Analysis of CLAS data on double charged-pion electroproduction.

V. I. Mokeev\textsuperscript{1,2}, V. D. Burkert\textsuperscript{1}, L. Elouadrhiri\textsuperscript{1}, G. V. Fedotov\textsuperscript{2}, E. N. Golovach\textsuperscript{2}, E. L. Isupov\textsuperscript{2}, B. S. Ishkhanov\textsuperscript{2}, N. V. Shvedunov\textsuperscript{2}, and CLAS Collaboration

\textsuperscript{1} Jefferson Lab, 12000, Jefferson Ave, Newport News, VA, 23606, USA
\textsuperscript{2} Skobeltsyn Nuclear Physics Institute at Moscow State University, 119899, Leninskie gory, Moscow, Russia.

Received: date / Revised version: date

Abstract. Recent developments in phenomenological analysis of the CLAS data on $2\pi$ electroproduction are presented. The contributions from isobar channels and $P_{11}(1440)$, $D_{13}(1520)$ electrocouplings at $Q^2$ from 0.25 to 0.6 GeV$^2$ were determined from the analysis of comprehensive data on differential and fully integrated $2\pi$ cross sections.

PACS. PACS-key 13.40.Gp, 13.60.Le, 14.20.Gk

1 Introduction

Studies of nucleon resonance electrocouplings at various photon virtualities in double charged-pion electroproduction play an important role in the $N^*$ program with the CLAS detector \cite{1,2}. Single and double pion photo and electroproduction are two major exclusive channels, contributing to the total photon-proton cross section in the $N^*$ excitation region. Both of these channels are sensitive to excited states. Photo and electroproduction of two pions are particularly sensitive to resonances with masses above 1.6 GeV. Many of these states decay preferentially to final states with two pions. Furthermore, $1\pi$ and $2\pi$ exclusive channels are strongly coupled by hadronic interactions in the final states (FSI). Hadronic cross section $\pi N \rightarrow \pi \pi N$ is the second strongest exclusive channel in value amongst exclusive $\pi N$ cross sections. Therefore, a combined analysis of at least the two major electroproduction channels is needed to assure the appropriate evaluation of $N^*$ electrocouplings. Eventually other exclusive channels with smaller cross sections may be included. For these final states, the hadronic interactions with major meson photo or electroproduction channels become even more important. Therefore, comprehensive information on mechanisms contributing to both $1\pi$ and $2\pi$ electroproduction is of particular interest for the entire $N^*$ program. This information may be obtained in a phenomenological analysis of the CLAS data on meson electroproduction offering valuable input for $N^*$ studies in advanced coupled channel approaches, which are currently under development at the Excited Baryon Analysis Center (EBAC) at JLAB \cite{23}.

In this proceeding we report results of an analysis of recent CLAS data on double charged-pion electroproduction \cite{4,5} at $W < 1.6$ GeV and $Q^2$ from 0.2 to 0.6 GeV$^2$. The objectives of this analysis were:

- establish all significant contributing mechanisms;
- determine the electrocouplings of $P_{11}(1440)$ and $D_{13}(1520)$ states.

2 JM06 model for phenomenological data analysis.

The exclusive $\gamma p \rightarrow \pi^-\pi^+ p$ channel offers numerous observables for the analysis. Even in measurements without use of polarization observables, there are nine independent differential cross sections in each ($W,Q^2$) bin. For the first time these data have become available from CLAS and some of them are shown in Fig. 3 and 4. The full data set obtained in the CLAS experiment \cite{4,5} may be found in Ref. \cite{6}. These data make it possible to establish all significant contributing mechanisms from the studies of their manifestations in observables, as peaks in invariant mass distributions or sharp slopes in angular distributions. Mechanisms without particular features may be determined, considering the correlations between shapes of their cross sections in various observables. We have developed a phenomenological model that incorporates particular meson-baryon mechanisms based on their manifestations in the observables.

