BLED WORKSHOPS
IN PHYSICS
VOL. 17, NO. 1
p. 55

Proceedings of the Mini-Workshop
Quarks, Hadrons, Matter
Bled, Slovenia, July 3 - 10, 2016

The perennial Roper puzzle

S. Širca[a,b]

[a] Faculty of Mathematics and Physics, University of Ljubljana, Jadranska 19, 1000 Ljubljana, Slovenia
[b] Jožef Stefan Institute, Jamova 39, 1000 Ljubljana, Slovenia

Abstract. A brief review of some of the recent advances regarding our knowledge of the elusive P11(1440) "Roper" resonance is presented. We refer to several experimental results from MAMI, Jefferson Lab and other laboratories; report on novel attempts at explaining the nature of this resonance within models involving meson-baryon or meson-quark dressing; and give a glimpse into the progress made in the past few years by Lattice QCD.

1 Introduction

The Roper resonance, $N^*(1440)$, which is the first excited state of the nucleon with equal quantum numbers, has been discovered in πN scattering about 50 years ago [1]. It has a very large Breit-Wigner width (extracted from partial-wave analyses), ranging from as low as 135 MeV to as high as 605 MeV according to the most recent (2016) Particle Data Group compilation of the corresponding partial-wave analyses, with an uncertainty of more than 100 MeV; its pion-nucleon scattering amplitude, $T_{\pi N}$, also has a very peculiar behavior with barely a hint of the characteristic maximum of the imaginary part at resonance. The Breit-Wigner approach at the description of the Roper is faulty by itself: the strong inelasticities simply prevent one from treating this resonance in an isolated manner.

Hence, in particular when compared to the familiar $\Delta(1232)$ excitation, the nature of the Roper remains a puzzle — in spite of it being awarded four-star PDG status. Part of the problem of course lies in the fact that it is next to impossible to oberve it directly in any kind of "simple" observables like partial cross-sections. The theoretical picture is just as obscure: for example, the mechanism in Lattice QCD that would cause the positive-parity $N^*(1440)$ resonance (a radial excitation) to drift below the negative parity $N^*(1535)$ (orbital) excitation when approaching the physical pion mass, remains elusive.

2 Phenomenological support for the "two-structure" picture

Studies of the Roper resonance within dynamical coupled-channels models based on baryon-meson degrees of freedom (see, for example, [2,3]) have shed further light into this picture by identifying multiple resonance poles originating in what is assumed to be the same bare state. These analyses tend to yield three P_{11} poles below 2 GeV, two of which are typically associated with the $N^*(1440)$ and one with $N^*(1710)$, although it is not totally clear whether the lower-lying pair is an artefact of the analysis or a genuine statement on the resonance(s). In the most recent analysis of [3], the poles belonging to the $N^*(1440)$ are located at $(1353 - i\,106)$ MeV and $(1357 - i\,114)$ MeV, respectively.

There are several older as well as more recent experiments whose conclusions were based on the argument that indeed *two* structures (or mechanisms, or particular interferences involving the Roper) are needed in order to explain the observed quantities. In other words, can the two-pole structure encountered in partial-wave analysis be in any way associated with features seen in individual measurements? For example, it has been shown in the study of αp and πN scattering in the Saturne Collaboration [4, 5] that the data on can be explained by assuming two structures, the lower of which ($M \approx 1.39$ GeV, $\Gamma \approx 0.19$ GeV) is only seen in α-p scattering in addition to πN elastic and $\pi N \to N(\pi\pi)_S$, while the upper one ($M \approx 1.39$ GeV, $\Gamma \approx 0.19$ GeV) is seen only in πN elastic and $\pi N \to \pi\Delta$. Strong interferences of the $N^*(1440) \to N(\pi\pi)^{T=0}_{S-\mathrm{wave}}$ and $N^*(1440) \to \pi\Delta$ processes have been claimed by [6] to be crucial in order to reproduce the $\pi\pi \to \pi\pi N$ data close to threshold as measured by the Crystal Ball collaboration. Similar conclusions were reached in the research conducted at Wasa/Promice [7] where the properties of the Roper excitation have been studied by the $pp \to pp\pi\pi$ process.

