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THE ROPER RESONANCE REVISITED

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Different approaches to the Roper resonance are reviewed, revealing the multiple facet of this state and the need for some crucial experiments.

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1. *Introduction*

The first excited state of the nucleon, the Roper resonance, seems to be a complicated object, characterized by its relatively low energy and by a rather peculiar behaviour of electroexcitation amplitudes, in particular the sign at $Q^2 = 0$, which cannot be reproduced in the framework of the non-relativistic quark model. Several models have been suggested to explain these features. On one hand, the predictions for the amplitudes are not yet conclusive, and on the other hand, the Q^2-dependence of the electroproduction is poorly measured. Therefore, it would be very important to perform new measurements in order to distinguish different models. We shall confront three classes of models:

- *The constituent quark model*
- *The breathing model*
- *Explicit non-quark degrees of freedom*

2. The constituent quark model

The dynamics in the three-quark Hilbert space has to mimic non-quark degrees of freedom by a corresponding effective quark-quark interaction. The Graz group [1] has shown, that one can get the Roper resonance lower than the negative parity excited states with a pion exchange interaction (while the one-gluon exchange interaction gives Roper resonance above negative parity states). It is still not known whether the Graz interaction is also sufficient to reproduce the amplitudes. If they use correct relativistic boosts, they get good elastic electromagnetic form factors. For inelastic processes (such as the electroexcitation of the Roper resonance) they have still many open questions regarding relativity, two-body currents, spin-orbit and tensor forces and vector meson exchanges; their work is in progress.

The importance of a correct relativistic treatment in CQM calculations of the EM amplitudes has been stressed by [2−4] yielding the correct sign at the photon point. In all of these approaches, the change of the amplitudes sign around $Q^2 \sim 0.2$–0.5 $(\mathrm{GeV}/c)^2$ is predicted – a feature that is absent in other approaches discussed below. This behaviour may therefore represent a crucial test of the model when more precise measurements will be available.

3. The breathing model

The explanation that the Roper state is a breathing mode seems physically plausible, but in addition to the three quarks also the chiral field (pions, sigmas) and the confining field (the *chromodielectric bag* or *glueball field*) should breathe. Obviously, with more degrees of freedom, the "inertial parameter" increases, lowering the vibration frequency.

A convenient relativistic model for the breathing mode is the chiral chromodielectric model with the Lagrangian [5]:

$$\mathcal{L} = \mathrm{i}\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi + \frac{\mathrm{g}}{\chi}\,\bar{\psi}(\hat{\sigma} + \mathrm{i}\boldsymbol{\tau}\cdot\hat{\boldsymbol{\pi}}\gamma_5)\psi + \mathcal{L}_{\sigma,\pi} + \mathcal{L}_{\chi}\,, \tag{1}$$

where

$$\mathcal{L}_{\chi} = \frac{1}{2}\partial_{\mu}\hat{\chi}\,\partial^{\mu}\hat{\chi} - \frac{1}{2}M^2\,\hat{\chi}^2\,, \quad \mathcal{L}_{\sigma,\pi} = \frac{1}{2}\partial_{\mu}\hat{\sigma}\partial^{\mu}\hat{\sigma} + \frac{1}{2}\partial_{\mu}\hat{\boldsymbol{\pi}}\cdot\partial^{\mu}\hat{\boldsymbol{\pi}} - \mathcal{U}(\hat{\boldsymbol{\pi}}^2 + \hat{\sigma}^2)\,, \tag{2}$$

and $\mathcal{U}$ is the usual Mexican hat potential.

A non-chiral version of this model has been used to describe coupled vibrations of valence quarks and the background chromodielectric field in the framework of the RPA [6]. The energy of the lowest excitation turned out to be 40 % lower than the pure 1s–2s excitations. A similar result was obtained by Guichon [7], using the MIT bag model and considering the Roper resonance as a collective vibration of valence quarks and the bag.

