Nucleon Resonance Studies with CLAS12

Spokespersons: R. Gothe, V. Mokeev, V. Burkert, P. Cole, K. Joo, and P. Stoler

Experiment Details

- Measure $N\pi$, $N\eta$, and $N\pi\pi$ electroproduction off an unpolarized proton target with an 11 GeV longitudinally polarized electron beam
- Measure the sets of correlated differential cross sections, exclusive structure functions for $W$ [1.07, 3.0 GeV], $Q^2$ [3, 12 GeV$^2$] and full angular coverage for all final hadrons

Experiment Goals

- Extraction of $\gamma_vpN^*$ electrocouplings for prominent $N^*$, $\Delta^*$ states in the mass range $W$ up to 3.0 GeV at the highest photon virtualities ever achieved, $Q^2$ up to 12 GeV$^2$
- Exploration of many facets of strong QCD dynamics behind the generation of excited nucleons of different quantum numbers over full $N^*$ spectrum
- Address the challenging open problems of the Standard Model on the nature of more than 98% of hadron mass, quark-gluon confinement, emergence of color charge from the results on $\gamma_vpN^*$ electrocouplings obtained at the distances where the transition from the strong to perturbative QCD regimes takes place
Acceptance for $\pi^0p$ and $\pi^+n$ Electroproduction

Simulation: GEMC 4a.2.1 and COATJAVA 4a.8.2
Beam energy: 10.6 GeV, Torus: -75% and +75%
Target: LH2, Z-vertex position from -2.5 to 2.5 cm

- Detection acceptance depends only weakly on the torus polarity and solenoid current within CLAS12 (electron and one hadron detected)
- Acceptance is 45% - 75% when e' hits the forward detector and roughly 70% when e' hits the forward tagger (FT)
- Acceptance also depends only weakly on all kinematic variable: $Q^2$, $W$, $\theta^*_\pi$, and $\phi^*_\pi$
- Positive torus current polarity, e' outbending, is preferred to study the low $Q^2$ region

$3 GeV^2 < Q^2 < 6 GeV^2$
$1.1 GeV < W < 2.2 GeV$
Count Rates for $\pi^0 p$ and $\pi^+ n$ Electroproduction

- Physics EG, GEMC 4a.2.1, COATJAVA 4a.8.2, and CLAS12 nominal luminosity are used to estimate the **count rates / averaged number of events per bin** in 20 days of the run time.
- The bin sizes are $\Delta Q^2 = 1$ GeV$^2$, $\Delta W = 20$ MeV, and 10 bins in both $\cos(\theta_{\pi}^*)$ and $\phi_{\pi}^*$, resulting in a total of $1.2 \times 10^5$ bins.
- Possible **prescale factors** for the FT rates (small $Q^2$) are not taken into account here.

<table>
<thead>
<tr>
<th>Reaction torus/solenoid</th>
<th>$0&lt;Q^2&lt;2$</th>
<th>$2&lt;Q^2&lt;5$</th>
<th>$5&lt;Q^2&lt;8$</th>
<th>$8&lt;Q^2&lt;12$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^0 p$ -75%/60%</td>
<td>3900 / 350K</td>
<td>35 / 2.1K</td>
<td>1.26 / 75</td>
<td>0.078 / 3.48</td>
</tr>
<tr>
<td>$\pi^0 p$ +75%/60%</td>
<td>9100 / 810K</td>
<td>37 / 2.2K</td>
<td>1.24 / 74</td>
<td>0.073 / 3.28</td>
</tr>
<tr>
<td>$\pi^+ n$ -75%/60%</td>
<td>6500 / 580K</td>
<td>55 / 3.3K</td>
<td>1.07 / 64</td>
<td>0.070 / 3.13</td>
</tr>
<tr>
<td>$\pi^+ n$ +75%/60%</td>
<td>6600 / 590K</td>
<td>52 / 3.1K</td>
<td>1.05 / 63</td>
<td>0.062 / 2.78</td>
</tr>
</tbody>
</table>

$Q^2$ in GeV$^2$ and count rates in Hz
For $2 \text{ GeV}^2 < Q^2 < 12 \text{ GeV}^2$ almost no dependence on torus current polarity, while at $Q^2 < 2.0 \text{ GeV}^2$ positive (+75% or +100%) polarity is favored.
## Count Rates for $\gamma_vp\rightarrow\pi^+\pi^-p$ Electroproduction

