PHENOMENOLOGICAL ANALYSIS OF THE CLAS DATA
ON DOUBLE CHARGED PION PHOTO AND ELECTRO-
PRODUCTION OFF PROTON.

V. I. MOKEEV, V. D. BURKERT AND L. ELOUADRHIRI

Jefferson Lab,
12000 Jefferson Ave., Newport News, VA 23606, USA

A. A. BOLUCHEVSKY, G. V. FEDOTOV, E. L. ISUPOV, B. S.
ISHKANOV AND N. V. SHVEDUNOV

Skobeltsyn Nuclear Physics Institute at Moscow State University,
119899 Vorobyevy gory, Moscow, Russia

First comprehensive data on the evolution of nucleon resonance photocouplings with photon virtuality \( Q^2 \) are presented for excited proton states in the mass range from 1.4 to 2.0 GeV. \( N^* \) photocouplings were determined in phenomenological analysis of CLAS data on \( 2\pi \) photo and electroproduction within the framework of the JLAB-MSU phenomenological model.

1. Introduction

Comprehensive studies of nucleon resonances were carried out in phenomenological analysis of CLAS data on double charged pion production by real and virtual photons \(^3,4\). The analysis was performed within the framework of the 2005 version of JLAB-MSU phenomenological model in the following referred to as JM05.

2. \( 2\pi \) model. From 2003 to 2005 version.

Electromagnetic production of two pions from proton is sensitive to contributions from both low-lying and high-lying \( N^* \) states. This exclusive channel offers an opportunity to determine electromagnetic transition form factors from the nucleon ground state to many excited states. Moreover, it is also a promising channel in the search for so-called "missing" \( N^* \) states. These states are predicted from symmetry principles of the symmetric constituent quark models. Many of these states are expected to
couple strongly to $N\pi\pi$ final state. However, $N^*$ decays into the $2\pi$ channel contribute only a fraction of the total $2\pi$ production; a large part is due to non-resonant production mechanisms. In such conditions, the development of reaction models, which provide reasonable background treatment and $N^*/\text{background}$ separation, become necessary for the evaluation of $N^*$ parameters.

We have developed a phenomenological model, that incorporates particular meson-baryon mechanisms based on their manifestations in observables: as enhancements in invariant mass distributions, sharp forward/backward slopes in angular distributions. The $p\pi\pi$ final state offers a variety of single differential cross sections for analysis. Any particular meson-baryon mechanism has distinctive reflections in different cross sections. Therefore, a combined analysis of an entire set of single differential cross sections makes it possible to establish the relevant meson-baryon mechanisms from the data fit. Our model is currently limited to the $N\pi^-\pi^+$ final state and incorporates particular meson-baryon mechanisms needed to describe $\pi^+p$, $\pi^+\pi^-,\pi^-p$ invariant masses and $\pi^-$ angular distribution. These cross sections were analyzed in the hadronic mass range from 1.41 to 1.89 GeV and in four $Q^2$ bins centered at 0., 0.65, 0.95, 1.30 GeV$^2$. The overall $Q^2$-coverage ranges from 0. to 1.5 GeV$^2$.

In the 2003 version (JM03)\(^1,2\) 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:

\begin{align*}
\gamma p \rightarrow \pi^-\Delta^{++} &\rightarrow \pi^-\pi^+p, \\
\gamma p \rightarrow \pi^+\Delta^0 &\rightarrow \pi^+\pi^-p, \\
\gamma p \rightarrow \rho^0 p &\rightarrow \pi^+\pi^-p, \\
\gamma p \rightarrow \pi^+D_{13}^0(1520) &\rightarrow \pi^+\pi^-p.
\end{align*}

Remaining residual mechanisms were parametrized as 3-body phase space with the amplitude fitted to the data. This amplitude was a function of photon virtuality $Q^2$ and invariant mass of the final hadronic system $W$ only. In this approach we were able to reproduce the main features of integrated cross sections as well as $\pi^+\pi^-, \pi^+p$ invariant masses and $\pi^-$ angular distributions in CLAS electroproduction data\(^3,5\).

The production amplitudes for the first three quasi-two-body mechanisms (1-3) were treated as sums of $N^*$ excitations in the $s$-channel and non-resonant mechanisms described in Refs\(^1,2\). The quasi-two-body mechanism (4) was entirely non-resonant\(^6\). In reactions (1-3) all well established
4 star resonances with observed decays to the two pion final states were included as well as the 3-star states \(D_{13}(1700), P_{11}(1710), P_{33}(1600), \) and \(P_{33}(1920)\). For the \(P_{33}(1600)\) a 1.64 GeV mass was obtained in our fit. This value is in agreement with the results of recent analyses of \(\pi N\) scattering experiments. \(N^*\) electromagnetic transition form factors were fitted to the data. Hadronic couplings for \(N^* \rightarrow \pi \Delta\) and \(\rho p\) decays were taken from the analyses of experiments with hadronic probes, except for \(P_{33}(1600), P_{13}(1720),\) the candidate \(3/2^+ (1720), D_{13}(1700), P_{33}(1920), F_{35}(1905), \) and \(F_{37}(1950)\) states. Poorly known hadronic decay parameters for these states were fitted to the data.

