V.I. Mokeev, Jefferson Lab and SINP MSU, on behalf of the CLAS Collaboration
Weak and Electromagnetic Interactions as the Tools for Exploration of the Ground and Excited Nucleon State Structure

Weak interaction: neutrino-nucleon scattering:

Electromagnetic interaction: electron (muon)-nucleon scattering:
N*-States in Inclusive Electron Scattering

The peak content

What we knew 30 years ago:

- three resonant peaks.
- different $Q^2$-evolution of these peaks
- different structure of different N*-states.

Total virtual photon cross sections

$\sigma$, mb
$W$, GeV
$Q^2$, GeV$^2$
Extraction of $\gamma_v NN^*$ Electrocouplings from the Data on Exclusive Meson Electroproduction off Protons

- Separation of resonant/non-resonant contributions within the framework of reaction models; Breit-Wigner ansatz for parameterization of resonant amplitudes; fit of resonance electrocouplings and hadronic parameters to the data.

Consistent results on $\gamma_v NN^*$ electrocouplings from different meson electroproduction channels and different analysis approaches demonstrate reliable extraction of N* parameters.

See details in:
The unique combination of the CEBAF continuous electron beam with the best worldwide parameters and the CLAS detector of nearly $4\pi$ acceptance makes Hall-B@JLAB the most versatile facility operational worldwide for exploration of the nucleon structure.
Motivation and Objectives for the Studies of the $\gamma pN^*$-Electrocouplings in Exclusive Meson Electroproduction

The CLAS experimental program seeks to determine $\gamma pN^*$ electrocouplings at photon virtualities up to 5.0 GeV$^2$ for most of the excited proton states through analyzing major meson electroproduction channels independently and in global multi-channel analyses.

This information is needed to study the evolution of relevant degrees of freedom in $N^*$ structure with distance and to access the non-perturbative strong interaction which generates $N^*$ states as bound systems of quarks and gluons: I. G. Aznauryuan et al., Int. J. Mod. Phys. E22, 133015 (2013).

The non-perturbative strong interaction represents the most important part of the Standard Model that we have yet to explore.
Non-Perturbatively Generated Effective Degrees of Freedom in the Ground and Excited Nucleon State Structure

Emergence of dressed constituent quarks (C.Q.) and gluons:

- Dressed quarks and gluons acquire dynamical, momentum dependent structure and masses in the regime of large $\alpha_s$ which is relevant for the $N^*$ formation.

- Their non-perturbative interactions are very complex and far beyond the scope of pQCD.
Resonance Electrocouplings as a Window into Non-perturbative Strong Interaction

Available/future data on elastic form factors and $\gamma vpN^*$-electrocouplings from CLAS/CLAS12 detectors offer the access to the dressed quark mass function in the range of momenta $p$ up to 1.15 GeV.

Exploration of the N/N* state structure addresses the most fundamental questions:

• Nature of >98 % of the hadron mass in Universe, which is generated non-perturbatively. The Higgs mechanism is almost irrelevant for the light hadron mass generation.

• How quark-gluon confinement in baryons emerges from the QCD.
The CLAS Data on $\pi^+\pi^-p$ Differential Cross Sections and their Description within the Framework of Meson-Baryon Reaction Model JM

G.V.Fedotov et al, PRC 79 (2009), 015204
1.30<$W<$1.56 GeV; 0.2<$Q^2<$0.6 GeV$^2$

M.Ripani, V.I,Mokeev et al, PRL 91 (2003), 022002
1.40<$W<$2.30 GeV; 0.5<$Q^2<$1.5 GeV$^2$

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

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

---

full JM calc.

$\pi^+\Delta^0$

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

$2\pi$ direct

$\rho p$

$\pi^+D^0_{13}(1520)$

$\pi^+F_{15}^0(1680)$
The JM Model for Analysis of the $\pi^+\pi^-p$ Electroproduction

Major objectives: extraction of $\gamma_vNN^*$ electrocouplings and the $\pi\Delta, \rho p$ decay widths.

