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Structure of the Roper resonance from pion electro-production experiments

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Abstract. The $P_{11}(1440)$ (Roper) resonance remains one of the least understood excited states of the nucleon. Relevant open issues of the theoretical and phenomenological analyses of the Roper are identified, and a proposal for a study of the Roper in a pion electro-production experiment with double-polarization observables is given.

1 Introduction

The $P_{11}(1440)$ (Roper) resonance [1] is the lowest positive-parity $N^\star$ state. It is visible only indirectly in partial-wave analyses of $\pi N \to \pi N$ and $\pi N \to \pi\pi N$ scattering as a shoulder around 1440 MeV with a large width. The Roper is buried underneath the Born backgrounds and merges with the tails of other neighbouring resonances (in particular the $P_{33}(1232)$, $D_{13}(1520)$, and $S_{11}(1535)$), and thus can not be resolved from the W-dependence of the cross-section alone. Furthermore, the methods by which the masses and widths of the Roper have been determined, differ significantly: from πN scattering, a Breit-Wigner mass of ~ 1470 MeV and width of ~ 350 MeV is extracted, while a speed-plot analysis (local maxima of $|dT/dW|$) yields ~ 1375 MeV and ~ 180 MeV, respectively [2]. In addition, due to its high inelasticity, the Roper resonance has a very atypical behaviour of $\mathrm{Im}T_{\pi N}$ and exhibits multiple T-matrix poles in the complex energy plane on auxiliary Riemann sheets.

Although this four-star resonance is within the energy range of many modern facilities, the experimental analyses so far have not ventured far beyond the determination of its mass, widths, and photon decay amplitudes. Very little is known about its internal structure.

2 Two "standard" views of the Roper

The photo-couplings and helicity amplitudes of the Roper resonance have been computed in a multitude of approaches, and have yielded a set of predictions which at this stage can not be conclusively confirmed or ruled out by data. In the SU(6) quark model, the Roper can be understood as a radial excitation of the proton to the $(1s)^2(2s)^1$ configuration. This excitation results in a "breathing mode" of the proton, implying a sizable Coulomb monopole contribution (C0 or S_{1-}). Some models describe the Roper as a gluonic partner of the proton, representing it as a (q^3g) hybrid baryon with three quarks oscillating against explicitly excited configurations of the gluon fields. In this picture, the C0 strength should thus be highly suppressed, implying a predominantly magnetic dipole transition (M1 or M_{1-}), in contrast to the concept of "breathing". These two opposing concepts result in rather different predictions for the Q^2-dependence of the transverse ($A^p_{1/2}$) and scalar ($S^p_{1/2}$) electro-production helicity amplitudes shown in Fig. 1. Of course, numerous other approaches have been suggested (see e.g. [3] for a review).

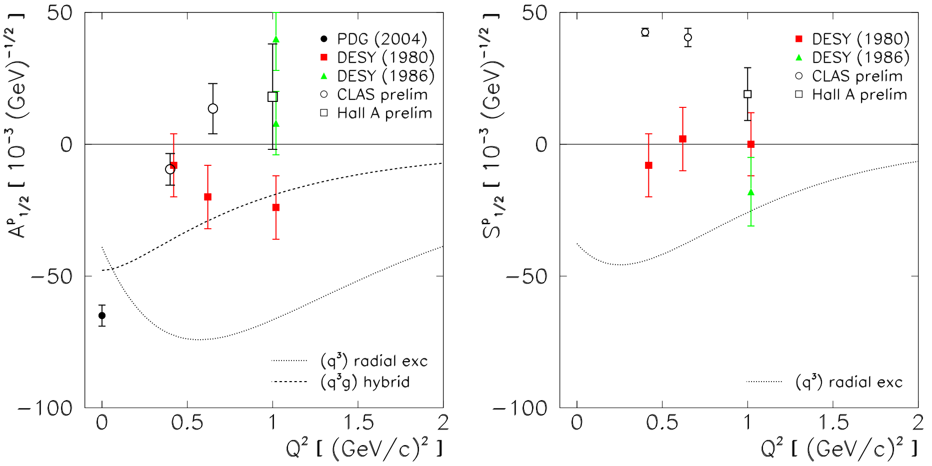

Fig. 1. Nucleon-Roper transverse (left) and scalar (right) helicity amplitudes for the charged (proton) state. The curves are for a Roper as a radially excited (q^3) state or a (q^3g) hybrid state.