3 The Roper in quark models and on the lattice

If the Roper were a purely radial excitation ("breathing mode") of the nucleon, corresponding to the $(1s)^3 \to (1s)^2(2s)^1$ quark transition, this should correspond to a sizeable scalar (monopole) transition strength, together with a non-zero transverse (dipole) amplitude. On the other hand, if the Roper were a q^3g hybrid, the monopole amplitude should be suppressed and the transverse part should dominate. Experimentally one observes a relatively large transverse helicity amplitude $A_{1/2}$ with a zero-crossing at $Q^2 \approx 0.5\,(\mathrm{GeV}/c)^2$, while the scalar helicity amplitude clearly does not vanish and is comparable in magnitude to the transverse amplitude [13], ruling out the hybrid picture. Almost all modern relativistic quark models [14–17] confirm such behavior, implying that the Roper can be seen as the first radial excitation of the q^3 ground state, although all models fail to describe the low-Q^2 behavior of $A_{1/2}$; see [19, 20] for a possible remedy within a "χPT-inspired" effective theory and models involving strong meson-baryon dressings. Moreover, the issue of meson dressing of the quark core opens the whole avenue of exploration by means of chiral quark models (optionally incorporated into coupled-channels models). For an overview see [18].

The correct level ordering of the positive-parity $N^*(1440)$ with respect to the negative-parity $N^*(1535)$ when approaching the physical pion mass remains an unsolved problem even in the most recent lattice QCD calculations. At most, one observes "evidence" of the correct level ordering; see, for example, the studies of Refs. [21–23] and the summary plots therein, as well as the most recent calculation of Ref. [24].

4 Accessing the Roper through pion electro-production

Identifying the signatures of the Roper resonance in processes induced by real or virtual photons is an option that has been recently pursued at major electron scattering facilities like MAMI and Jefferson Lab. There is a large amount of existing data on single-pion and two-pion electroproduction processes in the energy region of the Roper resonance; see e. g. Refs. [25–30]. The most sensitive observables are single-spin and beam-target double-spin asymmetries. As such they represent crucial testing grounds for the state-of-the-art models like MAID [31] and DMT [32], two distinct approaches to meson electroproduction calculations: unitary isobar models operating with dressed resonances versus dynamical models incorporating bare states and their subsequent dynamical dressing. No such measurement has ever been performed in the region of the Roper resonance, in particular at low momentum transfers where the effects of the pion cloud are expected to be most relevant. At MAMI, we have recently performed a dedicated $p(\vec{e}, e'\vec{p})\pi^0$ experiment [10] in order to provide precise beam-recoil double polarization data for the process in the energy region of the Roper.

The differential cross section for the $p(\vec{e}, e'\vec{p})\pi$ process involving beam polarization and recoil polarization analysis can be cast in the form

$$\frac{d^5\sigma}{dp'_e d\Omega'_e d\Omega^*_p} = \Gamma\bar{\sigma}\left(1 + hA + \vec{S}\cdot\vec{\Pi}\right) ,$$

where Γ is the virtual photon flux, $\bar{\sigma}$ is the unpolarized cross section, h is the electron helicity, A is the beam analyzing power (equal to zero assuming parity invariance), $\vec{S}$ is the spin direction for the recoil proton, and $\vec{\Pi} = \vec{P} + h\vec{P}'$ is the recoil polarization consisting of its helicity-independent and helicity-dependent parts. The cross section can be decomposed into products of precisely calculable kinematic factors, ν_α, which depend only upon electron kinematics, with the response functions, R_α, which carry the relevant hadronic information. The central kinematics of our experiment has been chosen such that $\theta^*_p \approx 90^\circ$ and $\phi^*_p \approx 0^\circ$ (in-plane measurement), resulting in three non-vanishing polarization components:

$$\begin{aligned} P'_\ell\bar{\sigma} &= \nu_0\left[\nu'_{LT}R'^{\ell}_{LT} + \nu'_{TT}R'^{\ell}_{TT}\right] , \\ P_n\bar{\sigma} &= \nu_0\left[\nu_L R^n_L + \nu_T R^n_T + \nu_{LT}R^n_{LT} + \nu_{TT}R^n_{TT}\right] , \\ P'_t\bar{\sigma} &= \nu_0\left[\nu'_{LT}R'^{t}_{LT} + \nu'_{TT}R'^{t}_{TT}\right] , \end{aligned}$$

where $\bar{\sigma} = \nu_0\left[\nu_L R_L + \nu_T R_T + \nu_{LT}R_{LT} + \nu_{TT}R_{TT}\right]$. The structure functions can be further represented in terms of the bilinear forms of electroproduction multipoles. For the Roper resonance the multipoles of interest are the scalar (monopole) S_{1-} and the magnetic dipole M_{1-}. To leading orders in the angular decomposition, the relevant terms in the structure functions are $R'^{\ell}_{TT} \propto \mathrm{Re}\, E^*_{0+}(3E_{1+} + M_{1+} + 2M_{1-})$ and $R^n_T \propto \mathrm{Im}\, E^*_{0+}(3E_{1+} + M_{1+} + 2M_{1-})$, hence P'_ℓ and P_n pick up the real and imaginary parts, respectively, of the same interference of the non-resonant E_{0+} multipole with the resonant M_{1-}. These interferences are the key to the sensitivity of our experiment to its Roper content as a small resonant amplitude is multiplied by a large non-resonant one. By the same token, since $R'^{\ell}_{LT} \propto \mathrm{Re} S^*_{1-} M_{1-}$ and $R^{n}_{LT} \propto \mathrm{Im} S^*_{1-} M_{1-}$, the same polarization components are also sensitive to the respective resonant-resonant interferences, but these terms are correspondingly smaller. As $P'_t \propto R'^{t}_{LT}$, the transverse component P'_t is sensitive to two interference terms involving resonant and non-resonant amplitudes: $R'^{t}_{LT} \propto \mathrm{Re}\,\left[S^*_{0+}(2M_{1+} + M_{1-}) + (2S^*_{1+} - S^*_{1-})E_{0+}\right]$.