- Developed in Collaboration between JLAB and SINP at MSU.
- Only available worldwide approach for extraction of resonance parameters from the $\pi^+\pi^-p$ electroproduction data.
Successful description of $N\Delta$ transition form factors was achieved taking into account the contributions from the external meson-baryon cloud and the internal core of three dressed constituent quarks.

Quark Core Contribution to $N \rightarrow \Delta$ Magnetic Form Factors from the QCD Lagrangian


Promising potential of DSEQCD approaches in describing the quark core contribution from the first principles of QCD.

- contact interaction.
- contact interaction & quark anomalous magn. moment.
- projection for quark running mass.
- bare $G^*_M$ inferred from exp. data within Argonne-Osaka c.c. approach.
The $P_{11}(1440)$ and $D_{13}(1520)$ Structure from the CLAS Electrocoupling Data

CLAS data:
- $N\pi$ 2009
- $\pi^+\pi^-p$ 2012
- $\pi^+\pi^-p$ prelim.

$P_{11}(1440)$ Quark core from the quark models:

I.G.Aznauryan,
PRC 76, 025212 (2007).


Meson-Baryon dressing:


- Consistent values of $P_{11}(1440)$ electrocouplings determined in independent analyses of $N\pi$ and $\pi^+\pi^-p$ exclusive channels strongly support reliable electrocoupling extraction.

- The physics analyses of these results revealed the $P_{11}(1440)$ and $D_{13}(1520)$ structure as a combined contribution of: a) quark core as a first radial and orbital $L=1$ excitations of the 3-quarks, respectively and b) meson-baryon dressing.
High-Lying Resonance Electrocouplings from the $\pi^+\pi^-p$ CLAS Data Analysis

$\pi^+\pi^-p$ electroproduction channel provided first preliminary results on $S_{31}(1620)$, $S_{11}(1650)$, $F_{15}(1685)$, $D_{33}(1700)$, and $P_{13}(1720)$ electrocouplings of a good accuracy.

SQTM approach:
Conclusions and Outlook

• High quality meson electroproduction data from the CLAS detector allowed us to determine electrocouplings of the most excited states in the mass range of \( W < 1.8 \) GeV from analyses of \( N\pi \) and \( N\eta \) and \( N\pi\pi \) exclusive electroproduction off protons for the first time. Consistent values of \( \gamma_vNN^* \) electrocouplings from independent analyses of \( N\pi/N\pi\pi \) and \( N\pi/N\eta \) channels confirmed reliable extraction of these fundamental quantities.

• Analyses of \( \gamma_vNN^* \) electrocouplings revealed the \( N^* \)-structure as internal core of three constituent quarks surrounded by external meson-baryon cloud. Resonances of different quantum numbers provided complementary information on the \( N^* \) structure. The data on electrocouplings of all prominent \( N^* \)-states are needed.

• Electrocouplings of most \( N^* \)-states in mass range up to 2.0 GeV will be determined in few years from analyses of \( N\pi\pi \) electroproduction at photon virtualities up to 5.0 GeV\(^2 \) and will be compared with the available/future results of \( N\pi \) and KY exclusive electroproduction.
Conclusions and Outlook

• The dedicated experiment on N* studies with the CLAS12 detector at the largest photon virtualities ever achieved in exclusive meson electroproduction $5.0<Q^2<12 \text{ GeV}^2$ is tentatively scheduled for the first year of running after completion of the Jefferson Lab 12 GeV Upgrade Project.

• The N* program with the CLAS12 detector opens up the prospects to explore the nature of confinement and dynamical chiral symmetry breaking in baryons and to elucidate the emergence of >98% of nucleon and N* masses from QCD.

Back up
The Ground and Excited Nucleon State Structure as a Key part in Exploration of Hadron Matter

Nucleons and pions are the first stable composite systems of quarks and gluons generated after the Big Bang by strong interaction in non-perturbative regime. They are the building blocks of atomic nuclei.