Analysis of CLAS \(2\pi\) electroproduction data within the framework of this approach revealed the structure around 1.7 GeV, which can not be explained by the contributions from conventional \(N^*\) only. We found two possible ways to describe CLAS data around \(W=1.7\) GeV: a) assuming drastically different \(\pi \Delta\) and \(\rho p\) hadronic couplings for the \(P_{13}(1720)\) state with respect to the established couplings, or b) keeping hadronic decay parameters for all \(N^*\)'s inside established uncertainties, a new baryon state with quantum numbers \(3/2^+ (1720)\) is needed to describe CLAS data around \(W=1.7\) GeV.

The analysis of preliminary CLAS data on \(2\pi\) photoproduction within the framework of JM03 revealed shortcomings in the description of \(\pi^-\) angular distributions at backward hemisphere (Fig. 1). Similar incompatibilities were also seen for electroproduction data. They are related to the parametrization of remaining mechanisms as 3-body phase, which is incompatible with the steep increase of the measured \(\pi^-\) angular distributions at backward angles. In JM05, the 3-body phase space description was replaced by the set of exchange terms shown in Fig. 2a. This allowed much improved description of the \(\pi^-\) angular distributions (solid lines in Fig. 1) in the entire \(Q^2\) range covered by the CLAS data. Parametrization of these exchange amplitudes is described in 7.

Such modifications for remaining mechanisms allow us to reproduce CLAS data on \(2\pi\) photo- and electroproduction at \(W \leq 1.7\) GeV reasonably well. Above 1.7 GeV the measured cross sections around \(\Delta^0\) mass in the \(\pi^- p\) mass distributions exceed the model cross sections (Fig. 3). To reproduce the strength of the \(\Delta^0\) peaks (solid lines in Fig. 3) as well as to improve description of the \(\pi^+ p\) mass distributions we implemented an additional contact term for isobar channels (1)-(2), shown on Fig. 2c. Parametrization of these mechanisms is presented in 8.

After these improvements we still have shortcomings in the descrip-
Figure 1. \( \pi^- \) CM angular distributions at \( W=1.49 \) GeV and at three photon virtualities. CLAS data [3-5] are shown in comparison with the JM05 results: solid lines represent full calculations; the contributions from \( 2\pi \) direct production mechanisms are shown by dashed-dotted lines. The full calculations within the framework of the JM03 are shown by dashed lines.

The gap in angular distributions may be filled by t-channel exchange mechanisms for \( \pi^+ P_{33}^{0+}(1660) \) intermediate state. The observed discrepancies thus indicate contributions from the isobar channels:

\[
\gamma p \rightarrow \pi^+ F_{15}^{0+}(1685) \rightarrow \pi^+ \pi^- p, \\
\gamma p \rightarrow \pi^- P_{33}^{1+}(1600) \rightarrow \pi^- \pi^+ p.
\]
Implementation of isobar channels (5)-(6) with amplitudes as outlined in 8 allow us to reproduce the data at \( W \geq 1.8 \) GeV reasonably well (solid lines in Fig. 4).

After these modifications, we succeeded in describing all available CLAS data on unpolarized observables in \( 2\pi \) photo and electroproduction. These results are presented in 8. We found no need for remaining mechanisms of unknown dynamics. Therefore, the quality of the CLAS data allow us to establish all significant mechanisms in \( 2\pi \) production, implementing particular meson-baryon diagrams as determined from the data fit.

The credibility of our description of non-resonant mechanisms and the separation of resonant and non-resonant contributions was tested in a combined analysis of CLAS data on \( 1\pi \) and \( 2\pi \) electroproduction 7. We found a common set of \( N^* \) photocouplings, which allowed us to reproduce all observables measured in these two exclusive channels combined. Since \( 1\pi \) and \( 2\pi \) channels represent two major contributors in \( N^* \) excitation region with considerably different background, their successful fit offers compelling evidence for credible background description and \( N^* \)/background separation achieved in JM05.

3. \( N^* \) analysis in \( 2\pi \) photo and electroproduction.
We fit all available CLAS data on \( 2\pi \) photo and electroproduction at \( W \leq 1.9 \) GeV and \( Q^2 \) from 0 to 1.5 GeV\(^2\) within the framework of JM05. \( N^* \) photocouplings were sampled according to the normal distribution around the values, obtained in the JM03 9. The photocouplings were varied within 0.3 \( \sigma \) from theirs starting values. Poorly known masses and hadronic couplings were also fluctuated inside the uncertainties established in experiments with hadronic probes. Adjustable parameters of non-resonant mech-
Figure 3. Evidence for complementary contact term contribution to the $\pi\Delta$ isobar channels. Full calculations in JM05 are shown by solid lines, while evaluations within the framework of JM03 are shown by dashed lines. $\pi^+\Delta^0$ channel contributions estimated in JM05 model are shown by dotted-dashed lines. CLAS $2\pi$ photo and electroproduction data are from [3-5].

