Recent Results from CLAS

K. Hicks (Ohio U.)
Sept. 26, 2017
Hadron 2017 International Conf.
Outline

• Goals of the CLAS Baryon Spectroscopy group
• Linear Polarization data: new N*’s?
• Reactions on the neutron: new $K^0\Lambda$ data
• Meson electroproduction: N* structure
• Photoproduction of $K_sK_s$: scalar mesons
Goals of CLAS Spectroscopy

• Search for “missing” resonances:
  – More N* resonances predicted than observed.
  – Some resonances may couple weakly to $\pi N$.
  – Multi-prong approach: analyze many final states.

• Search for “exotic” hadrons:
  – Ongoing program (not presented in this talk)
  – Scalar mesons: new data from $K_sK_s$ final state

• Many new results!! (I can show only a few)
Polarization Observables

\[
\sigma_{\text{total}} = \sigma_{\text{unpol.}} \left[ 1 - \delta_l \sum \cos(2\phi) \right] \\
+ \Lambda_x \left( -\delta_l H \sin(2\phi) + \delta_\odot F \right) \\
- \Lambda_y \left( -T + \delta_l P \cos2\phi \right) \\
- \Lambda_z \left( -\delta_l G \sin(2\phi) + \delta_\odot E \right) + \ldots
\]

\[\delta_\odot (\delta_l) : \text{degree of beam pol.}\]
\[\Lambda : \text{degree of target pol.}\]
Polarization Transfer: $\gamma p \rightarrow K^+\Lambda$

One example of a “missing” resonance now found!
Strong Evidence for Nucleon Resonances near 1900 MeV


\[ \gamma p \rightarrow K^+ \Lambda \text{ at } W=1.95-1.97 \text{ GeV}, \text{ fits using the Bonn-Gatchina model} \]
$\gamma p \rightarrow K^+ \Lambda$: Fits to the EM multipoles

<table>
<thead>
<tr>
<th>$J^P$ $= 1/2^-$</th>
<th>$J^P$ $= 1/2^+$</th>
<th>$J^P$ $= 3/2^+$</th>
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<tbody>
<tr>
<td><strong>$M_1$</strong></td>
<td>PDG $1640-1670$</td>
<td>BNGA $1658 \pm 10$</td>
</tr>
<tr>
<td>$\Gamma_1$</td>
<td>$100-170$</td>
<td>$102 \pm 8$</td>
</tr>
<tr>
<td>$</td>
<td>\text{Res}_1(\pi N \rightarrow K\Lambda)</td>
<td>$</td>
</tr>
<tr>
<td>$\Theta_1$</td>
<td>$\cdots$</td>
<td>$(110 \pm 20)^0$</td>
</tr>
<tr>
<td><strong>$M_2$</strong></td>
<td>$\cdots$</td>
<td>$1895 \pm 15$</td>
</tr>
<tr>
<td>$\Gamma_2$</td>
<td>$\cdots$</td>
<td>$132 \pm 30$</td>
</tr>
<tr>
<td>$</td>
<td>\text{Res}_2(\pi N \rightarrow K\Lambda)</td>
<td>$</td>
</tr>
<tr>
<td>$\Theta_2$</td>
<td>$\cdots$</td>
<td>$(8 \pm 30)^0$</td>
</tr>
</tbody>
</table>

Evidence for 2 new “missing” resonances & 3 with more precision. Made possible by precision data from CLAS.
Cont’d: comparison with $K^+\Lambda$

No “peak” near 1900 MeV for $K^0\Lambda$: photocouplings $\gamma n N^*$ and $\gamma p N^*$ are different.
g$_{14}$ beam-target helicity asymmetries for $\gamma n \to \pi^- p$ and $N^*$ states excited from the neutron

- 1st double-polarized $\vec{n}$ data
  PRL 118 (2017) 242002

- $E&M$ interaction is not isospin symmetric
- $\gamma nN^*$ and $\gamma pN^*$ couplings are different
- probes of dynamics in $N^*$ excitation