<table>
<thead>
<tr>
<th>Torus field $B_T$ % from maximal</th>
<th>Solenoid field $B_s$ % from maximal</th>
<th>$Q^2$-range GeV$^2$</th>
<th>Acceptance %</th>
<th>Count Rate Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>+75</td>
<td>+60</td>
<td>2.0-5.0</td>
<td>18</td>
<td>32</td>
</tr>
<tr>
<td>-75</td>
<td>+60</td>
<td>2.0-5.0</td>
<td>17</td>
<td>31</td>
</tr>
<tr>
<td>+75</td>
<td>+60</td>
<td>5.0-12.0</td>
<td>19</td>
<td>1.0</td>
</tr>
<tr>
<td>-75</td>
<td>+60</td>
<td>5.0-12.0</td>
<td>18</td>
<td>0.9</td>
</tr>
<tr>
<td>+75</td>
<td>+60</td>
<td>0.02-12.0</td>
<td>12</td>
<td>13K</td>
</tr>
</tbody>
</table>

- Acceptances and count rates are for the leading $\pi^-$ missing topology only
- About 99% of the count rates come from the low-photon-virtuality range $0.02 \text{ GeV}^2 < Q^2 < 2.0 \text{ GeV}^2$, FT might be prescaled.
- Preferred conditions
  - positive current for torus field below $Q^2 = 2.0 \text{ GeV}^2$, although no sensitivity to the torus polarity above $Q^2 = 2.0 \text{ GeV}^2$, and
  - torus current (100% or 75%)
### First Publication: $\pi^+n$ and $\pi^0p$ Beam Asymmetries

20 day run, $L=10^{35}$ cm$^2$ s$^{-1}$, results in 4-dim. $(W,Q^2,\theta,\phi)$-bins, bin grid: 12 $\phi$ bins, 8 $\theta$ bins, $W$-bin size 50 MeV, and $Q^2$-bin size 1.0 GeV$^2$

- W: 1.07-1.7 GeV, $Q^2$: 3.0-6.0 GeV$^2$
- Estimates for average value of beam asymmetry in a single $(W,Q^2,\theta,\phi)$-bin: $<A_{LU}> = 0.1$

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One of the first publication related to $N\pi$ will be based on the beam asymmetry $A_{LU}$ in $N\pi$ channels (unnormalized yields) that will be measured for the first time for $Q^2 > 3.3$ GeV$^2$

- CLAS studies (I.G. Aznauryan et al., PRC 80, 055203 (2009)) have shown that the beam asymmetry is sensitive to the variation of $\gamma_vpN^*$ electrocouplings
- New data on $A_{LU}$ at $3.3$ GeV$^2 < Q^2 < 6.0$ GeV$^2$ will be analyzed within a) JLab/Yerevan UIM/DR reaction models based on $\gamma_vpN^*$ electrocouplings extrapolated from the available CLAS data into the range of the aforementioned $Q^2$ adjusted to the data, and b) accounting for resonant contributions only
- A successful description of beam asymmetry data achieved with the same $N^*$ parameters in the approaches a) and b) will allow us to pin down the kinematics domain of dominant resonance contributions
**First Publication: \( \pi^+n/\pi^0p \) Cross Section Ratio**

Projected statistical uncertainties in a single \((W,Q^2)\)-bin

- \( Q^2=3.5 \text{ GeV}^2 \)
- \( Q^2=4.5 \text{ GeV}^2 \)
- \( Q^2=5.5 \text{ GeV}^2 \)

\(\pi^+n/\pi^0p\) cross section ratio from CLAS

20 day run, \( L=10^{35} \text{ cm}^{-2} \text{ s}^{-1} \), results for 2-dim. \((W,Q^2)\)-bins after integration over all \( \phi \) and \( \theta \) from 0° to 55°, W-bin size 50 MeV, \( Q^2 \)-bin size 1.0 GeV²

Cross sections at \( Q^2 > 4.0 \text{ GeV}^2 \) are evaluated assuming the same \( Q^2 \)-dependence for \( \pi^+n \) and \( \pi^0p \)

- Beam asymmetry results should be augmented by measurements of unnormalized \( \pi^+n \) and \( \pi^0p \) yields accounting for acceptance differences, i.e. \( \pi^+n/\pi^0p \) cross section ratios that will be measured for the first time above \( Q^2 = 3.5 \text{ GeV}^2 \)