The structure of the nucleon ground state from the studies of elastic form factors and different parton structure functions:

Particular features of nucleon structure:
- infinite amount of contributing current quarks and gauge gluons;
- leading role of quark/gluon creation and annihilation;
- all constituents are substantially off-shell;
- important role of relativistic effects;
- frame-dependence of nucleon structure.

Three valence current quarks (Q) embedded in the sea of gluons (g) and $\bar{q}q$-pairs
Summary of the CLAS Data on Exclusive Meson Electroproduction off Protons in N* Excitation Region

<table>
<thead>
<tr>
<th>Hadronic final state</th>
<th>Covered W-range, GeV</th>
<th>Covered Q²-range, GeV²</th>
<th>Measured observables</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\pi^+n)</td>
<td>1.1-1.40</td>
<td>0.15-0.40</td>
<td>(d\sigma/d\Omega)</td>
</tr>
<tr>
<td></td>
<td>1.1-1.55</td>
<td>0.3-0.6</td>
<td>(d\sigma/d\Omega)</td>
</tr>
<tr>
<td></td>
<td>1.1-1.7</td>
<td>1.7-4.2</td>
<td>(d\sigma/d\Omega, A_b)</td>
</tr>
<tr>
<td>(\pi^0p)</td>
<td>1.1-1.40</td>
<td>0.15-0.40</td>
<td>(d\sigma/d\Omega)</td>
</tr>
<tr>
<td></td>
<td>1.1-1.7</td>
<td>0.4-0.7</td>
<td>(d\sigma/d\Omega, A_b, A_t, A_{bt})</td>
</tr>
<tr>
<td></td>
<td>1.1-1.7</td>
<td>0.75-6.0</td>
<td>(d\sigma/d\Omega)</td>
</tr>
<tr>
<td>(\eta p)</td>
<td>1.5-2.0</td>
<td>0.2-4.0</td>
<td>(d\sigma/d\Omega)</td>
</tr>
<tr>
<td>(K^+\Lambda)</td>
<td>1.65-2.35</td>
<td>0.65-2.55</td>
<td>(d\sigma/d\Omega)</td>
</tr>
<tr>
<td></td>
<td>1.65-2.35</td>
<td>1.4-2.6</td>
<td>(P')</td>
</tr>
<tr>
<td>(K^+\Sigma^0)</td>
<td>1.7-2.1</td>
<td>0.5-2.55</td>
<td>(d\sigma/d\Omega)</td>
</tr>
<tr>
<td></td>
<td>1.8-2.5</td>
<td>1.5-3.50</td>
<td>(P')</td>
</tr>
<tr>
<td></td>
<td>1.7-2.6</td>
<td>1.8-3.50</td>
<td>(d\sigma/d\Omega)</td>
</tr>
<tr>
<td>(\pi^+\pi^-p)</td>
<td>1.3-1.6</td>
<td>0.2-0.6</td>
<td>Nine 1-fold differential cross sections</td>
</tr>
<tr>
<td></td>
<td>1.4-2.1</td>
<td>0.5-1.5</td>
<td></td>
</tr>
</tbody>
</table>

- \(d\sigma/d\Omega\) – CM angular distributions
- \(A_b, A_t, A_{bt}\) - longitudinal beam, target, and beam-target asymmetries
- \(P'\) – recoil polarization of strange baryon

Almost full coverage of the final hadron phase space in \(\pi N, \pi^+\pi^-p, \eta p,\) and KY electroproduction

The data are available in the CLAS Physics Data Base established at SINP@MSU:

http://depni.sinp.msu.ru/cgi-bin/jlab/db.cgi
Approaches for Extraction of $\gamma_{vNN^*}$ Electrocouplings from the CLAS Exclusive Meson Electroproduction Data

- Analyses of different meson electroproduction channels independently:

  - $\pi^+n$ and $\pi^0p$ channels:
    - Unitary Isobar Model (UIM) and Fixed-t Dispersion Relations (DR)

  - $\eta p$ channel:
    - Extension of UIM and DR
      - Data fit at $W<1.6$ GeV, assuming $S_{11}(1535)$ dominance

  - $\pi^+\pi^-p$ channel:
    - Data driven JLAB-MSU meson-baryon model (JM)

- Global coupled-channel analyses of the CLAS/world data of $\pi N$, $\gamma_{vN} \rightarrow \pi N$, $\eta N$, $\pi\pi N$, $K\Lambda$, $K\Sigma$ exclusive channels:
Elastic form factors are sensitive to momentum dependence of quark mass function.
Quark mass function extracted from elastic f.f. and $\gamma NN^*$ electrocouplings should be the same.
Data on $\gamma NN^*$ electrocouplings are of particular importance in order to access dressed quark mass function and dynamical structure.

