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Pion electro-production in the first and second resonance regions

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Abstract. Many pion photo- and electro-production experiments in the energy region of the $\Delta(1232)$ resonance have been performed in the past decade, and the multipole structure of the N-Δ transition is becoming increasingly well known at least at low values of momentum transfer. In contrast, the Roper resonance, while firmly established and seen in many pion-nucleon scattering observables, it resists a clear identification and characterization by the electro-magnetic probe. I will discuss some of the outstanding theoretical and experimental issues concerning the Roper and possible means to join them fruitfully.

1 Introduction and motivation

The primary motivation to study pion electro-production in the energy region reaching to about 700 MeV above the pion production threshold is to better understand the qualitative and quantitative features of the excited baryon spectrum, and to relate the structure of baryon resonances to the mechanism of confinement and to the chiral symmetry of QCD. In addition, the results of experimental studies of nucleon resonances represent an important testing ground of theoretical models, offering in particular a way to separate the effects of resonance structure from those related to the reaction mechanism.

2 The P_{33}(1232) resonance

After an initial set of precision pion photo- and electro-production studies in the 1990s, mostly at energies close to threshold and only partly devoted to the N-Δ program, the more recent experiments on the N-Δ transition have completed their second stage. We have witnessed great progress and a substantial accumulation of data at many Q^2 on both unpolarized and polarized observables. The most frequently utilized quantities, used as cross-over points of experiment and theory, are the EMR and CMR ratios

$$\mathrm{EMR} = \mathrm{Re}\left(E_{1+}^{(3/2)}/M_{1+}^{(3/2)}\right), \qquad \mathrm{CMR} = \mathrm{Re}\left(S_{1+}^{(3/2)}/M_{1+}^{(3/2)}\right)$$

which quantify the strength of the electric and Coulomb quadrupole amplitudes E_{1+} (or E2) and S_{1+} (or C2) for the $N \to \Delta$ transition in the isospin-3/2 channel relative to the dominant spin-isospin-flip transition amplitude M_{1+} (or M1).

The E2 and EMR are more difficult to isolate in pion electro-production than C2 and CMR because the transverse parts of the cross-section are dominated by the $|M_{1+}|^2$ term which is absent in the longitudinal parts.

The EMR and CMR ratios have been measured in a series of experiments ranging from very low Q^2 (pion cloud physics), mostly performed at Mainz [1], through moderate to high Q^2, mostly performed at Jefferson Lab [2]. In spite of these multivariate efforts, the experimental situation at both low and high Q^2 is unsatisfactory. There are disagreements between the data, at least some of which can be attributed to the *model* dependence of the experimental extraction of the amplitudes, and/or to the truncation of the partial-wave series. At very high Q^2, where a particular scaling of the EMR and CMR ratios is expected [3], there are no data, and it remains an immense experimental challenge to reach that region. Moreover, lattice calculations of the Δ [4], although reaching high levels of sophistication, are in their infancy and are burdened with large uncertainties, and no definitive conclusions can be reached from the comparisons.

3 The $P_{11}(1440)$ and $S_{11}(1535)$ resonances

The situation for the $P_{11}(1440)$ and $S_{11}(1535)$ resonances is even less clear. The $P_{11}(1440)$ (the Roper resonance) has an unusually large width and an atypical behaviour of the πN scattering amplitudes. The masses and the widths of the Roper as obtained in different phenomenological analyses differ [5].

The $S_{11}(1535)$ resonance has an intimate connection to the Roper, in particular from the viewpoint of the lattice calculations. In the chiral limit, the first radial excitation is expected to come below the first orbital excitation in the energy spectrum, while in the heavy-quark limit, the situation should be reverse. In the past few years, there have been several attempts by various groups to observe this level ordering (parity inversion), so far with no conclusive evidence that upon chiral extrapolation, such an effect is indeed seen [6,7]. On the other hand, lattice calculations do seem to support the simple picture of the Roper, i.e. that most of its essential physics is captured by using light quarks (i.e. no quark-antiquark pairs [6].

