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Recent results on Δ resonance production at MIT-Bates, MAMI, and JLab (Hall A)

S. Širca[a,b]

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

Abstract. Electro-production of mesons on nucleons is the optimal tool to investigate the dynamics of nucleon resonance excitation. In the past years, tremendous advances have been made based on new instrumental capabilities of modern electron beam facilities, in particular by measuring polarization observables. Some of the recent results on Δ resonance production from three major coincidence electron-scattering collaborations are presented.

1 The facilities

Modern electron-scattering facilities possess distinct instrumental features which allow for a mutually complementary kinematic coverage, exploitation of various polarization degrees of freedom (e.g. through measurement of double-polarization observables), and different controls of systematic uncertainties.

The MIT-Bates facility has two collaborations: the Out-of-Plane Spectrometer System (OOPS) and the Bates Large-Acceptance Spectrometer Toroid (BLAST). Both utilize $\sim 1\,\mathrm{GeV}$ polarized electron beams of the Bates linac, in extraction (quasi-CW) or storage mode, respectively. OOPS has recently stopped taking data and is now in the process of data analysis. It operated four relatively light-weight spectrometer modules that can be positioned almost independently about the momentum transfer direction, and out of the electron scattering plane, to detect protons and charged pions [1]; this ensures an excellent control of systematics. BLAST is a large-acceptance toroidal magnetic spectrometer [2] that has only recently started taking production data, with a capability of simultaneous detection of charged and neutral particles in large momentum and angular ranges, with a moderate energy resolution. Its key feature are the gaseous, isotopically pure, vector-polarized hydrogen, and vector- and tensor-polarized deuterium internal targets. In a high-luminosity environment of the MIT-Bates storage ring, excellent figures of merit are achievable, which enable us to access double-polarization observables in a number of physical channels.

The A1 Collaboration at the MAMI-B accelerator makes use of the high-polarization, $\sim 0.9\,\mathrm{GeV}$ CW beam in conjunction with either target (high-polarization $^3\vec{\mathrm{He}}$) or recoil polarimetry (focal-plane polarimeter), and a setup of three high-resolution spectrometers [3] (one of them can be positioned out of plane).

In addition, individual dedicated spectrometers or non-magnetic detector systems are installed periodically for measurements of specific reaction channels. The accelerator is presently being upgraded to the energy of 1.5 GeV, and one of the spectrometers is being added to the setup to accommodate the higher particle momenta.

The Hall A Collaboration at Jefferson Lab operates two high-resolution magnetic spectrometers and auxiliary detector systems, making use of the high-polarization CW beam of energies up to 6 GeV. Both target polarization ($^3\vec{\mathrm{He}}$ with similar operational parameters as at A1) and recoil polarimetry (focal-plane polarimeter with optimizable secondary-scattering configuration) are possible. The large kinematic freedom given by the high beam energies allows us to explore the nucleon resonance production at relatively high Q^2, with invariant energies W extending beyond $\sim 2\,\mathrm{GeV}$.

2 Pion-cloud effects at low Q^2

One of the key goals of the experiments devoted to the $N \to \Delta$ transition is to determine the electric (E2) and Coulomb (C2) quadrupole transition amplitudes. These are much smaller than the leading magnetic dipole amplitude (M1), and indicate that the nucleon and/or the Δ deviate from spherical symmetry. In models involving explicit pion degrees of freedom, large contributions to M1 and dominant contributions to E2 and C2 can be attributed, schematically, to the pion cloud surrounding the bare quark core (or pion loop effects). The motivation behind the recent $N \to \Delta$ program at MIT-Bates and MAMI is therefore to map out the M1, E2, and C2 multipoles in the region of low $Q^2 \simeq 0.1\,(\mathrm{GeV}/c)^2$ where pion-cloud effects are expected to play the most important role.

The electric quadrupole amplitude E2 is accessible through a particular combination of the partial cross-sections

$$\begin{aligned}\sigma_{0\pi}(\theta_\pi^\star) &= \sigma_0(\theta_\pi^\star) + \sigma_{TT}(\theta_\pi^\star) - \sigma_0(180^\circ)\\ &\sim 2\,(\cos\theta_\pi^\star + 1)\,\mathrm{Re}\,[E_{0+}^* M_{1+}] - 12\,\sin^2\theta_\pi^\star\,\mathrm{Re}\,[E_{1+}^* M_{1+}]\,,\end{aligned}$$

where $\theta_\pi^\star$ is the center-of-mass emission angle of the pion and $\sigma_0 = \sigma_T + \varepsilon\sigma_L$. It is clear that $\sigma_{0\pi}$ exhibits a large sensitivity to $EMR \sim \mathrm{Re}\,[E_{1+}^* M_{1+}]$. However, backgrounds like the electric dipole amplitude E_{0+} in the $\mathrm{Re}\,[E_{0+}^* M_{1+}]$ interference, as well as higher partial waves ($l \geq 2$), need to be obtained from a model in order to extract the EMR.