Similar studies for the $P_{33}(1232)$, $P_{11}(1440)$, and $S_{11}(1535)$ electrocouplings are in progress.
N* Electroexcitation in Exclusive Meson Electroproduction off Protons

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Δ(1232)P33</td>
<td>0.995</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N(1440)P11</td>
<td>0.55-0.75</td>
<td>0.3-0.4</td>
<td></td>
</tr>
<tr>
<td>N(1520)D13</td>
<td>0.55-0.65</td>
<td>0.4-0.5</td>
<td></td>
</tr>
<tr>
<td>N(1535)S11</td>
<td>0.48±0.03</td>
<td>0.46±0.02</td>
<td></td>
</tr>
<tr>
<td>Δ(1620)S31</td>
<td>0.20-0.30</td>
<td>0.70-0.80</td>
<td></td>
</tr>
<tr>
<td>N(1650)S11</td>
<td>0.60-0.95</td>
<td>0.03-0.11</td>
<td>0.1-0.2</td>
</tr>
<tr>
<td>N(1685)F15</td>
<td>0.65-0.70</td>
<td>0.30-0.40</td>
<td></td>
</tr>
<tr>
<td>Δ(1700)D33</td>
<td>0.1-0.2</td>
<td>0.8-0.9</td>
<td></td>
</tr>
<tr>
<td>N(1720)P13</td>
<td>0.1-0.2</td>
<td>&gt; 0.7</td>
<td></td>
</tr>
</tbody>
</table>

Hadronic decays of prominent N*s at W<1.8 GeV.

CLAS data on yields of meson electroproduction at $Q^2<4$ GeV$^2$
The Approaches for Extraction of $\gamma_{v}NN^{*}$ Electrocouplings from $N\pi$ Exclusive Electroproduction off Protons

The Model based on fixed-t Dispersion Relations (DR)

- the real parts of 18 invariant $N\pi$ electroproduction amplitudes are computed from their imaginary parts employing model independent fixed-t dispersion relations.

- the imaginary parts of the $N\pi$ electroproduction amplitudes at $W>1.3$ GeV are dominated by resonant parts and were computed from $N^{*}$ parameters fit to the data.


K.Park talk, Session B4, Wednesday, May 29th, 16.15-16.40
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

Legendre moments $D_l$ ($l=0,1,2$) from various structure functions.
Quark Core vs Meson-Baryon Cloud in the Structure of $P_{11}(1440)$

First evaluation of the quark core contribution to the $P_{11}(1440)$ electrocouplings starting from QCD Lagrangian within Dyson-Schwinger Equations of QCD:


- Poincare-covariant, symmetry preserving DSEQCD evaluation.
- Account for quark mass/structure formation in dressing of bare quark by gluon cloud.
- Simplified contact interaction generates momentum independent quark mass.

\[ g^2 D_{\mu\nu}(p-q) \Rightarrow \delta_{\mu\nu} \frac{4\pi \alpha_{ir}}{m_G^2} \]

\[ \frac{\alpha_{ir}}{4\pi} = 0.93 \quad m_G = 0.8 GeV \]

\[ m_q^{bare} = 0.007 GeV \Rightarrow m_q^{dressed} = 0.368 GeV \]

Consistent results on the quark core contribution from:

- DSEQCD.
- Global meson photo-, electro-, and hadroproduction data analysis within EBAC/Argonne-Osaka approach.