- eg. SAID Partial Wave Analysis (PWA):
  $A_{\gamma n}^{1/2}$ [N(2190)7/2-] $\to -16 \pm 5$ (10$^{-3}$ GeV$^{-1/2}$)
  $A_{\gamma n}^{3/2}$ [N(2190)7/2-] $\to -35 \pm 5$ (10$^{-3}$ GeV$^{-1/2}$)

$\Rightarrow$ PWA $\Rightarrow$

Talk by Tsuneo Kageya on Tuesday
# Neutron helicity amplitudes

A.V. Anisovich¹,², V. Burkert³, N. Compton⁴, K. Hicks⁴, F.J. Klein⁵, E. Klempt¹,³, V.A. Nikonov¹,², A.M. Sandorfi³, A.V. Sarantsev¹,², and U. Thoma¹

<table>
<thead>
<tr>
<th></th>
<th>$A_{1/2}$</th>
<th>Phase</th>
<th>$A^{(BW)}_{1/2}$</th>
<th>$A_{3/2}$</th>
<th>Phase</th>
<th>$A^{(BW)}_{3/2}$</th>
<th>$E$</th>
<th>Phase</th>
<th>$E^{(BW)}$</th>
<th>$M$</th>
<th>Phase</th>
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<td>5±4°</td>
<td>-118±5</td>
<td>88±4</td>
<td>5±4°</td>
<td>81±6</td>
<td>41±5</td>
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<td>-80±40</td>
<td>±(3±2)</td>
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<td>60±25°</td>
<td>-14±10</td>
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<td>5±20° 75±15</td>
<td>-12±10</td>
<td>-10±35 12±9</td>
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<td>-10±5°</td>
<td>51±4</td>
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<td>-60±35° 75±15</td>
<td>-12±10</td>
<td>-10±35 12±9</td>
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<td>3±2</td>
<td>-80±40</td>
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<td>81±30</td>
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<td>-12±10</td>
<td>-10±35 12±9</td>
<td>52±5</td>
<td>-10±5°</td>
<td>51±4</td>
<td></td>
<td></td>
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<tr>
<td>$N(1720)3/2^+$</td>
<td>(25±4)</td>
<td>-75±35°</td>
<td>-(28±4)</td>
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<td>5±20°</td>
<td>79±14</td>
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<td>-26±13</td>
<td>8±25°</td>
<td>-26±13</td>
<td>-77±15</td>
<td>5±20° 75±15</td>
<td>-12±10</td>
<td>-10±35 12±9</td>
<td>52±5</td>
<td>-10±5°</td>
<td>51±4</td>
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<tr>
<td>$N(1675)5/2^-$</td>
<td>-53±4</td>
<td>-3±5°</td>
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<td>-12±5° 72±5</td>
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<td>51±4</td>
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<td>-5±20°</td>
<td>52±24</td>
<td>12±7</td>
<td>-40±35° 12±7</td>
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<td>3±15°</td>
<td>-20±7</td>
<td>52±5</td>
<td>-10±5°</td>
<td>51±4</td>
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<td>$N(1680)5/2^+$</td>
<td>32±3</td>
<td>-7±5°</td>
<td>33±3</td>
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<td>$N(2000)5/2^+$</td>
<td>19±10</td>
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<td>±(19±10)</td>
<td>11±5</td>
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<td>5±20°</td>
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<td>0±20° 72±25</td>
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<td>$N(2190)7/2^-$</td>
<td>30±7</td>
<td>5±15°</td>
<td>30±7</td>
<td>-23±8</td>
<td>13±20°</td>
<td>-23±8</td>
<td>1±3</td>
<td>100±130°</td>
<td>1±3</td>
<td>8±12°</td>
<td>12±4</td>
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</table>