The analysis of earlier CLAS data \cite{7} incorporated particular meson-baryon mechanisms needed to describe $\pi^+ p$, $\pi^+\pi^-$, $\pi^- p$ invariant masses and $\pi^-$ angular distribution \cite{8-10}. These cross sections were analyzed in the hadronic mass range from 1.41 to 1.89 GeV. The overall $Q^2$-coverage ranges from 0.5 to 1.5 GeV$^2$. In the 2005 version of this analysis approach (JM05) \cite{11,12}, double charged-pion production was described by the superposition of quasi-two-body channels with the formation and subsequent decay of unstable particles in the intermediate states: $\pi^-\Delta^{++}$, $\pi^+\Delta^0$, $\rho^0 p$, $\pi^+ D_{13}^{0}(1520)$, $\pi^+ F_{15}^{0}(1520)$.
We modified the dynamics of direct $2\pi$ production mechanisms without formation of unstable intermediate particles described by a set of exchange terms with the amplitudes as outlined in [13]. The production amplitudes for the first three quasi-two-body intermediate states were treated as sums of $N^*$ excitations in the $s$-channel and non-resonant mechanisms described in Refs. [8–10,12]. All well established resonances with observed decays to the two pion final states were included as well as $3/2^+(1720)$ candidate state that was observed in the analysis of $2\pi$ electroproduction data [7]. The production amplitudes for the $\pi^- D_{13}^0 (1520)$, $\pi^+ F_{15}^0 (1685)$ and $\pi^- F_{33}^{1+} (1640)$ intermediate state are described in [12].

In the JM05 approach we succeeded in describing all before mentioned observables in the CLAS data [7]. These results are presented in [11,12].

In the analysis of the most recent data at $W<1.6$ GeV and photon virtualities from 0.2 to 0.6 GeV$^2$ [4,5] for we attempted the first time to fit contributing mechanisms to the set of nine single-differential cross sections in each $(W,Q^2)$ bin covered by measurements. In addition to the differential cross sections mentioned above, they also included $\pi^+$ and $p$ angular distributions and three distributions over angles $\alpha_{i,j}$ between two planes, composed by the momenta of the initial proton and final hadron (first plane) and two the other final hadrons (a second plane) for three possible combinations amongst these pairs. We found that the JM05 model reasonably describes the data over all invariant masses and $\pi^-$ angular distributions, as it is shown in Fig. 1. All these observables were previously studied in $2\pi$ electroproduction at higher photon virtualities [12]. However, JM05 model version failed in reproducing $\pi^+$ and $p$ CM angular distributions included in the analysis for the first time. As it follows from Fig. 1, where the contributions from various mechanisms are presented, this failure is related to shortcomings in the description of direct $2\pi$ production mechanisms in [13].

In order to achieve a reasonable description of all angular distributions, we modified the dynamics of direct $2\pi$ production mechanisms with respect to those used in the JM05 version. The mechanisms of [13] were substituted by ladder-type double exchange processes, shown in Fig. 2.

The amplitudes of these processes are parametrized as Lorentz-invariant contractions between spin-tensors of the initial and final particles, while the propagators for exchange mechanisms are described by exponents. We refer to this new approach as JM06 model. In this model we succeeded to describe recent CLAS data [4,5] in the entire kinematics covered by the measurements [4,5]. As a typical example, the description of single-differential $2\pi$ cross sections within the framework of the JM06 version is shown in Fig. 3 together with the contributions from various mechanisms of JM06 approach.

The shapes of cross sections for various contributing mechanisms are substantially different in the observables, but highly correlated by mechanism dynamics. Therefore, the successful description of all differential cross sections allowed us to pin down all major contributing processes and access their dynamics at the phenomenological level.