Similarly, the quadrupole amplitude C2 is accessed through LT-terms in the cross-section which contain interferences of the scalar quadrupole S_{1+} with the dominant magnetic dipole M_{1+}:

$$\sigma_{LT}(\theta_\pi^\star) \sim \sin\theta_\pi^\star\,\mathrm{Re}\,[S_{0+}^* M_{1+}] - 6\,\cos\theta_\pi^\star\,\sin\theta_\pi^\star\,\mathrm{Re}\,[S_{1+}^* M_{1+}]\,,$$

$$\sigma_{LT'}(\theta_\pi^\star) \sim -\sin\theta_\pi^\star\,\mathrm{Im}\,[(-6\cos\theta_\pi^\star\,S_{1+} + S_{0+})^* M_{1+}]\,.$$

The σ_{LT} is primarily sensitive to $CMR \sim \mathrm{Re}\,[S_{1+}^* M_{1+}]$ while $\sigma_{LT'}$, accessible only with a polarized beam and out-of-plane detection, probes $\mathrm{Im}\,[S_{1+}^* M_{1+}]$. (This is important as the relative phases between the multipoles need to be fixed.)

The analysis of all existing OOPS data at $Q^2 = 0.127\,(\mathrm{GeV}/c)^2$, including the latest runs with the CW beam at MIT-Bates [5], yield

$$\begin{aligned} \mathrm{EMR} &= (-2.3 \pm 0.3_{\mathrm{stat+sys}} \pm 0.6_{\mathrm{model}})\,\%\,, \\ \mathrm{CMR} &= (-6.1 \pm 0.2_{\mathrm{stat+sys}} \pm 0.5_{\mathrm{model}})\,\%\,. \end{aligned}$$

At this moment, these are the most accurately known EMR and CMR values at any finite value of Q^2. (Note that the E2 multipole and EMR are more difficult to isolate in electro-production than C2 and CMR because the transverse responses are dominated by $|M_{1+}|^2$ which is absent in the longitudinal sector.) The extracted CMR is in agreement with the older OOPS extractions, with the Mainz determination from recoil polarimetry at $Q^2 = 0.121\,(\mathrm{GeV}/c)^2$ which resulted in $\mathrm{CMR} = (-6.4 \pm 0.7_{\mathrm{stat}} \pm 0.8_{\mathrm{sys}})\,\%$ [6], as well as with the CLAS data in a broader Q^2-range [7]. (New preliminary results for EMR and CMR from CLAS exist at Q^2 up to $6\,(\mathrm{GeV}/c)^2$ and have been reported at various meetings in 2004.)

In addition to the extractions of EMR and CMR at low Q^2, the present data sets will be used to try to answer several open questions arising from previous experiments at MIT-Bates and MAMI (see contribution of S. Širca to the 2003 Proceedings [8]). When final results in σ_{LT}, $\sigma_{\mathrm{LT}'}$, and other partial cross-sections from OOPS and MAMI become available, they will help constrain the models of pion electro-production [9–11]. In particular the observables involving polarized beams in conjunction with either polarized targets or recoil polarimetry, represent severe tests of the models. Preliminary results on $\sigma_{\mathrm{LT}'}$ from the MAMI runs in 2003 are shown in Fig. 1.

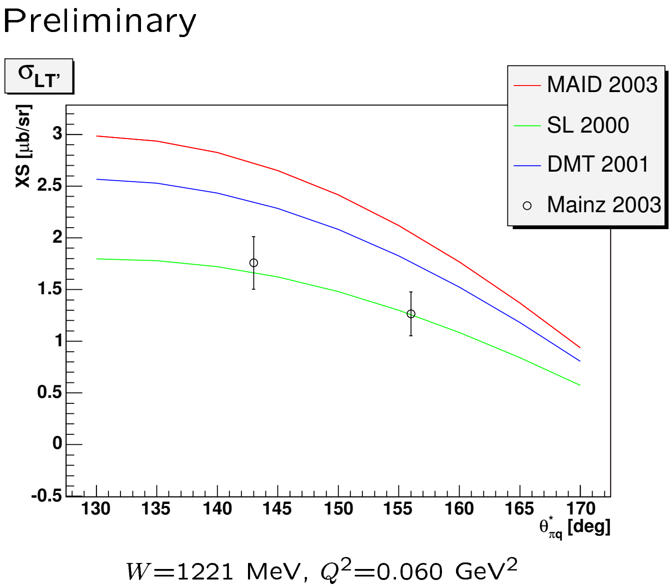

Fig. 1. Preliminary results on $\sigma_{\mathrm{LT}'} \sim \mathrm{Im}\,[S^*_{1+} M_{1+}]$ from MAMI, compared to three state-of-the-art model calculations [9–11].