3 Assessment of experimental situation

Experimentally, the Q^2-dependence of the helicity amplitudes is not well known (see Fig. 1). A re-analysis of old DESY and NINA electro-production experiments yielded $S^p_{1/2}$ consistent with zero, and gave contradictory results for the $A^p_{1/2}$. The lack of (double)-polarized measurements is, to a great extent, responsible for such large uncertainties. Newer, polarized experiments at Jefferson Lab have yielded more precise values of $S^p_{1/2}$ at $Q^2 = 0.4$ and $0.65\,(\text{GeV}/c)^2$. The $A^p_{1/2}$ has also been extracted at $Q^2 = 0.4$, 0.65, and $1.0\,(\text{GeV}/c)^2$. It appears to exhibit a zero-crossing in the vicinity of $Q^2 = 0.5\,(\text{GeV}/c)^2$, although the situation remains unclear due to limited Q^2-coverage and modest error-bars.

Kinematically most extensive data sets on single-pion electro-production in the Roper region come from Hall B of Jefferson Lab. Angular distributions and

W-dependence of the electron beam asymmetry $\sigma_{LT'}$ have been measured for both channels in the $P_{33}(1232)$ region at $Q^2 = 0.4$ and $0.65\,(\mathrm{GeV}/c)^2$ [4,5]. A complete angular coverage was achieved, and different non-resonant amplitudes were be separated in a partial-wave analysis. The Legendre moments D'_0, D'_1, and D'_2 of the expansion were determined. The D'_1 appears to be sensitive to higher resonances, with contributions of about $15-20\,\%$ coming mainly from the $\mathrm{Im}(M^*_{1-}S_{1+})$ interference, pointing to the relevance of the Roper.

Dispersion-relation techniques and unitary isobar models have been applied to analyze the CLAS $\sigma_{LT'}$ data at $Q^2 = 0.4$ and $0.65\,(\mathrm{GeV}/c)^2$ spanning also the second resonance region, in order to extract the contributions of the $P_{33}(1232)$, $P_{11}(1440)$, $D_{13}(1520)$, and $S_{11}(1535)$ resonances to single-pion production. Since both the $p\pi^0$ and the $n\pi^+$ channel were measured (facilitating isospin decomposition), the transverse helicity amplitude $A^p_{1/2}$ as well as the scalar $S^p_{1/2}$ could be extracted. The results show a rapid fall-off of $A^p_{1/2}$ and indicate its zero-crossing at $Q^2 \sim 0.5-0.6\,(\mathrm{GeV}/c)^2$ shown in Fig. 1. It was also shown that $\sigma_{LT'}$ is mainly sensitive to the imaginary part of $P_{11}(1440)$, while the cross-section is sensitive to the real part of the P_{11} multipoles.

In Hall B, further experiments will be devoted to single-pion photo-production in both $p(\gamma,\pi^+)n$ and $p(\gamma,p)\pi^0$ channels, with polarized beam and longitudinally as well as transversely polarized target using the CLAS detector. There is also a competing real-photon experiment of the A2 Collaboration at MAMI devoted to the measurement of polarized asymmetry G.

These uncertainties, in particular the location of the zero-crossing in Q^2, are motivating the Hall A study of the Roper by means of double-polarization observables. A measurement over a broad range of W and Q^2 would provide us with a rich data set on the transition amplitudes in electro-production.