![Fig. 1. Description of differential $2\pi$ cross sections at $W=1.51$ GeV and $Q^2=0.425$ GeV$^2$ in comparison within the framework of JM05 (solid lines). The contributions from $\pi^- \Delta^{++}$, $\pi^+ \Delta^0$ isobar channels and direct $2\pi$ production mechanisms are shown by dashed, dotted and dot-dashed lines, respectively.](image)

To check the reliability of the amplitudes for contributing processes, derived in this phenomenological data analysis, we fixed all JM06 parameters, fitting them to six single-differential cross sections: all invariant masses, and three final state angular distributions. The remaining three distributions over the $\alpha_{i,j}$ angles were calculated, keeping JM06 parameters fixed. A reasonable description of $\alpha_{i,j}$ angular distributions was achieved in the entire kinematics covered by measurements. Therefore, we confirmed the
reliability of 2π electroproduction mechanisms established in phenomenological data analysis within the framework of the JM06 model.

### 3 Cross sections for contributing mechanisms and $N^*$ electrocouplings.

The contributions from isobar channels to the 2π electroproduction, and the electrocouplings for $P_{11}(1440)$ and $D_{13}(1520)$ resonances at $Q^2 < 0.6$ GeV$^2$ were determined within the framework of the JM06 approach. Electrocouplings of all resonances were varied around their initial values, that were obtained by interpolating previous CLAS and world data. They were varied randomly according to a normal distribution with a $\sigma$ of 30 %. Simultaneously, non-resonant mechanism parameters were varied with a $\sigma$ of 10 %. For each trial set of JM06 parameters we calculated nine differential cross sections in all $(W,Q^2)$ bins, covered in the CLAS measured data [4,5]. Normalized to the amount of data points $\chi^2/d.p.$ were estimated from the comparison between measured and calculated differential cross sections. Finally, we selected calculated differential cross sections, which were closest to the experimental data applying the restriction for $\chi^2/d.p.$ listed in Table 1.

The differential cross sections selected from the fit at $W=1.43$ GeV and $Q^2=0.425$ GeV$^2$ are shown in Fig. 4 by various dashed lines. For each calculated differential cross section, selected in fitting procedure, we estimated the contribution from all isobar channels combined. The contribution from all isobar channels combined is shown in Fig. 4 by vertical bars. The information on the isobar channel contributions to all nine differential 2π cross sections was obtained in our analysis for the first time. Fits within the framework of JM06 also enabled us to obtain amplitudes for the superposition of all quasi-two-body processes mentioned in the Section 2, as well as for any individual isobar channel.

This information is of particular interest for future $N^*$ studies in a combined analysis of an 1π and 2π exclusive channels within the framework of an advanced coupled channel approach, which is currently under development by EBAC [3]. Moreover, the data on isobar channel differential cross sections and amplitudes open up new opportu-
Fig. 4. Fit of differential $2\pi$ cross sections within the framework of JM06 at $W=1.43$ GeV and $Q^2=0.425$ GeV$^2$. Bunch of curves represent calculated cross section, selected in fitting procedure (see Sect 3). Cross sections corresponding to contribution from all isobar channels combined are shown by vertical bars.

Fig. 5. Electromagnetic transition form factors for the $P_{11}(1440)$ (left) and $D_{13}(1520)$ (right) states, determined from analysis of CLAS single pion data (squares) and double pion data (open circles). The results from the combined $1\pi/2\pi$ data analysis at $Q^2=0.65$ GeV$^2$ are shown by filled circles. The photocouplings from the PDG are shown by triangles.

nities to establish explicit meson-baryon mechanisms contributing to various isobar channels. Predictions from various models, based on effective meson-baryon Lagrangians [3,16,17] may be compared with isobar channel cross sections and amplitudes determined from the CLAS $2\pi$ data analysis.

Fig. 5 shows the electrocouplings of the $P_{11}(1440)$ and $D_{13}(1520)$ states. For the first time, we obtain the $Q^2$ evolution of electrocouplings for these states from the $\pi^+\pi^-p$ channel at $Q^2$ from 0.2 to 0.6 GeV$^2$.