3 Multipole decompositions at high Q^2

To minimize the model dependence of the extracted multipole amplitudes, a measurement with a sufficient number of independent observables is needed. The $N \to \Delta$ transition cross-section in the case of a polarized beam, unpolarized target, and recoil polarimetry, can be decomposed into 18 independent structure functions, each one of which contains different forms of multipole bilinears. Through a partial-wave analysis of the measured angular distributions of the structure functions, all relevant multipoles can be extracted from the data in a model-independent way. By measuring the angular distributions of 16 independent structure functions in broad angular ranges, the Hall A experiment E91-011 has succeeded in delivering Re and Im parts of all $l = 0, 1$ multipoles in the vicinity of $Q^2 = 1.0\,(\mathrm{GeV}/c)^2$ and $W = 1232\,\mathrm{MeV}$. The residual model-dependence is due to the higher partial waves ($l \geq 2$) which were constrained by MAID.

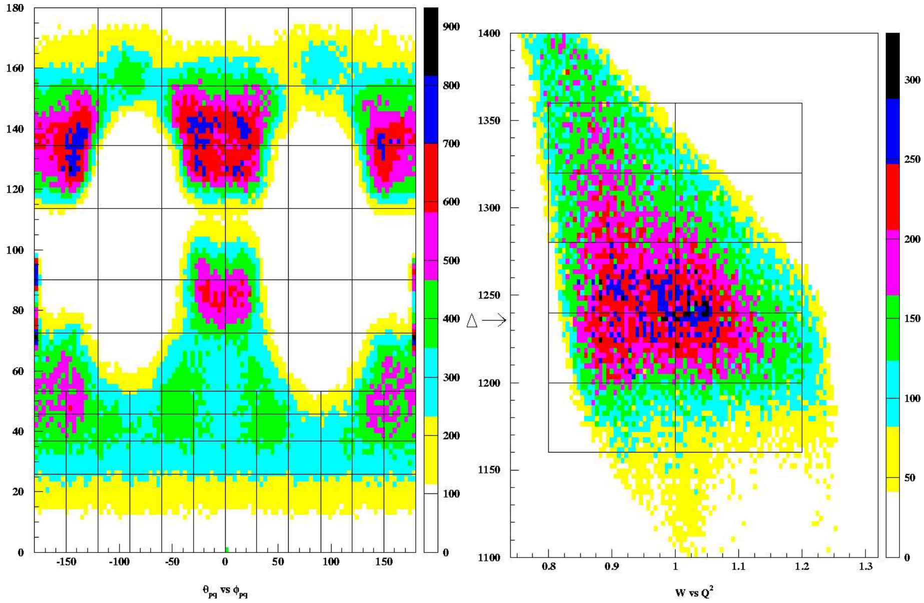

Fig. 2. Kinematical coverage in the E91-011 experiment, with indicated binning for the polarization analysis. Left: angular acceptance in recoil nucleon center-of-mass angles; Right: acceptance in W and Q^2.

Recoil polarimetry in the $p\pi^0$ channel is indeed the most powerful and hence the preferred method to cleanly disentangle individual multipoles; however, this goal could be achieved because of the strong kinematic focusing of the proton emission cone into the spectrometer acceptance at relatively high Q^2. In this way, a substantial angular coverage was achieved (see Fig. 2). The measured structure functions at $W = (1.23 \pm 0.02)\,\mathrm{GeV}$ and $Q^2 = (1.0 \pm 0.2)\,(\mathrm{GeV}/c)^2$ are shown in Fig. 3. The final analysis which will result in the individual multipoles, as well as the EMR and the CMR is almost complete, and will be reported soon.

