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Nucleon resonance structure from CLAS and CLAS12 experiments

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Abstract

The recent results on the photo- and electrocouplings extraction from the reaction of one- and two-pion photo- and electroproduction off protons in the resonances region are presented. The production of two charged pions is of particular importance for evaluation of the photocouplings for the $\Delta(1620)\frac{1}{2}^-$, $\Delta(1700)\frac{3}{2}^-$, $N(1720)\frac{3}{2}^+$, $\Delta(1905)\frac{5}{2}^+$, and $\Delta(1905)\frac{7}{2}^+$ resonances, while the single-meson-baryon channels have limited sensitivity to these high-lying nucleon excited states. In preparation for the fututre experiments with the CLAS12 detector, integrated cross sections of the electroproduction of π^+n, π^0p, $K^+\Lambda$, and $K^+\Sigma^0$ were extrapolated from the region $Q^2 < 5.0$ GeV^2, where the CLAS data are available, into the region 5.0 GeV$^2 < Q^2 < 12.0$ GeV^2, which will accessible with CLAS12 for the first time.

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1. Introduction

The CLAS detector at Jefferson Lab has provided major part of all available worldwide data on exclusive meson electroproduction off protons in the resonance region. [4–7]. The channels πN, ηp, KY, ωp, and $\pi\pi p$ were studied with nearly complete coverage of the final hadron phase space [8]. All measured observables can be found in the CLAS Physics Data Base [9].

The future studies in the experiments with the CLAS12 detector at JLAB will allow to study $\gamma_v pN^*$ electrocouplings of nucleon resonances at the unexplored distance scales. The kinematics regions at very low (0.05 GeV^2 $< Q^2 < 0.5$ GeV^2) and high photon virtualities (5.0 GeV$^2 < Q^2 < 12.0$ GeV^2) will become accessible. The expected results can shed light on the most important open problems of the Standard Model: the nature of more than 98% of hadron mass, quark-gluon confinement, and description of the excited nucleon state structure in QCD [1, 2], as well as allowing a search for the new states of hadron matter [3] predicted in QCD.

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2. Resonance electrocouplings from the CLAS data

Photo- and electroexcitation of nucleon resonance are described by two transverse $A_{1/2}(Q^2)$, $A_{3/2}(Q^2)$ and a longitudinal $S_{1/2}(Q^2)$ electrocoupling amplitudes, which give information about the structure of nucleon resonance. Most of the results on $\gamma_v pN^*$ electrocouplings have been extracted from independent analyses of $\pi^+ n$, $\pi^0 p$, and $\pi^+\pi^- p$ electroproduction off protons. Differential cross sections and polarization observables were obtained with CLAS at $W < 2.0$ GeV and 0.2 GeV^2 $< Q^2 <$ 6.0 GeV^2.

One-pion data were analyzed in the context of two essentially different approaches: a unitary isobar model (UIM) and dispersion relations (DR) [10, 11]. UIM describes the resonance part of the electroproduction amplitude as a N^* electroexcitations in the s-channel. The non resonant part is a superposition of reggeized ρ- and ω- in the t-channel plus non-resonant Born terms. DR approach relates the real and imaginary parts of the invariant amplitudes describing the πN electroproduction. Consistent and reasonable description of the one-pion cross sections were obtained in both approaches at $W <$ 1.7 GeV and $Q^2 < 5.0$ GeV^2.

Two-pion electroproduction data were analyses in the framework of the JM reaction model [12, 13]. This model includes the formation of $\pi^-\Delta^{++}$, $\pi^+\Delta^0$, $\rho^0 p$, $\pi^+ N(1520)3/2^-$, $\pi^+ N(1685)5/2^+$, and $\pi^-\Delta(1620)5/2^{++}$ in the intermediate state as well as direct production of $\pi^+\pi^- p$ without formation of unstable hadrons in the intermediate state. All well established resonances with masses below 2 GeV were included in the resonant amplitudes of $\pi\Delta$ and ρp sub-channels in the framework of the unitarized Breit-Wigner ansatz [12]. The JM model provides successful description of the $\pi^+\pi^- p$ electroproduction differential cross sections at $W < 1.8$ GeV and 0.2 GeV^2 $< Q^2 < 1.5$ GeV^2 and the preliminary $\pi^+\pi^- p$ photoproduction data at $W <$ 2 GeV. The achieved quality of the CLAS data description allows us determine both resonance electrocouplings and $\pi N\pi, \Delta$, and ρp decay widths from the fit of experimental data to the nine single differential cross section.