- Consistent description of asymmetries and cross section ratios with the same \( N^* \) parameters will support the preliminary estimates of electrocouplings for many resonances in the mass range <1.7 GeV at still unexplored photon virtualities 4.3-6.0 GeV²
Exclusive N* → KY Studies with CLAS12

Spokespersons: D.S. Carman, R. Gothe, V. Mokeev

E12-06-108A

Experiment Details

- Measure K⁺Λ and K⁺Σ⁰ electroproduction off an unpolarized proton target with an 11 GeV longitudinally polarized electron beam
- Measure differential cross sections, separated structure functions, induced and recoil hyperon polarization for W [1.6, 3.0 GeV], Q² [2, 12 GeV²], and cosθ⁺ [-1.0, 1.0]

Experiment Goals

- Extraction of γᵥNN* electrocoupling amplitudes for prominent N*, Δ* states that couple to KY final states – complementing the Nππ final state
- Search for evidence of hybrid baryon contributions through Q² evolution of electrocouplings
- Understand KY reaction dynamics and quark pair creation operators via polarization observables
KY Monte Carlo Studies

CLAS12 Simulation Studies:
\( \text{ep} \rightarrow \text{e}'\text{K}^+\text{Y}, \text{Y} = \Lambda, \Sigma^0 \)

Monte Carlo:
GEMC: 4a.2.1

Reconstruction:
COATJAVA: 4a.8.2

Conditions:
\( E_b = 10.6 \text{ GeV} \)
Torus: \( \pm 60\%, \pm 75\%, \pm 100\% \)
Solenoid: 60%, 80%
\( W = 1.6 – 3.0 \text{ GeV} \)
\( Q^2 = 2.0 – 12.0 \text{ GeV}^2 \)
\( \cos \theta_{K^*} = [-1.0,1.0] \)
5-cm LH$_2$ target

Event Generator:
Modified RPR/MSU model

Comparison of generated and reconstructed kinematics for final state particles: \( \text{e}', \text{K}^+, \text{p}, \pi^- \)

Torus: 100%, solenoid: 60%
KY Torus Field Studies

Missing Mass $\text{MM}(e'K^+)$ and Resolution $\sigma_{\text{MM}}$

Note:
Simulations do not include radiative effects or backgrounds
$\Rightarrow$ reality will be worse than demonstrated here

Torus 75%  Torus 100%

Torus at 75% field limits kinematic reach in $Q^2$ as KY final states cannot be separated much beyond 6 GeV$^2$
KY Rate Studies – Spring 2018 Run

Assuming that spring RG-A run amounts to 20 PAC days:

- Estimate expected yields at $Q^2=1.5 \text{ GeV}^2$ and $5.5 \text{ GeV}^2$ for $E_b=10.6 \text{ GeV}$ compared to yields from the CLAS elf analysis at $1.8 \text{ GeV}^2$

- The statistics allow for precision electroproduction measurements at lower $Q^2$ even in the exclusive channels and for viable measurements at high $Q^2$

Average Acceptance
- $e'K^+ : 10 \rightarrow 35\%$
- $e'K^+p : 5 \rightarrow 25\%$
- $e'p\pi^- : 5 \rightarrow 15\%$

larger at $\cos\theta_{K^*} > 0$
smaller at $\cos\theta_{K^*} < 0$

$\Delta W=50 \text{ MeV}$, $\Delta Q^2=1 \text{ GeV}^2$, $\Delta \cos\theta_{K^*}=0.2$, $\Delta \phi=45^\circ$, Torus 100%, and Solenoid 60%
The first publication related to KY will be based on measurements of unnormalized yields ⇒ hyperon recoil and beam-recoil transferred polarization.

Previous CLAS studies (PRL, CERN Courier) have shown that transferred polarization is sensitive to the quark-pair creation operator $ss$.