Lattice findings are in stark contrast to two recent calculations which include also quark-antiquark components in the Roper wave-function. These studies were motivated by the failure to understand relatively large $S_{11}(1535) \rightarrow \phi N$ couplings in near-threshold $pp \rightarrow pp\phi$ and $\pi^- p \rightarrow n\phi$ processes, as well as large $S_{11}(1535) \rightarrow \Lambda K$ couplings in $\Psi \rightarrow p\overline{p}$ [8] and $\Psi \rightarrow \overline{p}\Lambda K^+$ decays [9], all of which are hard to reconcile in the 3q picture due to the OZI rule. Li and Riska [10] find that an $\approx 30\%$ admixture of the $qqqq\overline{q}$ components in the Roper reproduces the measured total width. An and Zou [11] found that the lowest 5q configuration in the $S_{11}(1535)$ resonance is $qqqs\overline{s}$; that correct $P_{11}(1440)$ vs. $S_{11}(1535)$ level ordering can thus be achieved; and that large $S_{11}(1535) \rightarrow \phi N, \Lambda K$ couplings can be understood without violating the OZI rule. Recent measurements of double-polarized asymmetries in eta electro-production at the $S_{11}(1535)$ resonance at MAMI/A1 also yielded interesting results which can only be explained by a phase rotation between the E_{0+} and $E_{2-} + M_{2-}$ multipoles [12].

4 Helicity amplitudes

Helicity amplitudes represent the strengths of the electro-magnetic vertex of the pion electro-production process. The $Q^2 \to 0$ limit of the amplitudes are the helicity couplings. The most comprehensive analysis of the couplings for all nucleon resonances below $W \sim 1.8\,\mathrm{GeV}$ are being performed at Jefferson Lab [13], and are fed by the multitude of data from single- and double-pion electro-production experiments of Hall B at that laboratory. It is the complete angular distribution that makes these data so powerful.

A coherent picture has started to emerge for the $A_{1/2}$ and $S_{1/2}$ helicity amplitudes for the $P_{11}(1440)$. A zero crossing of the $A_{1/2}$ at $Q^2 \approx 0.5\,\mathrm{GeV}^2$ is now firmly established. The Q^2-dependence of the $A_{1/2}$ rules out hybrid q^3g models of the Roper [14] which predict no zero crossing and a rapid decrease of the amplitude to zero. Moreover, the $S_{1/2}$ should vanish in the q^3g configuration, while the experimental data exhibit a large $S_{1/2}$ with a strong Q^2-dependence.

The $A_{1/2}$ helicity amplitude for the $S_{11}(1535)$ has recently been obtained with much greater precision and in a much larger Q^2-range than previously [15]. The $S_{1/2}$ has been measured for the first time in pion electro-production. The $A_{1/2}$, $A_{3/2}$ and $S_{1/2}$ for $D_{13}(1520)$ have also been obtained from the dispersion-relation analysis of all available data.

5 Experimental proposal for the $P_{11}(1440)$

In spite of all recent measurements of single- and double-pion electro-production, double-polarized experiments beyond the $\Delta(1232)$ region are rare birds. Measuring double-polarization observables allows one to access excitation amplitudes (or their bilinear forms, or interferences) much more selectively, with much greater predictive and interpretive power. Unfortunately, double-polarized measurements typically suffer from low yields and/or figures of merit and are notoriously hard to perform in the region of higher nucleon resonances where the reaction rates are small. Nevertheless, the tremendous lever arm one obtains by measuring carefully selected highly sensitive observables far outweighs the difficulties.

At MAMI, the A1 Collaboration presently pursues a feasibility study to measure recoil polarization components of protons ejected in the $p(\mathbf{e}, e'\mathbf{p})\pi^0$ process at the Roper resonance. The experiment would be devised in analogy to the well-established procedure from the $\Delta(1232)$ case.