Our study of $p(\vec{e}, e'\vec{p})\pi^0$ was performed at the three spectrometer facility of the A1 Collaboration at the Mainz Microtron (MAMI). The kinematic ranges covered were $W \approx (1440 \pm 40)$ MeV for the invariant mass, $\theta^*_p \approx (90 \pm 15)^\circ$ and $\phi^*_p \approx (0 \pm 30)^\circ$ for the CM scattering angles and $Q^2 \approx (0.1 \pm 0.02)(\mathrm{GeV}/c)^2$ for the square of the four-momentum transfer. The analysis is ongoing.

References

1. D. Roper et al., Phys. Rev. Lett. **12** (1964) 137.
2. N. Suzuki et al., Phys. Rev. Lett. **104** (2010) 042302.
3. D. Rönchen et al., Eur. Phys. J. A **49** (2013) 44.
4. H. P. Morsch, P. Zupranski, Phys. Rev. C **61** (1999) 024002.
5. H. P. Morsch, P. Zupranski, Phys. Rev. C **71** (2005) 065203.
6. H. Kamano, M. Arima, Phys. Rev. C **73** (2006) 055203.
7. J. Pätzold et al., Phys. Rev. C **67** (2003) 052202(R).
8. K. Joo et al. (CLAS Collaboration), Phys. Rev. C **72** (2005) 058202.
9. G. V. Fedotov et al. (CLAS Collaboration), Phys. Rev. C **79** (2009) 015204.
10. H. Merkel (spokesperson), *Study of the Roper resonance in the* $p(\vec{e}, e'\vec{p})\pi^0$ *process*, MAMI Proposal A1–2/09.
11. J. Kelly et al. (Hall A Collaboration), Phys. Rev. Lett. **95** (2005) 102001.
12. J. Kelly et al. (Hall A Collaboration), Phys. Rev. C **75** (2007) 025201.
13. I. G. Aznauryan, V. D. Burkert, Prog. Part. Nucl. Phys. **67** (2012) 1.
14. H. J. Weber, Phys. Rev. C **41** (1990) 2783.
15. S. Kapstick, B. D. Keister, Phys. Rev. D **51** (1995) 3598.
16. F. Cardarelli et al., Phys. Lett. B **397** (1997) 13.
17. I. G. Aznauryan, Phys. Rev. C **76** (2008) 025212.
18. B. Golli, S. Širca, M. Fiolhais, Eur. Phys. J. A **42** (2009) 185.
19. T. Bauer, S. Scherer, L. Tiator, Phys. Rev. C **90** (2014) 015201.
20. S. Mokeev et al., Phys. Rev. C **86** (2012) 035203.
21. M. S. Mahbub et al., Phys. Lett. B **693** (2010) 351.
22. M. S. Mahbub et al., Phys. Lett. B **707** (2012) 389.
23. D. S. Roberts, W. Kamleh, D. B. Leinweber, Phys. Lett. B **725** (2013) 164.
24. C. B. Lang, L. Leskovec, M. Padmanath, S. Prelovsek, arXiv:1610.01422 [hep-lat].
25. V. I. Mokeev et al., Phys. Rev. C **93** (2016) 025206.
26. V. I. Mokeev et al., Phys. Rev. C **86** (2012) 035203.
27. I. G. Aznauryan et al., Phys. Rev. C **80** (2009) 055203.
28. I. G. Aznauryan et al., Phys. Rev. C **71** (2005) 015201.
29. I. G. Aznauryan et al., Phys. Rev. C **72** (2005) 045201.
30. A. S. Biselli et al., Phys. Rev. C **78** (2008) 045204.
31. D. Drechsel, S. S. Kamalov, L. Tiator, Eur. Phys. J. A **74** (2007) 69.
32. G. Y. Chen, S. S. Kamalov, S. N. Yang, D. Drechsel, L. Tiator, Phys. Rev. C **76** (2007) 035206.