Recoil polarization data at $Q^2 = 0$ and $Q^2 > 0$ show differences, likely due to $\gamma_L^*$. A 20 day run will allow for precision measurements of hyperon polarization observables at $Q^2 < 3\text{GeV}^2$ to shed light on these issues.

\[ \text{\textbf{A beam-recoil transferred polarization}} \]
Search for Hybrid Baryons with CLAS12


Experiment Details

- Measure $K^+\Lambda$, $K^+\Sigma^0$, and $N\pi^+\pi^-$ electroproduction off an unpolarized proton target with longitudinally polarized electron beam at low $Q^2$
- Measure differential cross sections, separated structure functions, and induced and recoil hyperon polarization for $W [1.6,3.0 \text{ GeV}]$, $Q^2 [0.02,3 \text{ GeV}^2]$, and $\cos \theta_{K_{cm}} [-1.0,1.0]$

Experiment Goals

- Measure $\gamma_{\nu}NN^*$ electrocoupling amplitudes for $N^*$, $\Delta^*$ states that couple to KY or $N\pi\pi$ final state, in kinematical regions complementary to E12-06-108A and E12-09-003 proposals
- Search for evidence of hybrid baryon contributions through low $Q^2$ evolution of the $\gamma_{\nu}NN^*$ electrocouplings
**Event Simulation in CLAS12**

**K⁺ missing mass resolution**

- **E_b = 8.8 GeV**
- Torus 100%

- **σ = 15 MeV**
- **σ = 13 MeV**

**Minimum measurable Q²**

- **E_b = 10.6 GeV**
- **0.2 GeV²**

**Trigger Conditions:**
- One electron in CLAS12 or one electron in the FT and one (potentially prescaled) or two charged particles in CLAS12
- Integrated reconstructed count rate of 90 Hz for W [1.6,3.0 GeV], Q² [0.2,3.0 GeV²] and full angular coverage for all final hadrons

**Acceptance**

<table>
<thead>
<tr>
<th>E_b</th>
<th>one missing hadron</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.6 GeV</td>
<td>33%</td>
</tr>
</tbody>
</table>
Transition Form Factor of the $\eta'$ with CLAS12

Experiment Goals

- Many physics issues suggest physics beyond the Standard Model
  - Currently a promising candidate to provide a signal for physics beyond SM is the muon anomaly ($a_\mu = (g - 2)/2$)
  - Largest uncertainty arise from the hadronic quantum correction

- HLbL correction can be improved by measuring the time-like transition form factor at low-to-moderate momenta
  - Using electroproduction $ep \rightarrow e'pX \rightarrow e'p\gamma*\gamma \rightarrow e'p e^+ e^- \gamma$

- Improvements to the $\pi^0, \eta, \eta'$ TFF can improve precision of the HLbL correction by 14%, 23%, and 15%, respectively [2] and the foundation of strong QCD theory

$\eta'$ Generation with GiBUU

Simulation: GEMC4a.2.0 and COATJava4a.7.3
Generated: $ep \rightarrow e'\eta'p \rightarrow e'^+e^-p\gamma$
Reconstructed: $ep \rightarrow e'\eta'p \rightarrow e'^+e^-p(\gamma)$

Background from choosing incorrect $e^-$ in $M_x(pe^-)$

Yield per 28 MeV

Yield per 9.6 MeV
η’ Reconstruction with CLAS12

Generated: $ep \rightarrow e'\eta'p \rightarrow e'^+e'^-\gamma$
Reconstructed: $ep \rightarrow e'\eta'p \rightarrow e'^+e'^-p(\gamma)$
Detectors used: FT, DC, HTCC, ECAL

Background from choosing incorrect $e^-$ in $M_x(pe^-)$

Yield per 28 MeV

$M_x(pe^-)$ in GeV

Yield per 9.6 MeV

$M(e^+e^-)$ in GeV

Yield per 28 MeV
\[ \eta' \text{ Dalitz Decay Event Yields in 20 Days} \]

Reconstructed: \( ep \rightarrow e' \eta' p \rightarrow e'^+ e^- p(\gamma) \)

- Torus -75%
- Solenoid 60%
- Errors are statistical
- Area accessible in previous TFF determination

\( \sim 4x \) greater statistics than best measurement

- Torus 100%
- Solenoid 60%
- Errors are statistical
- Area accessible in previous TFF determination

\( \sim 1.7x \) greater statistics than best measurement

M. Kunkel
First Experiment Hadron Structure Group

Manpower, Affiliation, and Association

Baryon Structure (E12-09-003, E12-06-108A, E12-16-010)

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- **Students:** V. Klimenko (MSU), K. Neupane (USC), and D. Shukla (UCONN)

Meson Structure (E12-06-108B)

- **PI:** M. Kunkel (FZ Juelich) and D. Lersch (FZ Juelich)
- **Senior Scientists:** J. Ritman (FZ Juelich) and S. Schadmand (FZ Juelich)