Nucleon resonance electrocouplings from CLAS data on pion electroproduction

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Primary objectives in the studies of $\gamma_v NN^*$ electrocouplings with CLAS

Current experimental program with 6.0 GeV electron beam:

- seeks to determine $\gamma_v NN^*$ transition helicity amplitudes (electrocouplings) at photon virtualities $0.2 < Q^2 < 5.0 \text{ GeV}^2$ for most excited proton states from analyzing several meson electroproduction channels combined;
- employs advanced coupled channel approach under development at EBAC and worldwide.

Proposal on the future studies of $N^*$ electrocouplings at $5.0 < Q^2 < 12 \text{ GeV}^2$ with CLAS12 detector was approved by PAC.

The information on $Q^2$ evolution of the $\gamma_v NN^*$ electrocouplings will allow us to

- determine the active degrees of freedom in $N^*$ structure versus distance scale;
- study the non-perturbative strong interactions which are responsible for the ground and excited nucleon state formation;
- explore how $N^*$’s emerge from QCD.
N* parameters from analyses of exclusive electroproduction channels

- Separation of resonant and non-resonant contributions represents most challenging part, and can be achieved within the framework of reaction models.
- N* ‘s can couple to various exclusive channels with entirely different non-resonant amplitudes, while their electrocouplings should remain the same.
- Consistent results from the analyses of major meson electroproduction channels Nπ and π⁺π⁻p show that model uncertainties in extracted N* electrocouplings are under control.
Summary of the CLAS data on $N\pi$ electroproduction off protons

Number of data points >116000, $W<1.7$ GeV, $0.15<Q^2<6.0$ GeV$^2$, almost complete coverage of the final state phase space.

<table>
<thead>
<tr>
<th>Observables</th>
<th>$Q^2$ area, GeV$^2$</th>
<th>Number of data points</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d\sigma/d\Omega(\pi^0)$</td>
<td>0.16-1.45, 3.0-6.0</td>
<td>39830, 9000</td>
</tr>
<tr>
<td>$d\sigma/d\Omega(\pi^+)$</td>
<td>0.25-0.60, 1.7-4.3</td>
<td>25588, 30 849</td>
</tr>
<tr>
<td>$A_e(\pi^0), A_t(\pi^0)$</td>
<td>0.25-0.65</td>
<td>3981</td>
</tr>
<tr>
<td>$A_e(\pi^+), A_t(\pi^+)$</td>
<td>0.40-0.65, 1.7 - 3.5</td>
<td>1730, 3 535</td>
</tr>
<tr>
<td>$A_{et}(\pi^0)$</td>
<td>0.25-0.61</td>
<td>1521</td>
</tr>
</tbody>
</table>

**Low Q$^2$ results:**
I. Aznauryan et al., PRC 71, 015201 (2005); PRC 72, 045201 (2005).

**High Q$^2$ results on Roper:**
I. Aznauryan et al., PRC 78, 045209 (2008).

**Final analysis:**

All data sets can be found in: http://clasweb.jlab.org/physicsdb/
Unitary Isobar Model (UIM) for $N\pi$ electroproduction

- Based on MAID model

- All well established $N^*$’s with $M<1.8$ GeV, Breit-Wigner amplitudes.

- Non-resonant Born terms:
  - pole/reggeized meson $t$-channel exchange;
  - $s$- and $u$-nucleon terms.

- Final-state $\pi N$ rescattering in K-matrix approximation.