4 Lessons learned from E91-011

Polarized electron beam and recoil-polarimetry capability of Hall A allow access to double-polarization observables in single-pion electro-production. Recoil-polarization observables are composed of different combinations of multipole amplitudes than observables accessible in the case of a polarized target. In the sense of experimental method, the measurements of Hall A would be complementary to the efforts with CLAS in Hall B.

A complete angular coverage of the outgoing hadrons to the extent of the CLAS detector in not possible in Hall A due to relatively small angular openings of the Hall A HRS spectrometers *except* at high Q^2 where the Lorentz boost from the center-of-mass to lab frame focuses the reaction products into a cone narrow enough to provide a virtually complete out-of-plane acceptance. The E91-011 neutral-pion electro-production experiment in Hall A [6] was performed at sufficiently high $Q^2 = (1.0 \pm 0.2)\,(\mathrm{GeV}/c)^2$ and $W = (1.23 \pm 0.02)\,\mathrm{GeV}$ to allow for a measurement of all accessible response functions, even those that vanish for coplanar kinematics. Two Rosenbluth combinations and 14 structure functions were separated, allowing for a restricted partial-wave analysis giving access to all $l \leq 1$ multipole amplitudes relevant to the $N \to \Delta$ transition. Both extracted M_{1-} and S_{1-} multipoles [6] in the $p\pi^0$ channel indicate a rising trend approaching the $W \sim 1440$ MeV region, pointing towards the Roper.

Unfortunately, the cross-sections at $W \sim 1440$ MeV (for any Q^2) are about an order of magnitude smaller than in the Δ-peak. For high $Q^2 \sim 1\,(\mathrm{GeV}/c)^2$, where a large out-of-plane coverage would allow for a decent partial-wave analysis in Hall A, the cross-sections are even smaller. Furthermore, due to the zero-crossing uncertainty of the M_{1-} multipole, it is not clear what value of Q^2 to choose in order to have a prominent $M1$ signal. Furthermore, models indicate that the crucial features of the Roper multipoles (or helicity amplitudes) are visible at relatively small Q^2 of a few $0.1\,(\mathrm{GeV}/c)^2$, nullifying the boost-advantage of the HRS.

We believe that a measurement in the spirit of the E91-011, attempting a precise extraction of the Roper multipoles from a complete partial-wave analysis at a *single* Q^2-point, is not the most effective strategy at this moment. Instead, we believe that a precise measurement of a more restricted set of double-polarization observables, highly sensitive to the Roper multipoles, and spanning a broad range in Q^2 and W, would yield a more rewarding and critical insight into the structure of the $N \to R$ transition through comparison with models.

5 Options for a Roper experiment in Jefferson Lab Hall A

We believe that an attempt at a large-scale analysis of the Roper multipoles, aiming at a complete partial-wave analysis at a single Q^2-point in the spirit of the $N \to \Delta$ experiment E91-011 [6], presently may not be the most effective approach to study the structure of the $N \to R$ transition. We are working on designing an experiment that would measure recoil polarization components which exhibit high sensitivities to the Roper resonant multipoles and span a broad range in Q^2 and W. It is this extended coverage that would allow for a more instructive study of the transition through comparison with models.

In anti-parallel kinematics for the $p(\mathbf{e}, e'\mathbf{p})\pi^0$ process, the polarization components of the ejected proton P_x' and P_y have the following multipole structure:

$$\begin{aligned} P_x' \sim R_{LT'}^{t} = \mathrm{Re}\{ & L_{0+}^* E_{0+} \\ & + (L_{0+}^* - 4L_{1+}^* - L_{1-}^*) M_{1-} + L_{1-}^* (M_{1+} - E_{0+} + 3E_{1+}) \\ & - L_{0+}^* (3E_{1+} + M_{1+}) + L_{1+}^* (4M_{1+} - E_{0+}) + 12 L_{1+}^* E_{1+} \,, \qquad (1) \\ P_y \sim R_{LT}^{n} = - \mathrm{Im}\{ & \cdots \} \,. \qquad (2) \end{aligned}$$