Mechanisms were varied within $0.2\sigma$. For each trial set of model parameters we calculated all kind of single differential cross sections in all available $W$ and $Q^2$ bins. From comparison between calculated and measured single differential cross sections $\chi^2$/d.p. were estimated. We isolated a bunch of calculated cross sections inside the data uncertainties, applying restriction $\chi^2 \leq \chi^2_{th}$, where $\chi^2_{th}$ is a predetermined maximal allowed value. Integrated $2\pi$ cross sections in comparison with selected calculated cross sections are shown in Fig. 5. A reasonable description of all cross sections was achieved.

$N^*$ photocouplings for selected cross sections were averaged and mean values were treated as extracted from the data fit, while dis-
Figure 4. Manifestation of $\pi^+F_{15}^+(1685)$ and $\pi^-P_{33}^{++}(1600)$ isobar channels. The photoproduction CLAS data at $W=1.86$ GeV are compared to the JM05: full calculations (solid lines); isobar channels (5),(6) are absorbed in 3-body phase space (dashed lines). The contributions from channels (5),(6) are shown by dotted and dotted-dashed lines respectively.

persions were assigned to photocoupling uncertainties. In this way we obtained the photocouplings for the states: $P_{31}(1440)$, $D_{13}(1520)$, $S_{31}(1620)$, $S_{11}(1650)$, $P_{33}(1600)$, $F_{15}(1680)$, $D_{13}(1700)$, $D_{33}(1700)$, candidate $3/2^+(1720)$, $P_{13}(1720)$, $F_{35}(1905)$, $P_{33}(1920)$, and $F_{37}(1950)$.

In Fig. 6 we present the photocouplings for the well studied $D_{13}(1520)$ state in comparison with previously available data. Reasonable overlap between our results and previous ones support the reliability of our procedure for the extraction of $N^*$ photocoupling from $2\pi$ data fit. For the first time, we determine the electrocouplings for high lying $N^*$, which preferably decay with $2\pi$ emission: $D_{13}(1700)$, $D_{33}(1700)$, candidate $3/2^+(1720)$, $P_{13}(1720)$,
Figure 5. Total $2\pi$ electroproduction cross sections calculated within the framework of JM05 with $N^*$ parameters fitted to the CLAS data [3-5] at photon virtuality 0.65 $GeV^2$.

$F_{35}(1905)$, $P_{33}(1920)$, and $F_{37}(1950)$. In Fig. 7 we present photo- and electrocouplings for the $D_{33}(1700)$ and $P_{13}(1720)$ states extracted from the CLAS $2\pi$ data, as well as couplings obtained in previous studies of $1\pi$ production. The analysis of the CLAS $2\pi$ data for the first time provides accurate information on electrocouplings for high lying nucleon excitations.

4. Conclusions.

A phenomenological model for the description of $2\pi$ production from protons in the nucleon resonance region was developed with most complete accounting for all relevant mechanisms. The reliability of the background treatment and $N^*$/background separation was confirmed by the reason-
Figure 6. $D_{13}(1520)$ photocouplings extracted from the analysis of CLAS $2\pi$ data [3-5] (filled squares) in comparison with world data [10] (open circles) and results of analysis of the CLAS $1\pi$ and $2\pi$ data combined [7] (filled triangles).

able description obtained for of all unpolarized observables in this exclusive channel, as well as in the combined analysis of $1\pi$ and $2\pi$ production. Electromagnetic transition form factors were extracted at photon virtualities $Q^2 \leq 1.5 \text{ GeV}^2$ for $N^*$ states in the mass range from 1.4 to 2.0 GeV. For the first time transition form factors were obtained for many high lying proton states with major $2\pi$ decay.

References
1. V. Mokeev et. al., Phys, of Atom. Nucl. 64, 1292 (2001).
2. V.D Burkert, et. al., Phys, of Atom. Nucl. 66, 2199 (2003).
3. M. Ripani et. al., Phys. Rev. Lett. 91, 022002 (2003).
4. M.Bellis, et.al., Proceedings of NSTAR2004 workshop , March 24-27, 2004,
Figure 7. $D_{33}(1700)$, $P_{13}(1720)$ photocouplings extracted from analysis of CLAS $2\pi$ data in comparison with previous results. Symbols are the same as in the Fig. 6.

5. CLAS Physics Data Base, http://clasdb3.jlab.org.
6. V. Mokeev et. al., Proceedings of NSTAR2004 workshop, March 24-27, 2004, Grenoble, France, World Scientific, ed. by J.-P. Bocquet, V. Kuznetsov, D. Rebreyend, 139.
7. I. G. Amauryan et. al., Phys. Rev. C72, 045201 (2005).
8. V.I. Mokeev http://hadron.physics.fsu.edu/nstar/scientificProg.htm
9. V.D. Burkert, et. al., Proc. of the 17 International UPAP Conference on Few-Body Problems in Physics, Durham, NC, USA, 5-10 June 2003, Elsevier, 2004, ed.by W. G. Glöckle, W. Tornow, S231.
10. V.D. Burkert, et. al., Phys. Rev. C67, 035204 (2003).