Measured dressed electrocouplings are substantially different from the estimated quark core contribution. Different data analyses suggest sizable meson-baryon cloud at $Q^2<5.0$ GeV$^2$ which gradually decreases with $Q^2$. 
High lying resonance electrocouplings from the $\pi^+\pi^-p$ CLAS data analysis

MAID analysis of $N\pi$ electroproduction

The results from $\pi^+\pi^-p$ channel confirmed the previously available from MAID analysis of $N\pi$ electroproduction.


Bethe-Salpeter Bonn model by M.Ronninger, B.Ch.Metsch, EPJ A49, 8 (2013).

Difference between the experimental results and QM expectations is likely related to meson-baryon cloud contributions.

Evaluations of meson-baryon cloud contributions to electrocouplings of high mass resonances are needed.
High lying resonance electrocouplings from the $\pi^+\pi^-p$ CLAS data analysis

Hypercentral constituent quark model by M.Giannini, E.Santopinto, PRC 86, 065202 (2012).

Bethe-Salpeter Bonn model by M.Ronninger, B.Ch.Metsch, EPJ A49, 8 (2013).

- Only known $N^*$-state with dominant longitudinal electroexcitation at $Q^2>0.5$ GeV$^2$.
- This feature is well reproduced within the framework of hypercentral quark model.

- Data on electrocouplings of most excited proton states in mass range up to 1.8 GeV demonstrated distinctive differences in the structure of resonances of different quantum numbers.
- The studies of the ground and all prominent excited state structure combined are needed in order to explore the mechanisms of the ground and $N^*$-state formation from quarks and gluons.
CLAS12 supports a broad program in hadronic physics.

Plans to study excited baryons and mesons:

- Search for hybrid mesons and baryons
- Spectroscopy of $\Xi^*$, $\Omega^-$
- $N^*$ Transition form factors at high $Q^2$. 
Resonance Transitions with the CLAS12

Resonance electrocouplings in regime of quark core dominance can be related to the running quark masses and their dynamical structure.

12 GeV experiment E12-09-003 will extend access to electrocouplings for all prominent N* states in the range up to $Q^2=12\text{GeV}^2$.

Probing the transition from confinement to pQCD regimes, allowing us to explore how confinement in baryons emerge from QCD and how >98% of baryon masses are generated non-perturbatively via dynamical chiral symmetry breaking.
Impact of the Recent LQCD studies of N* Spectrum and Structure on the N* Program with CLAS/CLAS12


• each N* state with $M_{N^*} < 1.8$ GeV has partner in computed LQCD spectrum, but level ordering is not always consistent to the data.

• wave functions of the low-lying N* states dominate by 1-2 SU(6) configurations, while the wave function of high lying N*’s may contain many SU(6) configurations.

• presence of hybrid-N*’s with dominant contribution of hybrid components at $M_{N^*} > 1.9$ GeV marked by

New direction in N* studies proposed in V.D.Burkert, arXiv:1203.2373 [nucl-ex]:
Search for hybrid N*-states looking for:
➢ overpopulation of SU(6)-multiplet;
➢ particular behavior of $\gamma_v NN^*$ electrocouplings, which reflects presence of the hybrid component.

Should be verified by experiment!
Resonant /non-resonant contributions from the fit of $\pi^+\pi^-p$ electroproduction cross sections within the JM model

W=1.51 GeV, $Q^2=0.38$ GeV$^2$

W=1.51 GeV, $Q^2=0.43$ GeV$^2$

Reliable isolation of the resonant cross sections is achieved

full cross sections within the JM model

resonant part

non-resonant part
Transition N-P_{11}(1440) form factors in LQCD

Includes the quark loops in the sea, which are critical in order to reproduce the CLAS data at $Q^2<1.0$ GeV$^2$

$A_{1/2}, S_{1/2} \Rightarrow F_1^*, F_2^*$

$M_{\pi} = 390, 450, 875$ MeV

L box = 3.0, 2.5, 2.5 f

• Exploratory LQCD results provide reasonable description of the CLAS data from the QCD Lagrangian.

• Prospects for LQCD evaluation with improved projection operators, approaching physical $m_\pi$ in the box of appropriate size.