Ideally, one would access the polarization components in parallel (or anti-parallel) kinematics for the *pion* (i.e. $\cos\theta = \pm 1$). In this case, they can be expressed in terms of three structure functions:

$$\begin{aligned}
\sigma_0(P'_x/P_e) &= \pm\sqrt{2\varepsilon_L^\star(1-\varepsilon)}\,R^t_{LT'}\,, \\
\sigma_0 P_y &= -\sqrt{2\varepsilon_L^\star(1+\varepsilon)}\,R^n_{LT}\,, \\
\sigma_0(P'_z/P_e) &= \mp\sqrt{1-\varepsilon^2}\,R^l_{TT'}\,.
\end{aligned}$$

where P_e is the electron polarization. The multipole decomposition of $R^t_{LT'}$ up to p-waves is

$$\begin{aligned}R^t_{LT'} = \mathrm{Re}\{\, & L^*_{0+}(2M_{1+} + M_{1-}) + (2L^*_{1+} - L^*_{1-})E_{0+} \\ & - \cos\theta\,(\, L^*_{0+}E_{0+} - 2L^*_{1+}(3E_{1+} + 7M_{1+} + 2M_{1-}) \\ & \qquad + L^*_{1-}(3E_{1+} + 7M_{1+} + 2M_{1-})\,) \\ & - \cos^2\theta\,(\, 3L^*_{0+}(E_{1+} + M_{1+}) + 6L^*_{1+}E_{0+}\,) \\ & - \cos^3\theta\,(\, 18L^*_{1+}(E_{1+} + M_{1+})\,)\,\}\end{aligned} \tag{1}$$

(note that the scalar and longitudinal multipoles are connected through $L \equiv (\omega/q)S$). In anti-parallel kinematics, the $R^t_{LT'}$ and R^n_{LT} measure the real and the imaginary parts respectively of the same combination of interference terms given by (1), up to a sign:

$$\begin{aligned}P'_x \sim R^t_{LT'} &= \mathrm{Re}\{\, L^*_{0+}E_{0+} \\ &\quad + (L^*_{0+} - 4L^*_{1+} - L^*_{1-})M_{1-} + L^*_{1-}(M_{1+} - E_{0+} + 3E_{1+}) \\ &\quad - L^*_{0+}(3E_{1+} + M_{1+}) + L^*_{1+}(4M_{1+} - E_{0+}) + 12L^*_{1+}E_{1+}\,, \\ P_y \sim R^n_{LT} &= -\mathrm{Im}\{\cdots\}\end{aligned}$$

In the case of the Roper resonance, the "M1-dominance" approximation applicable in the Δ region can not be used as many multipoles are comparable in size. With model guidance (MAID), we can estimate the role of individual terms in the expansion. 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.

The expansion of the $R^l_{TT'}$ response (or P'_z) in anti-parallel kinematics is

$$\begin{aligned}P'_z \sim R^l_{TT'} = \mathrm{Re}\{\, & E^*_{0+}(3E_{1+} + M_{1+} + 2M_{1-})\,\} \\ & + |E_{0+}|^2 + 9\,|E_{1+}|^2 + |M_{1+}|^2 + |M_{1-}|^2 \\ & - 6\,\mathrm{Re}E^*_{1+}M_{1+} - 2\,\mathrm{Re}M^*_{1+}M_{1-} - 3\,\mathrm{Re}E^*_{0+}(3E_{1+} + M_{1+})\,.\end{aligned}$$

This response is dominated by E_{0+} and M_{1+} multipoles and is therefore less sensitive to the Roper, but it would still be important as a benchmark measurement and for calibration purposes. Most of our attention will be devoted to P'_x and P_y.