Fixed-$t$ Dispersion Relations for invariant Ball amplitudes

\( \gamma^* p \rightarrow N \pi \)

The Ball amplitudes \( B_i^{(\pm,0)} \) are invariant functions in the transition current:

**Dispersion relations for 6*3 invariant Ball amplitudes:**

\[ \bar{u}_N \gamma_5 I^\mu u_P \phi_{\pi} \]

17 Unsubtracted Dispersion Relations

\[ \text{Re } B_i^{(\pm,0)} \left[ \text{Re } B_i^{(\pm,0)} (s, t, Q^2) \right] = \]

\[ \text{(i=1,2,4,5,6)} \]

\[ \text{Re } B_i^{(\pm,0)} (s, t, Q^2) = R_i^{(v,s)} (Q^2) \left( \frac{1}{s - m_N^2} + \frac{\eta_i \eta}{u - m_N^2} \right) + \frac{P}{\pi} \int_{S_{thr}}^{\infty} \text{Im } B_i^{(\pm,0)} \left( \frac{1}{s' - s} + \frac{\eta_i \eta}{s' - s} \right) ds' \]

1 Subtracted Dispersion Relation

\[ \text{(i=3)} \]

\[ \text{Re } B_3^{(-)} (s, t, Q^2) = R_3^{(v)} (Q^2) \left( \frac{1}{s - m_N^2} + \frac{1}{u - m_N^2} \right) - \text{eg } \frac{F_\pi (Q^2)}{t - m_\pi^2} + f_{sub} (t, Q^2) \]

+ \frac{P}{\pi} \int_{S_{thr}}^{\infty} \text{Im } B_3^{(-)} \left( \frac{1}{s' - s} + \frac{1}{s' - s} \right) ds' \]

\[ \text{defined mostly by } N^* \text{'s} \]
Fits to $\gamma p \rightarrow \pi^+ n$ differential cross sections and structure functions

$Q^2 = 2.05 \text{ GeV}^2$

- DR
- DR w/o P11
- UIM

$Q^2 = 2.44 \text{ GeV}^2$

- DR
- UIM

L=0 Legendre moments from various structure functions
The CLAS data on $\pi^+\pi^-p$ differential cross sections and description within the JM model

G.V. Fedotov et al, PRC 79 (2009), 015204

M. Ripani et al, PRL 91 (2003), 022002

$W=1.5125$ GeV, $Q^2=0.375$ GeV$^2$

$W=1.71$ GeV, $Q^2=0.65$ GeV$^2$

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The diagrams show the differential cross sections for $\pi^+\pi^-p$ interactions at different $W$ and $Q^2$ values. The plots compare the experimental data with the full JM calculation and various contributions such as $\pi^+\Delta^0$, $\pi^-\Delta^{++}$, $2\pi$ direct, $\rho p$, $\pi^+D^{0}_{13}(1520)$, and $\pi^+F^0_{15}(1685)$. The graphs illustrate the agreement between the data and the theoretical predictions.
JLAB-MSU meson-baryon model (JM) for $\pi^+\pi^-p$ electroproduction

**Isobar channels included:**

$\pi^-\Delta^{++}$

- All well established $N^*$s with $\pi\Delta$ decays and $3/2^+(1720)$ candidate.
- Reggeized Born terms with effective FSI and ISI treatment (absorptive approximation).
- Extra $\pi\Delta$ contact term.

$\rho^0p$

- All well established $N^*$s with $\rho p$ decays and $3/2^+(1720)$ candidate.
- Diffractive ansatz for non-resonant part and $\rho$-line shrinkage in $N^*$ region.
JLAB-MSU meson-baryon model (JM) for $\pi^+\pi^-p$ electroproduction

3-body processes:

\[ \gamma \to \pi^+ (\pi^-) \]

(P++33(1640)) \rightarrow F^0_{15}(1685) \rightarrow (\pi^+) \]

\[ p \rightarrow D_{13}(1520) \]

Isobar channels included:

- $\pi^+D_{13}^0(1520)$, $\pi^+F^0_{15}(1685)$, $\pi^-P^{++}_{33}(1640)$

Isobar channels observed for the first time in the CLAS data at $W > 1.5$ GeV.