The $L_{0+}^* E_{0+}$ interference is relatively large and prominent in all kinematics. The combinations $L_{1-}^*(-E_{0+} + 3E_{1+})$ and $(-4L_{1+}^* - L_{1-}^*)M_{1-}$ involving M_{1-} and/or L_{1-} are either relatively small or cancel substantially. The terms largest in magnitude and sensitivity are the $L_{0+}^* M_{1-}$ and the $L_{1-}^* M_{1+}$ each involving one of the relevant Roper multipoles linearly. The contributions of the M_{1-} and S_{1-} multipoles to P_x' and P_y depend strongly on Q^2 and W, so a measurement of P_x' and P_y in a broad range of Q^2 and W would allow us to quantify these dependencies.

We are considering performing two W-scans at fixed momentum transfers of Q^2 of 0.13 and $0.33\,(\mathrm{GeV}/c)^2$ to explore the behaviour on and away from the resonance position, and a more extensive Q^2-scan at the resonance position $W = 1440\,\mathrm{MeV}$, with two overlapping settings. The W-scans could be performed at relatively small Q^2 because the predicted asymmetries and their sensitivities to the relevant multipoles appear to be largest there. Two beam energies (2 and 3 GeV) could be used. The lower beam energy is needed in order to accommodate the low-Q^2 end of the Q^2-scan (and the corresponding W-scan) without running into the geometrical limits of the HRS spectrometers in Hall A. The proposed kinematics coverage is illustrated in Fig. 2.

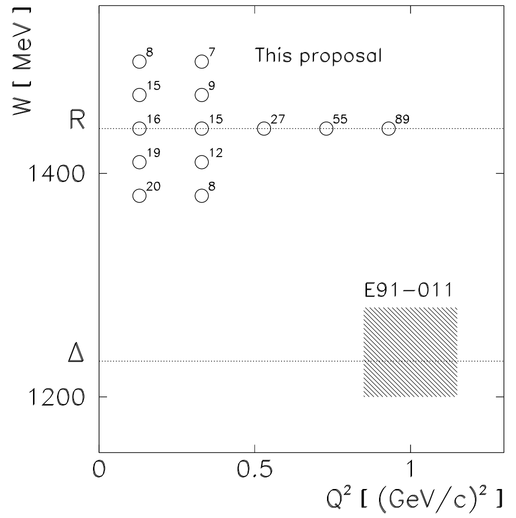

Fig. 2. The kinematic coverage in W and Q^2 of the E91–011 experiment in Hall A (hatched area) and of the present proposal.

The sensitivity of P_y to the resonant Roper multipoles M_{1-} (proportional to the helicity coupling $A^p_{1/2}$) and S_{1-} (proportional to $S^p_{1/2}$) is different at low and high Q^2, and varies through the W-range. At $Q^2 = 0.13\,(\mathrm{GeV}/c)^2$ (Fig. 3 left), the full prediction for P_y at the resonance position is almost +100 %, with comparable M_{1-} and S_{1-} contributions, while it is close to zero with the Roper switched off. At $Q^2 = 0.33\,(\mathrm{GeV}/c)^2$, P_y drops to about +40 % (Fig. 3 right), dropping to about −40 % with the Roper switched off, with different roles of M_{1-} and S_{1-}. At high $Q^2 = 0.73\,(\mathrm{GeV}/c)^2$ and above (not shown), the full P_y is about −50 %, and only S_{1-} plays an appreciable role.

The role of the resonant multipoles changes very quickly, resulting in dramatic changes in the polarization components on a relatively narrow range in W (about ±60 MeV away from the resonance position to each side plus some additional coverage due to extended acceptance). The P_y being so large (on the order of several tens of %), a measurement in a broad range of Q^2 and W would therefore enable us to study its dependencies quite precisely.