Note: $N(1685)1/2^+$ not needed!
### $\gamma nN^*$ vs $\gamma pN^*$ couplings

<table>
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<tr>
<th>$(10^{-3}$ GeV$^{-1/2}$)</th>
<th>$A_n^{1/2}$</th>
<th>$A_p^{1/2}$</th>
<th>$A_n^{3/2}$</th>
<th>$A_p^{3/2}$</th>
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<tr>
<td><strong>SAID</strong></td>
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<td>N(1720)3/2$^+$</td>
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<td>95 ±2$^6$</td>
<td>13 ±4$^4$</td>
<td>-48 ±2$^6$</td>
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<tr>
<td>N(1895)1/2$^-$</td>
<td>----</td>
<td>----</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td>N(1975)3/2$^+$</td>
<td>----</td>
<td>----</td>
<td>----</td>
<td>----</td>
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<tr>
<td>N(2190)7/2$^-$</td>
<td>-16 ±5$^4$</td>
<td>- -</td>
<td>-35 ±5$^4$</td>
<td>- -</td>
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<tr>
<td><strong>BnGa</strong></td>
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<tr>
<td>N(1720)3/2$^+$</td>
<td>-(28 +40/-15)$^3$</td>
<td>110 ±45$^5$</td>
<td>±(103 ±35)$^3$</td>
<td>150 ±30$^5$</td>
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<tr>
<td>N(1895)1/2$^-$</td>
<td>-15 ±10$^3$</td>
<td>-11 ±6$^5$</td>
<td>-77 ±15$^3$</td>
<td>- -</td>
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<tr>
<td>N(1975)3/2$^+$</td>
<td>-26 ±13$^3$</td>
<td>- -</td>
<td>-23 ±8$^1$</td>
<td>+35 ±17$^5$</td>
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<tr>
<td>N(2190)7/2$^-$</td>
<td>+30 ±7$^1$</td>
<td>-65 ±8$^5$</td>
<td>- -</td>
<td>- -</td>
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</table>

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4. R.L. Workman and A. Švarc (priv. comm.)

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Slide borrowed from A. Sandorfi
Extracted spin-density matrix elements:

\[ \rho_{00} \]

and \( \Lambda \) recoil polarization:

Additional fits to differential cross sections and other spin-density \((\rho_{10}, \rho_{11})\) done.
CLAS $\gamma p \to K^*0\Lambda$ Total Cross Section

Considerable s-channel strength is needed

Bonn-Gatchina model fit has two possible solutions (bounded hatched regions)

**t-channel only**
CLAS $\gamma p \rightarrow K^{*0}\Lambda$ BoGa fit results:

Possible new high-mass $N^*$'s

Often we see $N^*$ resonances near the threshold of higher-mass meson production.
Extraction of $\gamma_v NN^*$ Electrocouplings from Exclusive Meson Electroproduction off Nucleons

Resonant amplitudes

Non-resonant amplitudes

Definition of $N^*$ photo-/electrocouplings employed in the CLAS data analyses:

\[
\Gamma_\gamma = \frac{k_{\gamma N^*}^2}{\pi} \frac{2M_N}{(2J_r+1)M_{N^*}} \left[A_{1/2}^2 + |A_{3/2}|^2\right]
\]

$\Gamma_\gamma$: $N^*$ electromagnetic decay widths; $W=M_{N^*}$ on the real energy axis.