Unitarized Breit-Wigner Anstaz for resonant amplitudes

I.J.R. Aitchison, Nuclear Physics, A189 (1972), 417

Inverse of JM unitarized $N^*$ propagator:

\[ S^{-1}_{\alpha \beta} = M_{\alpha N^*}^2 \delta_{\alpha \beta} - i \left( \sum_i \sqrt{\Gamma_{\alpha i}} \sqrt{\Gamma_{\beta i}} \right) \sqrt{M_{N^* \alpha} M_{N^* \beta}} - W^2 \delta_{\alpha \beta} \]

Off-diagonal transitions incorporated into JM:

- $S_{11}(1535) \leftrightarrow S_{11}(1650)$
- $D_{13}(1520) \leftrightarrow D_{13}(1700)$
- $3/2^+(1720) \leftrightarrow P_{13}(1700)$
JLAB-MSU meson-baryon model (JM) for $\pi^+\pi^-p$ electroproduction

Direct $2\pi$ production required by unitarity:

Most relevant at $W<1.60$ GeV.
Negligible at $W>1.70$ GeV

• Lorentz invariant contraction of the initial and the final particle spin-tensors
• Exponential propagators for two unspecified exchanges

Magnitudes and relative phases fit to the data

phases=0
$W=1.51$ GeV
$Q^2=0.65$ GeV$^2$

phases fit to the data
$W=1.51$ GeV
$Q^2=0.65$ GeV$^2$
Good agreement between the electrocouplings obtained from the $N\pi$ and $N\pi\pi$ channels. $N^*$ electrocouplings are measurable and model independent quantities.
High lying resonance electrocouplings from $\gamma p \rightarrow \pi^+\pi^-p$

Studies of $\pi^+\pi^-p$ electroproduction offer best opportunity for extraction of electrocouplings for $N^*$ states with masses above 1.6 GeV. Most of them decay preferably to $N\pi\pi$ final states.

Electrocouplings of $S_{31}(1620)$, $S_{11}(1650)$, $F_{35}(1685)$, $D_{33}(1700)$, and $P_{13}(1720)$ states were obtained for the first time from the $\pi^+\pi^-p$ electroproduction data.

All CLAS results on $N^*$ electrocouplings can be found in: www.jlab.org/~mokeev/resonance_electrocouplings/
Mystery of $P_{11}(1440)$ structure is solved

Quark models:
- I. Aznauryan LC
- S. Capstick LC
- Relativistic covariant approach by G. Ramalho / F. Gross.

EBAC-DCC

MB dressing (absolute values).

Meson-baryon dressing amplitudes:

The electrocouplings are consistent with $P_{11}(1440)$ structure as a combined contribution of: a) internal quark core as a first radial excitation of three dressed quarks in the ground proton state, and b) external meson-baryon dressing.
§ Still quenched

0f anisotropic clover ($a \approx 0.1\,\text{fm}$, $\xi \approx 3$)

$M_\pi \approx 480, 720, 1100\,\text{MeV}$

Computed from CLAS results on $P_{11}(1440)$ electro couplings

Approaching physical pion mass, and accounting for quark loops in the sea, LQCD is making progress toward evaluation of $N^*$ electrocouplings from first QCD principles.

§ Turn on the quark loops in the sea

$\sim 2+1f$ anisotropic clover with $M_\pi \approx 390, 450, 875$ MeV

Experimental data.

* With Saul Cohen (BU) $Q^2$ [GeV$^2$]

† Calculation performed using (NSF MRI PHY-0922770) Hyak cluster at U. Washington
**S_{11} (1535) electrocouplings and their interpretation**

Analysis of $p\eta$ channel assumes $S_{1/2}=0$
Branching ratios: $\beta_{N\pi} = \beta_{N\eta} = 0.45$

- $A_{1/2}(Q^2)$ from $N\pi$ and $p\eta$ are consistent
- First extraction of $S_{1/2}(Q^2)$ amplitude

- *QCD-based LQCD & LCSR calculations (black solid lines) by Regensburg Univ. Group reproduces data trend at $Q^2 > 2.0$ GeV$^2*
- *Successful description of $S_{11}(1535)$ electrocouplings based on OCD!*

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*V.I.Mokeev  Hadron2011, June 13 -17, 2011, Munich*
Resonance Transitions at 12 GeV

Experiment E12-09-003 will extend access to transition FF for many prominent states in the range up to $Q^2=12\text{GeV}^2$.