The W-dependencies of both P'_x and P'_z become washed out at high Q^2. However, the large asymmetries persist in P_y and, to some extent, also in the P'_x. A measurement of the Q^2-dependence of P_y and P'_x (see Fig. 4) therefore gives us yet another handle to quantify the role of the individual multipoles, and can be mapped onto the zero-crossing of the $A^p_{1/2}$ helicity amplitude.

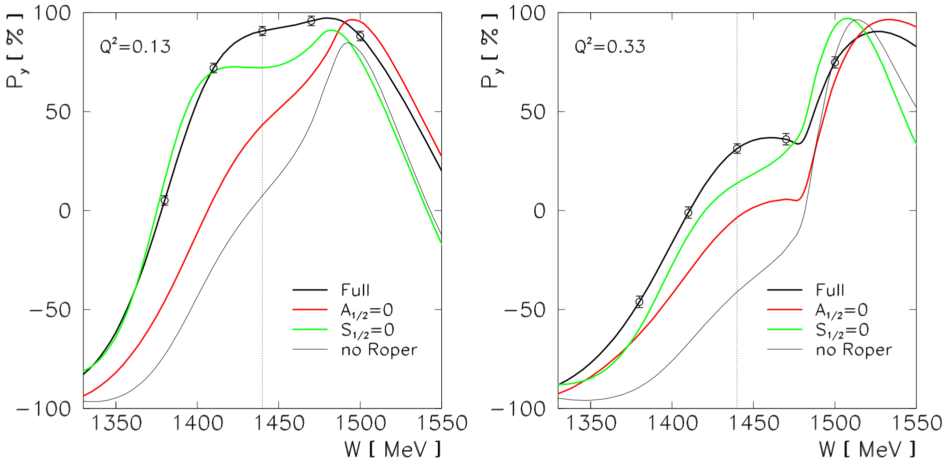

Fig. 3. Sensitivity of P_y to the resonant Roper multipoles M_{1-} (helicity amplitude $A^p_{1/2}$) and S_{1-} ($S^p_{1/2}$), as a function of W at $Q^2 = 0.13$ and 0.33 $(\mathrm{GeV}/c)^2$. The expected statistical uncertainties of the proposed measurement are also shown.

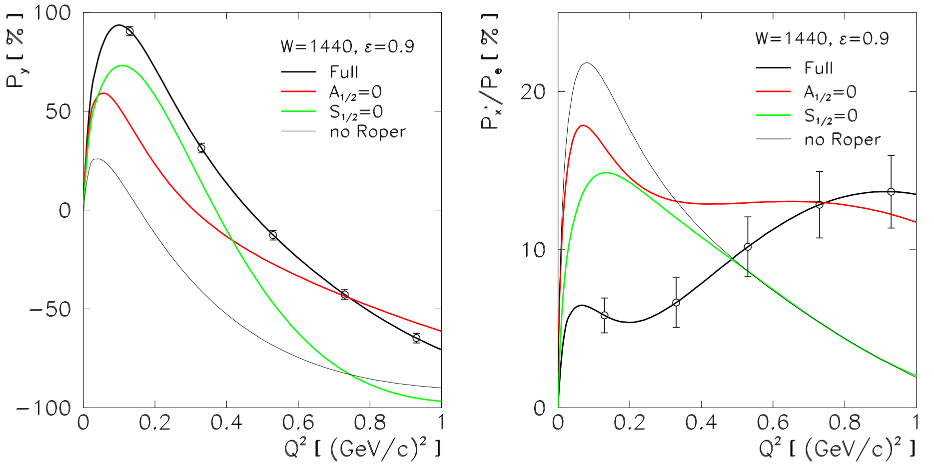

Fig. 4. Sensitivity of the normal (induced) recoil polarization component P_y and of the in-plane component P'_x/P_e to the resonant Roper multipoles M_{1-} and S_{1-}, as a function of Q^2 at $W = 1440$ MeV.

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