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

Slides borrowed from V. Mokeev
## Summary of Published 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>1.1-1.38&lt;br&gt;1.1-1.55&lt;br&gt;1.1-1.7&lt;br&gt;1.6-2.0</td>
<td>0.16-0.36&lt;br&gt;0.3-0.6&lt;br&gt;1.7-4.5&lt;br&gt;1.8-4.5</td>
<td>$d\sigma/d\Omega$&lt;br&gt;$d\sigma/d\Omega$&lt;br&gt;$d\sigma/d\Omega$, $A_b$&lt;br&gt;$d\sigma/d\Omega$</td>
</tr>
<tr>
<td>$\pi^0p$</td>
<td>1.1-1.38&lt;br&gt;1.1-1.68&lt;br&gt;1.1-1.39</td>
<td>0.16-0.36&lt;br&gt;0.4-1.8&lt;br&gt;3.0-6.0</td>
<td>$d\sigma/d\Omega$&lt;br&gt;$d\sigma/d\Omega$, $A_b$, $A_t$, $A_{bt}$&lt;br&gt;$d\sigma/d\Omega$</td>
</tr>
<tr>
<td>$\eta p$</td>
<td>1.5-2.3</td>
<td>0.2-3.1</td>
<td>$d\sigma/d\Omega$</td>
</tr>
<tr>
<td>$K^+\Lambda$</td>
<td>thresh-2.6</td>
<td>1.40-3.90&lt;br&gt;0.70-5.40</td>
<td>$d\sigma/d\Omega$&lt;br&gt;$P^0$, $P'$</td>
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<tr>
<td>$K^+\Sigma^0$</td>
<td>thresh-2.6</td>
<td>1.40-3.90&lt;br&gt;0.70-5.40</td>
<td>$d\sigma/d\Omega$&lt;br&gt;$P'$</td>
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<tr>
<td>$\pi^+\pi^-p$</td>
<td>1.3-1.6&lt;br&gt;1.4-2.1&lt;br&gt;1.4-2.0</td>
<td>0.2-0.6&lt;br&gt;0.5-1.5&lt;br&gt;2.0-5.0</td>
<td>Nine 1-fold differential cross sections</td>
</tr>
</tbody>
</table>

- $d\sigma/d\Omega$—CM angular distributions
- $A_b$, $A_t$, $A_{bt}$—longitudinal beam, target, and beam-target asymmetries
- $P^0$, $P'$—recoil and transferred polarization of strange baryon

**Recent extensions**

Almost full coverage of the final hadron phase space in $\pi N$, $\pi^+\pi^-p$, $\eta p$, $K\Sigma$ electroproduction

The measured observables from CLAS for the exclusive electroproduction of all listed final states are stored in the CLAS Physics Data Base [http://clas.sinp.msu.ru/cgi-bin/jlab/db.cgi](http://clas.sinp.msu.ru/cgi-bin/jlab/db.cgi).

Slides borrowed from V. Mokeev
N(1440)1/2+ electrocoupling

2002

V. Burkert, Baryons 2002

2016

$A_{1/2}^{*1000}$ (GeV^{-1/2})

$Q^2$ (GeV^2)

$N\pi$
$p\pi^+\pi^-$
$\text{RPP}$
$\text{CLAS}^*$

V. D. Burkert, Baryons 2016

Slides borrowed from V. Mokeev
DSE analyses of the CLAS data on $\Delta(1232)3/2^+$ electroexcitation for the first time demonstrated that dressed quark mass is running with momentum.

Good data description at $Q^2 > 2.0$ GeV$^2$ achieved with the same dressed quark mass function for the ground and excited nucleon states of distinctively different structure provides strong evidence for:

- the relevance of dressed quarks with dynamically generated mass and structure;
- access to quark mass function from the data on elastic and $N \rightarrow N^*$ transition form factors.

One of the most important achievements in hadron physics of the last decade obtained in synergistic efforts between experimentalists and theorists.

Slides borrowed from V. Mokeev
New CLAS $\pi^+\pi^-p$ Electroproduction Data at High Photon Virtualities

Fully integrated $\pi^+\pi^-p$ electroproduction cross sections off protons

$1.40 \text{ GeV} < W < 2.00 \text{ GeV}, \ 2.0 \text{ GeV}^2 < Q^2 < 5.0 \text{ GeV}^2$


**Analysis objectives:**

- Extraction of $\gamma_pN^*$ electrocouplings for most $N^*$s in mass range up to $W=2.0 \text{ GeV}$ and $2.0 < Q^2 < 5.0 \text{ GeV}^2$.

- Search for new baryon states through their manifestations in exclusive $\pi^+\pi^-p$ electroproduction with $Q^2$-independent masses and decay widths.