Electromagnetic form factors are sensitive to the dynamical dressed quark mass.

In this experiment we will probe the transition from “dressed quarks” to current pQCD quarks for the first time.
Conclusions and Outlook

• The measurements with CLAS in N* excitation region extended considerably data on Nπ electroproduction cross sections, polarization asymmetries with full coverage of the final state phase space. Nine independent differential and fully integrated π⁺π⁻p electroproduction cross section were obtained for the first time.

• Good description of the data on Nπ and π⁺π⁻p electroproduction was achieved, allowing us to separate resonant and non-resonant contributions, needed for the evaluation of N* electrocouplings.

• For the first time consistent results on electrocouplings of several N* states were obtained in independent analyses of dominant Nπ and π⁺π⁻p electroproduction channels with completely different non-resonant contributions, offering an evidence for reliable electrocoupling extraction.

• Preliminary results on electrocouplings of high lying S_{31}(1620), S_{11}(1650), F_{15}(1685), D_{33}(1700), and P_{13}(1720) states have become available from π⁺π⁻p electroproduction for the first time.
Conclusions and Outlook

- Analyses of the CLAS data on N* electrocouplings within the framework of different quark models and the EBAC-DCC coupled channel approach showed that the structure of resonances with masses < 1.6 GeV is determined by internal quark core and external meson-baryon cloud.

- Lattice QCD, Dyson-Schwinger equations of QCD are making progress toward evaluation of N* electrocouplings from first principles of QCD. Analyses of experimental data on N* electrocouplings within the framework of these approaches offer a promising avenue to explore how excited proton states emerge from QCD.

- The future studies of N* electrocouplings at $Q^2 > 5.0$ GeV$^2$ with CLAS12 will allow us for the first time to access quark degrees of freedom almost directly, and to explore how dynamical dressed quark masses, structure and their interactions, that are responsible for N* formation in confinement regime, come from QCD.

  N* electrocoupling studies are of particular importance in order to understand how diverse world of hadron matter is created by fundamental QCD interactions.
Back-up
Comparison between the CLAS and MAID results

$P_{11}(1440)$

$A_{1/2}$

$S_{1/2}$

$A_{1/2} \times 1000 \text{ GeV}^{1/2}$

$S_{1/2} \times 1000 \text{ GeV}^{1/2}$
Comparison between the CLAS and MAID results

$D_{13}(1520)$

$A_{1/2}$

$A_{3/2}$

$S_{1/2}$
Resonant and non-resonant parts of $\pi^+\pi^-p$ cross sections as determined from the CLAS data fit within the framework of JM model.
### N* decay parameters to Nππ final states from the CLAS π⁺π⁻p electroproduction data

#### D<sub>13</sub>(1520)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>CLAS π⁺π⁻p electro production data</th>
<th>PDG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Γ total, MeV</td>
<td>126±7</td>
<td>100-125</td>
</tr>
<tr>
<td>πΔ BF, %</td>
<td>24-33</td>
<td>15-25</td>
</tr>
<tr>
<td>ρp BF, %</td>
<td>7-16</td>
<td>15-25</td>
</tr>
</tbody>
</table>

#### S<sub>11</sub>(1535)

Note: uncertainties for Γ tot were obtained by varying Nππ decay widths only.

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<tbody>
<tr>
<td>Γ total, MeV</td>
<td>136±8</td>
<td>125-175</td>
</tr>
<tr>
<td>πΔ BF, %</td>
<td>5-11</td>
<td>&lt;1</td>
</tr>
<tr>
<td>ρp BF, %</td>
<td>3.6-13.7</td>
<td>&lt;4</td>
</tr>
</tbody>
</table>

Nππ decays of D<sub>13</sub>(1520) are close to those reported in the PDG.

For S<sub>11</sub>(1535) they are greater than the PDG values with almost equal πΔ and ρp BF’s.