These photon virtualities are particularly sensitive to the contributions from $N^*$ meson-baryon dressing. The electrocouplings obtained from this analysis are in reasonable agreement with the results from $1\pi$ exclusive channel [15], as well as from the combined $1\pi/2\pi$ analysis [13]. The consistency of the data on the $P_{11}(1440)$, $D_{13}(1520)$ electrocouplings, obtained from analysis of the two major $1\pi$ and $2\pi$ exclusive channels with substantially different non-resonant processes demonstrates that a reliable evaluation of these fundamental quantities can be obtained from the $1\pi$ and $2\pi$ electroproduction data. The analysis of the CLAS data on $2\pi$ electroproduction provides compelling evidence for the sign flip of the $A_{1/2}$ electro-
coupling of the $P_{11}(1440)$ state at $Q^2$ in the range from 0.4 to 0.5 GeV$^2$ (Fig. 5).

4 Conclusions and outlook.

- The analysis of CLAS data on $2\pi$ electroproduction [4, 5] allowed us to establish all significant mechanisms in this exclusive channel at $W < 1.6$ GeV and $Q^2$ from 0.2 to 0.6 GeV$^2$. The JM06 model provides a reasonable description of all CLAS and world $2\pi$ electroproduction data and may be used to separate resonant and non-resonant amplitudes in $2\pi$ electroproduction with the goal of determining $N^*$ electrocouplings.

- The contributions to the double charged-pion electroproduction from isobar channels were established and will be used in future studies of nucleon resonances in a combined analysis of the CLAS data on $1\pi$ and $2\pi$ electroproduction within the framework of an advanced coupled channel approach [3].

- The $P_{11}(1440)$ and $D_{13}(1520)$ electrocouplings were determined for the first time from $2\pi$ electroproduction data at $Q^2 < 0.6$ GeV$^2$. This kinematic regime is expected to be particularly sensitive to meson-baryon dressing effects in the nucleon resonance structure. The analysis will be extended to obtain electrocouplings for excited proton states with masses less then 2.5 GeV and in a large range of photon virtualities.

- Comprehensive information on $N^*$ electrocouplings in a wide $Q^2$ range offers new challenging opportunities for baryon structure theory to access fundamental mechanisms responsible for baryon formation.

References

1. V.D. Burkert, Prog. Part. Nucl. Phys. 55, (2005) 108.
2. V.D. Burkert, Physics at CLAS, in this Proceedings.
3. A.Matsuyama, et. al., Phys.Rep. 439, (2007) 193; B.Juliandia, et.al., arXiv:0704.1615.
4. G.V. Fedotov, et. al., Bull. of Russian Academy of Science 71, (2007) 328.
5. G.V. Fedotov, et. al., CLAS Collaboration, in preparation for PRC.
6. CLAS Physics Data Base, http://clasdb3.jlab.org.
7. M. Ripani et al., CLAS Collaboration, Phys. Rev. Lett. 91, (2003) 022002, see full data set in CLAS Physics Data Base.
8. V. Mokeev et. al., Phys. of Atom. Nucl. 64, (2001) 1292.
9. V. Mokeev et. al., Phys. of Atom. Nucl. 64, (2003) 2149.
10. V. Mokeev et. al., Phys. of Atom. Nucl. 70, (2007) 427.
11. V.I. Mokeev, V.D. Burkert, AIP Conf. Proc. 842, (2006) 339.
12. V.I. Mokeev, V.D. Burkert et al., Proceedings of the Workshop on Physics of Excited Nucleons NSTAR2005, ed. by S.Capstick, V.Crede, P.Eugenio, 47.
13. I.G. Aznauryan et al., Phys. Rev. C 72, (2005) 045201.
14. V.I. Mokeev, V.D. Burkert, J. Phys. Conf. Ser. 69, (2007) 012019.
15. I.G. Aznauryan et al., Phys. Rev. C 71, (2005) 015201.
16. A. Kiswandhi, et. al., J. Phys. Conf. Ser. 69, (2007) 012018.
17. J.C. Nacher, E. Oset, Nucl. Phys. A697, (2002) 372.