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**Mass range where the signals from new baryon states were reported,**

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Slides borrowed from V. Mokeev
CLAS12 N* Program at High $Q^2$

E12-09-003  
Nucleon Resonance Studies with CLAS12  
Gothe, Mokeev, Burkert, Cole, Joo, Stoler

E12-06-108A  
KY Electroproduction with CLAS12  
Carman, Gothe, Mokeev

Measure exclusive electroproduction cross sections from an unpolarized proton target with polarized electron beam for $N\pi$, $N\eta$, $N\pi\pi$, KY:

$$E_b = 11 \text{ GeV}, \quad Q^2 = 3 \rightarrow 12 \text{ GeV}^2, \quad W \rightarrow 3.0 \text{ GeV} \text{ with the almost complete coverage of the final state phase space}$$

Key Motivation

Study the structure of all prominent $N^*$ states in the mass range up to 2.0 GeV vs. $Q^2$ up to 12 GeV$^2$.

CLAS12 is the only facility foreseen in the world capable to map-out $N^*$ quark core under almost negligible contributions from meson-baryon cloud

The experiments will start at the end of 2017!
Photoproduction can give info on the coupling of the $f_0$ meson to the photon.
What previous experiments observed

$p\bar{p} \rightarrow \pi^0\eta\eta$

$p\bar{p}$ annihilation: Crystal Barrel

$f_0(1500)$ is seen in the $\eta\eta$ mass projection

BES II

$J/\Psi \rightarrow \gamma\pi\pi$

PWA: $J=0 \rightarrow f_0(1500)$

Shaded region = $J/\Psi \rightarrow \pi^+\pi^-\pi^0$ WA102 Central production

The $f_0(1500)$ is clearly seen


ZEUS Experiment: detected $K^0_S K^0_S$

Why choose strange decay?

M. Chanowitz suggests in PRL 95, 172001 (2005) that glueballs are more likely to decay to strange channels.

Why choose $K^0_S K^0_S$? Ensure that the final state has the same $PC = ++$ as the lightest glueball.

CLAS: $\gamma p \rightarrow K_s^0 K_s^0 p$ (g12 run)

The plot of the two $K_s^0$ plotted against each other shows the high correlation between them.

There is a clear kaon peak above the combinatorial background.

Only those events are selected which have a missing mass of the proton.

The plot of the two $K_s^0$ plotted against each other shows the high correlation between them.

4 combinations of $\pi^+\pi^-$ are possible. We select the 2 combinations that most closely match the value of the $K_s$ mass.
Invariant mass: \( f_0 \rightarrow K_S^0 K_S^0 \)

All events: \( M(4\pi): M(K_S K_S) + \) sidebands

Sideband-subtracted events

<table>
<thead>
<tr>
<th>Cut Level</th>
<th>Type of Cut</th>
<th>Size of Cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Timing Cut for identification of pions</td>
<td>( \pm 1 \text{ ns} )</td>
</tr>
<tr>
<td>2</td>
<td>Fiducial Cut</td>
<td>Fit to CLAS acceptance</td>
</tr>
<tr>
<td>3</td>
<td>Missing mass (proton)</td>
<td>( \pm 0.0497 \text{ GeV} (3\sigma) )</td>
</tr>
<tr>
<td>4</td>
<td>Photon beam energy</td>
<td>2.7-3.0 and 3.1-5.1 GeV</td>
</tr>
<tr>
<td>5</td>
<td>( K_S^0 ) peak and sideband subtraction</td>
<td>0.01614 GeV (3\sigma)</td>
</tr>
</tbody>
</table>
Figure 6. Background subtracted plots for the $4\pi$ invariant mass for $|t| < 1$ GeV$^2$ (left) and $|t| > 1$ GeV$^2$ (right).
Angular distributions (G.J.-frame)
Summary

• CLAS data, including polarization observables, are being used to identify “missing” N*’s.
  – KY data has been especially fruitful here.

• Electroproduction data used to extract the N* electrocouplings to give info on N* structure.
  – Meson-baryon terms contribute significantly:
    • Complex interplay of 3-quark core and meson-baryon cloud
• Preliminary results indicate $f_0(1500)$ produced via t-channel photoproduction.
  – Contrary to expectation of a “pure” glueball.