Resonance electrocouplings were obtained from CLAS data in the exclusive channels: πN at $Q^2 < 5.0$ GeV^2 in the mass range up to 1.7 GeV, ηp at $Q^2 < 4.0$ GeV^2 in the mass range up to 1.6 GeV, and $\pi^+\pi^- p$ at $Q^2 < 1.5$ GeV^2. Photocouplings and $\pi\Delta$ and ρN hadronic decay widths of all well established resonances in the mass range from 1.6 GeV to 2.0 GeV that decay preferentially into the $\pi^+\pi^- p$ final states were extracted. Photocouplings extracted from the $\pi^+\pi^- p$ photoproduction are consistent with the results of RPP [14], where photocouplings were obtained from analyses of πN photoproduction.

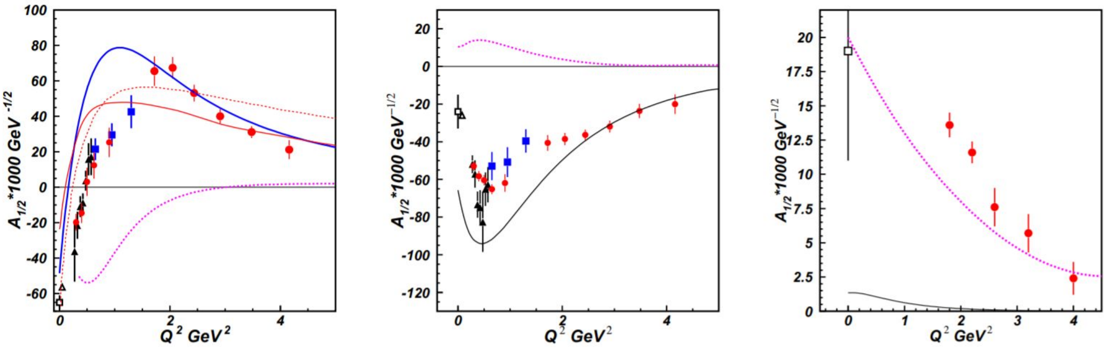

Figure 1: $A_{1/2}$ electrocouplings of $N(1440)1/2^+$ (left), $N(1520)3/2^-$ (center), and $N(1675)5/2^-$ (right) resonances from analyses of the CLAS electroproduction data off protons in the πN [10, 11] (red circles) and $\pi^+\pi^- p$ [12] channels (black triangles) with new preliminary results from the same channel [16] (blue squares). The results are compared with the Dyson-Schwinger Equations of QCD (DSEQCD) [17] (blue thick solid) and CQM calculations [18] (thin red solid), [19] (thin red dashed), and [20] (thin black solid). The meson-baryon cloud contributions are presented by the magenta thick dashed lines. In case of the $N(1440)1/2^+$ resonance they are based on the DSEQCD results and the extracted electrocoupling data, whereas the absolute values at the resonance poles taken from Argonne-Osaka coupled channel analysis [21] are shown for $N(1520)3/2^-$ and $N(1675)5/2^-$. Photocouplings are taken from [14] (black open squares) and the CLAS data analysis [22] of πN photoproduction.

The studies of the $N(1440)1/2^+$ and $N(1520)3/2^-$ resonances with the CLAS detector [12, 15] gave information on their electrocouplings in the Q^2 range from 0.25 GeV^2 to 5.0 GeV^2. The low-lying resonances $N(1440)1/2^+$, $N(1520)3/2^+$, $\Delta(1232)3/2^+$, and $N(1535)1/2^-$ are the most explored excited nucleon states. Furthermore, electrocouplings $\gamma_v pN^*$ for the high-lying $N(1675)5/2^-$, $N(1680)5/2^+$, and $N(1710)1/2^+$ states have recently been determined for the first time from the CLAS πN data at 1.5 GeV^2 $<$ $Q2$ <4.5 GeV^2 [11].