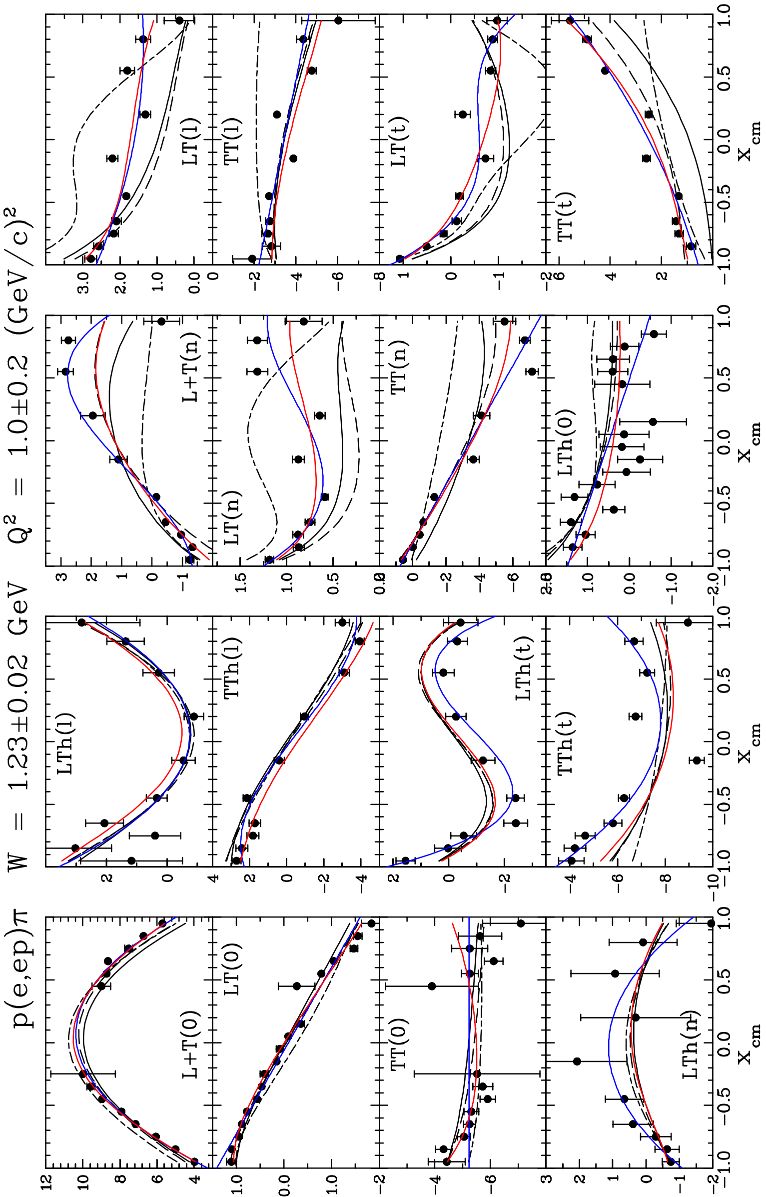

Fig. 3. Preliminary E91-011 results for the polarized structure functions in $p(\vec{e}, e'\vec{p})\pi^0$ at $W = (1.23 \pm 0.02)$ GeV and $Q^2 = (1.0 \pm 0.2)\,(\mathrm{GeV}/c)^2$, compared to the pion electroproduction models, and different multipole fits.

4 Work in progress and outlook

The analysis of the data taken with the OOPS spectrometer system at $Q^2 = 0.127\,(\mathrm{GeV}/c)^2$ is underway both in the $p\pi^0$ and the $n\pi^+$ channels, at the resonance ($W = 1232\,\mathrm{MeV}$) and below it ($W = 1175\,\mathrm{MeV}$). Selected unpolarized responses have measured which allow for a precise extraction of the EMR and CMR ratios with a relatively small model dependence. By measuring two channels, a first step towards the isospin decomposition of the amplitudes will have been made.

Preliminary responses in the $p\pi^0$ channel from A1 at MAMI are already available, while the full analysis is expected to be complete soon. We expect it to yield five unpolarized responses and the EMR and CMR ratios at $Q^2 = 0.06$ and $0.2\,(\mathrm{GeV}/c)^2$, where the effects of the pion cloud appear to be most prominent. The measurement of σ'_{LT} alone, with respect to the older A1 [12] and the latest CLAS (JLab) [13] data set, will represent an important constraint on the state-of-the-art models, in particular by constraining the $l = 0$ background amplitudes. (In σ'_{LT}, the discrepancies between the theories in the $l = 0$ partial waves arise predominantly through the $\mathrm{Im}\,[M^{*}_{1+}S_{0+}]$ interference.)

The data analysis of the $N \to \Delta$ experiment in Hall A has been concluded and is being prepared for publication. The focal-plane polarimetry approach used in this experiment can be straightforwardly extended to the energy region of the Roper resonance; an experiment proposal is presently being considered. However, the cross-sections in the second resonance region are far smaller than in the Δ region, and the sensitivities to the resonant Roper multipoles appear to be largest at small Q^2 where the kinematic focusing is too weak to allow for a full partial-wave decomposition.

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