Unfortunately, due to instrumental or kinematics constraints, the measurements can only be performed at an angle near 90°. Even at this angle, all polarization components exhibit tremendous sensitivities to the inclusion or exclusion of the Roper, as predicted by both the unitary isobar model MAID and the DMT dynamical model; see Figs. 1 and 2. These are state-of-the-art calculations which predict very different Q^2- and θ-, and W-) dependencies, mostly because resonances are treated in distinct way in the two approaches. MAID works with dressed resonances (in terms of effective Lagrangians); DMT incorporates bare resonances which are dressed dynamically through generation of pion loops.

From the experimental standpoint, the polarization components (the magnitudes of which roughly correspond to the sizes of the measured raw asymmetries) are very large, on the scale not typically seen in other resonances. Given sufficient beam time and a careful selection of kinematics, our measurements could help distinguish between the methods.

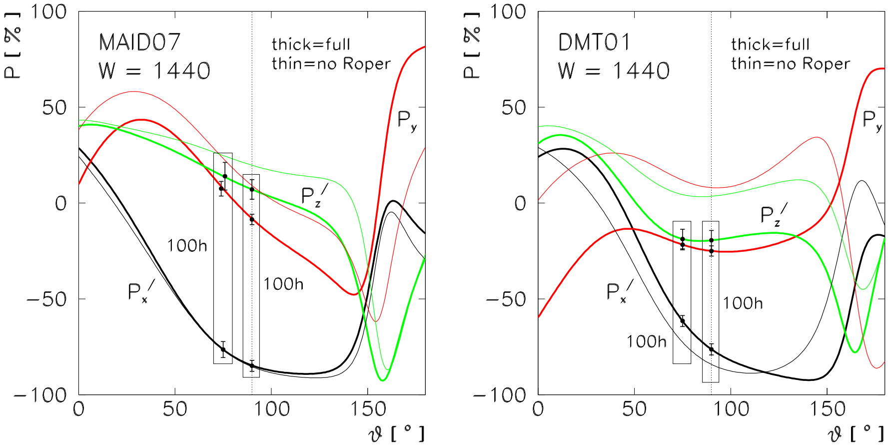

Fig.1. Recoil polarization components of protons ejected in the $p(\mathbf{e}, e'\mathbf{p})\pi^0$ process as a function of the CM emission angle. Calculations are in the MAID2007 unitary isobar model and the DMT2001 dynamical model. Shown is the effects of switching the Roper on or off. The rectangles show possible kinematical regions where measurement appear to be feasible and would have a significant impact.

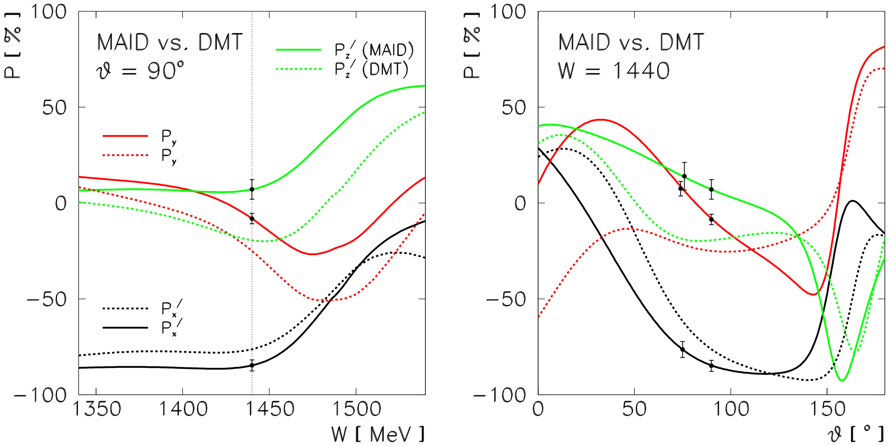

Fig.2. Recoil polarization components of protons ejected in the $p(\mathbf{e}, e'\mathbf{p})\pi^0$ process as a function of the invariant mass R and of the CM emission angle. Shown is the comparison of MAID2007 and DMT2001 models. Projected error bars are as mentioned in Fig. 1.

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