Fig. 1 shows electrocouplings for $N(1440)1/2^+$, $N(1520)3/2^-$, and $N(1675)5/2^-$ together with the preliminary results on the $N(1440)1/2^+$ and $N(1520)3/2^-$ electrocouplings from the CLAS $\pi\pi p$ electroproduction off protons at 0.5 GeV^2 $<$ Q^2 $<$ 1.5 GeV^2 [16]. Consistent results for the γ_vpN* electrocouplings of $N(1440)1/2^+$ and $N(1520)3/2^-$ determined in independent analyses of the electroproduction channels, πN and $\pi\pi p$ demonstrates reliability of the extracted quantities, since these channels have quite different background contributions.

Analyses of the CLAS results strongly suggest that the structure of nucleon resonances for $Q^2 < 5.0$ GeV^2 is determined by a complex interaction between the inner core of three dressed quarks and the external meson-baryon cloud which depends on the quantum numbers of the excited nucleon state.

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3. Extrapolation of the integrated cross section at $Q^2 >$5 GeV

The maximal achievable Q^2 value will be extended to 12 GeV^2 in the CLAS12 detector. The knowledge of the approximate cross sections of the meson electroproduction off protons are required to evaluate the CLAS12 detector efficiency. The efficiency will be evaluated by the method of Monte-Carlo. It requires an event generators based on the realistic cross sections, while the experimental data are not available at $Q^2 > 5.0$ GeV^2. The procedure was developed to extrapolate the cross section from the region $Q^2 <$ 5.0 GeV^2, where the CLAS data are available, into the region 5.0 GeV$^2 < Q^2 <$ 12.0 GeV^2 for the electroproduction channels π^+n, π^0p, $K^+\Lambda$ and $K^+\Sigma^0$.

The procedure is based on the extrapolation of the contribution of the exclusive channels to the structure functions [23]. Structure functions $F_1(W,Q^2)$ and $F_2(W,Q^2)$ can be calculated from the transversal and longitudinal components of the inclusive cross section as

$$F_1^i = M_p \frac{K}{4\pi^2\alpha}\sigma_T(W,Q^2), \quad F_2^i = \nu \frac{\sigma_T(W,Q^2)+\sigma_L(W,Q^2)}{4\pi^2\alpha}\frac{(2\nu M_p - Q^2)Q^2}{2M_p(Q^2+\nu^2)}, \tag{1}$$

where M_p is a mass of proton, ν is tranfered energy, and $K = \frac{2\nu M_p - Q^2}{2M_p}$. The contribution of the exclusive channel (i) to the structure functions (F_1^i and F_2^i) is calculated when using exclusive cross sections σ_T^i and σ_L^i in (1). Operator Product Expansion approximation predicts Q^2-evolution of the momenta of the inclusive structure functions F_1 and F_2 [24]. We assumed that the same approximation can be applied to the structure functions as well as to the contribution of the exclusive channels to the structure function at $Q^2 \gg \Lambda^2_{QCD}$. Thus, $F_1^i(W,Q^2)$ and $F_2^i(W,Q^2)$ can be parameterized as

$$F_1^i = C_{0,1}^i(W) + \frac{C_{1,1}^i(W)}{Q^2} + \frac{C_{2,1}^i(W)}{Q^4} + \ldots, \quad F_2^i = C_{0,2}^i(W) + \frac{C_{1,2}^i(W)}{Q^2} + \frac{C_{2,2}^i(W)}{Q^4} + \ldots, \tag{2}$$