The inclusion of chiral mesons, in particular the σ-meson which accounts for the $(\pi\pi)^{I=0}_{\mathrm{s-wave}}$ N decay, can further decrease the energy of the Roper resonance. The Ljubljana/Coimbra group [8, 9] has described the Roper resonance as a superposition of quark excitations coupled to the “breathing” chromodielectric field (see Fig. 1) and the lowest vibrational mode of the σ-field on top of the ground state

$$\Psi_{\rm Roper} = \frac{c_1}{\sqrt{1-c^2}}\left((1s)^2(2s) - c(1s)^3\right) + c_2\hat{a}^\dagger_\sigma\,(1s)^3 .$$

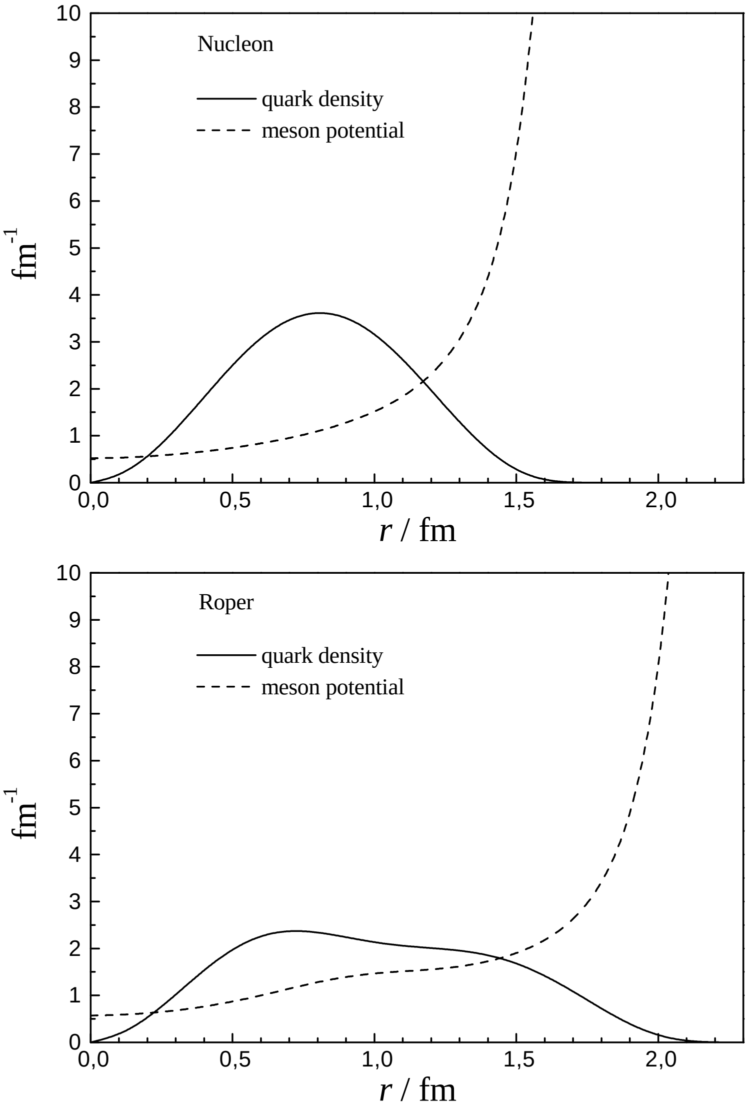

Fig. 1. The baryon densities (solid lines) and the effective potentials (dashed lines) generated by the self-consistently determined π, σ and χ fields in the nucleon and the Roper. One can see the broader density distribution and softer effective potential in the case of Roper.

For a sufficiently low mass of the σ-meson, the inclusion of the σ vibration can lower the energy of the Roper resonance. Furthermore, since the photon is not coupled to this mode, the electroproduction amplitudes are reduced compared to those calculated from the quarks alone.

The important role of the σ-meson has been also found by Kukulin and collaborators [10, 11]. Here the σ-meson is coupled to the $(1s)^1(1p)^2$ quark configuration rather than to the $(1s)^2(2s)^1$.

