances are found. The Roper is the most puzzling of those states. It is usually viewed as a radial excitation of the nucleon, but the standard non-relativistic constituent quark model (NRQM) fails to describe its properties. This outcome has prompted further studies. All of them predict specific behaviors for the electroproduction amplitudes $A^{p,n}_{1/2}$, $S^{p,n}_{1/2}$, which has consequences for the nuclear response functions. Here we use as input for our calculations the helicity amplitudes obtained in the NRQM [1], a hybrid model, in which the Roper has a gluonic component [1], a light-front relativistic quark model (LF) [2], a chiral chromodielectric one (ChD) [3] and a model with extended vector-meson dominance (EVMD) [4].

Using the relativistic Fermi gas model, the PC response functions can be written in terms of the single-nucleon tensor, which carries the dynamical information. For the $N-N^*(1440)$ transition, the tensor is given by [5]

$$f^{\mu\nu} = \frac{1}{2}\frac{W}{m_N}\mathrm{Tr}\left[\frac{(\not{p}+m_N)}{2m_N}\left(\gamma_0 J^{\dagger\mu}\gamma_0\right)\frac{(\not{p}'+W)}{2W}J^\nu\right], \tag{1}$$

with W being the invariant mass of the resonance. The electromagnetic (em) current is a function of two FF, which can be related to the helicity amplitudes

$$J^\alpha = \bar{u}_{N^*}(p')\left[F_1(q^2)\left(\not{q}q^\alpha - q^2\gamma^\alpha\right) + iF_2(q^2)\sigma^{\alpha\beta}q_\beta\right]u(p). \tag{2}$$

The results for a ${}^{12}C$ nucleus shown in Fig. 1 are clearly different for the various models. In the transverse channel, the Roper contribution is negligible compared to the Δ one. Indeed, the strong $N-\Delta\ M1$ transition appears at full strength in this observable. The situation is different in the longitudinal channel where the Δ response is tiny. Hence,

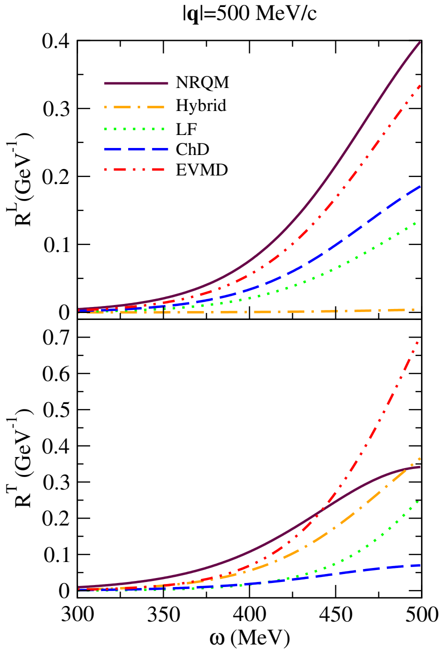

FIGURE 1. Electromagnetic longitudinal and transverse $N-N^*(1440)$ responses.

the Roper could have a considerable impact on the Coulomb sum rule (the integral of R^L over the energy transfer in the space-like region). This can be seen in Fig. 2, where we show the following ratio

$$\mathscr{R}(|\vec{q}|) = \frac{\int_0^{|\vec{q}|} d\omega \left[R^L_{QE}(|\vec{q}|,\omega) + R^L_{\Delta,N^*}(|\vec{q}|,\omega) \right]}{\int_0^{|\vec{q}|} d\omega R^L_{QE}(|\vec{q}|,\omega)} . \tag{3}$$

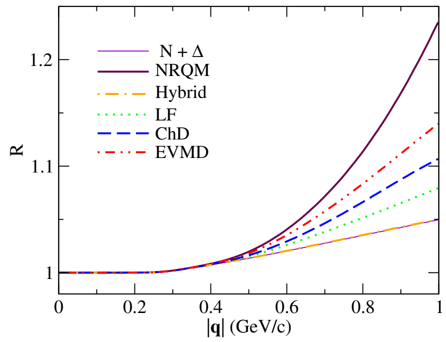

FIGURE 2. Coulomb sum rule. The thin line includes only the Δ and the thick ones – both Δ and Roper.

The PV responses are calculated in a similar way. Now the single-nucleon tensor arises from the interference between the em and the weak neutral currents. The later contains a vector part, with the same structure as the em current, and an axial part given by

$$J_A^\alpha = \bar{u}_{N^*}(p')\left[\widetilde{G}_A\gamma^\alpha\gamma_5 + \widetilde{G}_P q^\alpha\gamma_5\right]u(p) \tag{4}$$

as in the nucleon case. Lacking any information about $\widetilde{G}_A$, we take

$$2\widetilde{G}_A^{p(n)} = G_A^{p(n)} - G_A^{n(p)} = \pm 2 f_\pi \frac{\tilde{f}}{m_\pi}\left(1-\frac{q^2}{M_A^2}\right)^{-2}, \tag{5}$$

where the value at $q^2 = 0$ has been derived assuming pion pole dominance in the divergence of the axial current; $\tilde{f}$ is the $N^* \to N\pi$ coupling. The dipole form for the q^2 dependence is inspired by the analogous behavior of the nucleon axial FF. $\widetilde{G}_P$ can be related to $\widetilde{G}_A$ if one assumes PCAC but it does not contribute to the PV responses.

In Fig. 3 we show the asymmetry including the QE contribution, the Δ and the $N^*(1440)$ at $|\vec{q}| = 1000$ MeV$/c$ for a forward and a backward angles. In some models, the Roper contribution changes the asymmetry above the QE peak appreciably. Nevertheless, the striking effect predicted in [6], namely of an increase in magnitude of the asymmetry of about a factor three occurring at forward angles in passing from the QE to the Δ peak domain, still persists.

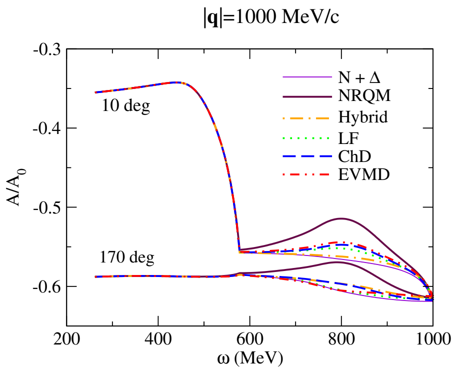

FIGURE 3. The asymmetry in the $N+\Delta$ (thin solid line) and $N+\Delta+N^*$ cases. The contribution of the Roper is displayed for the various models of the transition amplitudes.

To conclude, we should stress that our treatment of nuclear effects is restricted to the inclusion of Fermi motion. More work is required in order to treat the second resonance region with the same level of sophistication achieved for the Δ and the QE peaks.

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