where $C_{k,l}^i$ are parameters. We limited ourselves to three parameters $C_{0,l}^i$, $C_{1,l}^i$, and $C_{2,l}^i$ for every channel and they were determined from the fit of F_1^i and F_2^i to the experimental data at $Q^2 < 5.0$ GeV^2 for the channels π^+n, π^0p, $K^+\Lambda$ and $K^+\Sigma^0$. Fitting procedure was applied in each bin of W independently requiring the ratios $\frac{F_{1,2}^i}{F_{1,2}}$ to be from 0 to 1. Then F_1^i and F_2^i were extrapolated into the region 5.0 GeV$^2 < Q^2 <$ 12.0 GeV^2 according to (2) with the parameters $C_{0,l}^i$, $C_{1,l}^i$, and $C_{2,l}^i$ determined from the fit. An example of the interpolated and extrapolated F_1^i is shown in Fig. 2. The extrapolated cross section was calculated starting from extrapolated F_1^i and F_2^i. Right plot of Fig. 2 demonstrates an example of the extrapolated integrated cross section The shape of the differential cross sections at $Q^2 > 5.0$ GeV^2 were assumed to be the same it is at $Q^2 = 5.0$ GeV^2.

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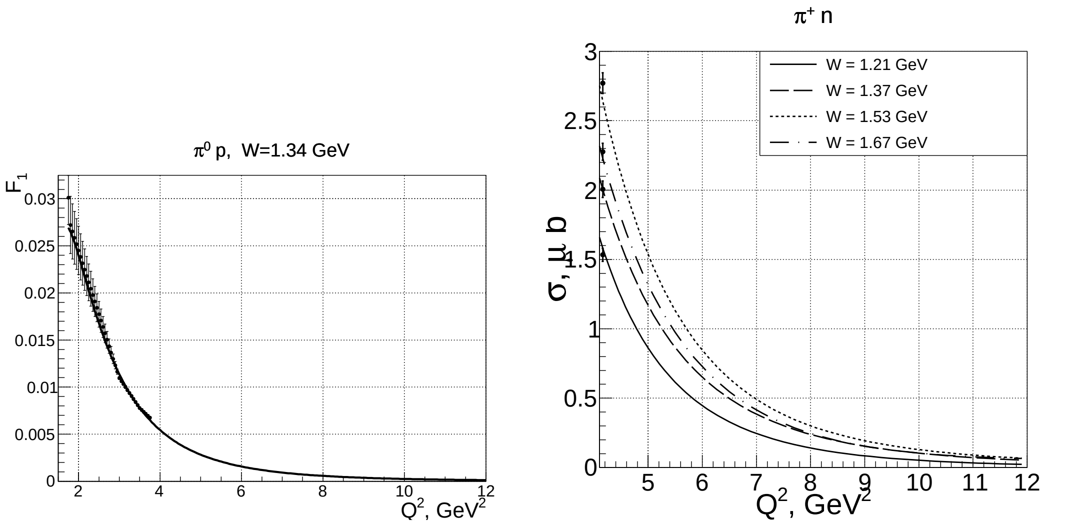

Figure 2: Interpolated and extrapolated F_1^i (left) for the channel $\pi^0 p$. Extrapolated integrated cross sections for the channel $\pi^+ n$ (right).

4. Summary

High quality meson electroproduction data from CLAS allowed to determine the electrocouplings of most well-established resonances with the masses below 1.8 GeV from analyses of the $\pi^+ n$, $\pi^0 p$, and $\pi^+\pi^- p$ electroproduction channels. CLAS data showed the structure of excited nucleon states as a complex interaction between inner core of three dressed quarks and external meson-baryon cloud. After the 12 GeV upgrade, CLAS12 will be be able of obtaining electrocouplings of all prominent resonance at still unexplored ranges of low photon virtualities down to 0.05 GeV^2 and highest photon virtualities ever from 5.0 GeV^2 to 12 GeV^2. The expected results will allow us to search for new states of baryon matter. Integrated cross sections from the CLAS data for the reactions $\pi^+ n$, $\pi^0 p$, $K^+\Lambda$ and $K^+\Sigma^0$ were extrapolated into the region $5 < Q^2 < 12$ GeV^2, which will be accessible by the CLAS12 detector. These cross sections will be used to evaluate the CLAS12 detector efficiency by the Monte-Carlo method.

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