The presence of σ-meson vibrations is consistent with the recent phase shift analysis by Krehl et al. [12] who found that the resonant behaviour in the P_{11} channel can be explained solely through the coupling to the σ-N channel, without assuming any internal (i.e. quark) radial excitation of the nucleon. In our view, radial excitations of quarks are needed in order to explain relatively large electroproduction amplitudes, which would indicate that the σ-N channel couples to all nucleon $\frac{1}{2}^+$ excitations rather than to the Roper resonance alone.

4. *Explicit non-quark degrees of freedom*

The "hybrids" (the non-quark degrees of freedom) can be incorporated, together with mesonic degrees of freedom, in a superposition

$$\Psi_{\mathrm{Roper}} = c_{qqq}\psi_{qqq} + c_{qqq\pi}\psi_{qqq\pi} + c_{qqq\sigma}\psi_{qqq\sigma} + c_{qqqG}\psi_{qqqG} + c_{qqqg}\psi_{qqqg} + \cdots ,$$

with an obvious notation (G = glueball, g = gluon). Several authors estimated it [12 − 14] and their suggestions are still inconclusive. Experiment is called for to "determine" the expansion coefficients c.

Krehl et al. [12] coupled the πN, σN, $\pi\Delta$ and ηN channels for the phase shifts, showing the importance of the σ excitation, as mentioned before. Li et al. [13] consider the Roper resonance as a $qqqg$ hybrid with the glue field excited; then the transverse helicity amplitude decreases rapidly with Q^2, while the longitudinal one vanishes. Carlson et al. [14] also argue that the Roper resonance might be a $qqqg$ hybrid characterized with the suppression of the transverse electroproduction; the transverse-to-longitudinal ratio is proposed as a good diagnostics.

5. *The meson-nucleon-Roper coupling*

The virtual Roper state can play an important role in three-body nuclear forces in a process in which tree nucleons N_1, N_2 and N_3 exchange mesons in the following way:

$$N_1 \to N_1 + \pi, \quad N_2 + \pi \to N^* \to N_2 + \sigma, \quad N_3 + \sigma \to N_3 \,.$$

Therefore, the knowledge of the $g_{\pi NN^*}$ and $g_{\sigma NN^*}$ couplings is of interest. They can be deduced from partial width of the Roper resonance decays, but this experimental input is still very rough. For $\Gamma = 350 \pm 100$ MeV and branching ratios 60 − 70%

$(5-10\%)$ for the $\mathrm{N}\pi$ ($\mathrm{N}\sigma$) channel, it follows $g^2_{\pi\mathrm{NN}^*}/4\pi = 3.4 \pm 1.2$ and $g^2_{\sigma\mathrm{NN}^*}/4\pi = 0.34 \pm 0.21$. The latter value is too uncertain to decide whether the cancellation between the σ and ω exchange will lead to an attractive or repulsive contribution to nuclear forces.

An alternative analysis using the photoproduction of ρ or ω has been proposed by Madeleine Soyeur [15]:

$$[(\gamma \to \omega) + \mathrm{p}\ \overrightarrow{(\pi^0 - \text{exchange})}\ \rho^0 + \mathrm{N}^{*+}] + [(\gamma \to \rho^0) + \mathrm{p}\ \overrightarrow{(\sigma - \text{exchange})}\ \rho^0 + \mathrm{N}^{*+}],$$

and analogously for ω. While the photoproduction of ρ is sensitive to $g_{\pi\mathrm{NN}^*}$, the photoproduction of ω is sensitive to $g_{\sigma\mathrm{NN}^*}$. Accurate measurements are recommended.

6. *Conclusion*

While several models can explain the low excitation energy of the Roper resonance, they do differ in their predictions regarding the sign, magnitude, transverse-to-longitudinal ratio and σ-to-ω branching ratio of electroproduction amplitudes. Accurate experiments are called for to resolve these issues as well as the Q^2-dependence of the amplitudes.

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RAZMATRANJE ROPEROVE REZONANCIJE

Dajemo pregled nekoliko mogućih tumačenja Roperove rezonancije, te ukazujemo na složenost tog stanja, kao i na potrebu za novim mjerenjima.