Single $\pi^0$ Electroproduction in the Resonance Region with CLAS

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Electromagnetic Excitation of N*

- Allows to address the central question: What are the relevant degrees-of-freedom at varying distance scale?
Electromagnetic Excitation of N*’s

The experimental N* Program has two major components:

1) Accurate measurements of transition form factors \( (A_{3/2}, A_{1/2}, S_{1/2}) \) of known states as photon virtuality \( (Q^2) \) to probe their internal structure and confining mechanism.

2) Search for undiscovered new baryon states.

Both parts of the program are being pursued in various decay channels, e.g. \( N\pi, p\eta, p\pi^+\pi^- , K\Lambda, K\Sigma, p\omega, pp^0 \) using cross sections and polarization observables.
SU(6)xO(3) Classification of Low Lying N*
Transition Form Factors of Low Lying $N^*$ States

$p\pi^0$ channel is important to study:

The $\gamma^*N\Delta(1232)$ Quadrupole Transition

$N^*$ Transition Form Factors in the 2nd Resonance Region -
“Roper” $P_{11}(1440)$, $S_{11}(1535)$, $D_{13}(1520)$
The $\gamma^*N\Delta(1232)$ Quadrupole Transition

SU(6): $E_{1+} = S_{1+} = 0$

<table>
<thead>
<tr>
<th></th>
<th>E/M</th>
<th>S/M</th>
</tr>
</thead>
<tbody>
<tr>
<td>pion cloud</td>
<td>~0.03</td>
<td>-0.1</td>
</tr>
<tr>
<td>one-gluon exch.</td>
<td>~0.01</td>
<td></td>
</tr>
<tr>
<td>pQCD</td>
<td>+1 const.</td>
<td></td>
</tr>
</tbody>
</table>

Shape at low $Q^2$

E/M < 0

E/M > 0

pQCD limit

pQCD limit
$\gamma^* N\Delta$ Multipole Ratios $R_{EM}, R_{SM}$ before JLab

$R_{EM} = \frac{E_{1+}}{M_{1+}}$

$R_{SM} = \frac{S_{1+}}{M_{1+}}$

Sign @ $Q^2 > 0$ ?

$Q^2$ dependence?
\(\gamma^* N\Delta\) Multipole Ratios \(R_{EM}, R_{SM}\) with JLab

- \(R_{EM} = -2\) to \(-4\%\) at \(0 \leq Q^2 \leq 6\) GeV\(^2\).

- \(R_{SM} < 0\), increasing in magnitude.

- \(R_{EM} < 0\) favors oblate shape of \(\Delta(1232)\).

- Pion contributions needed to explain shape, magnitude.

- No trend towards asymptotic behavior \(R_{EM} \to 100\%\).
<table>
<thead>
<tr>
<th>Resonance</th>
<th>Description</th>
</tr>
</thead>
</table>
| $P_{11}(1440)$ | Poorly understood in nrCQMs. Other models:  
  - Hybrid baryon with gluonic excitation $|q^3G>$  
  - Quark core with large meson cloud $|q^3m>$  
  - Nucleon-sigma molecule $|N\sigma>$  
  - Dynamically generated resonance |
| $S_{11}(1535)$ | Hard form factor (slow fall off with $Q^2$)  
  Not a quark resonance, but $K\Sigma$ dynamical system? |
| $D_{13}(1520)$ | Change of helicity structure with increasing $Q^2$ from $\lambda=3/2$ dominance to $\lambda=1/2$ dominance, predicted in nrCQMs, pQCD. |
Roper $P_{11}(1440)$ Helicity amplitudes

2. Capstick, PRD51 (1995) 3598
5. Aznauryan, PRC76 (2007) 025212

I. G. Aznauryan et al. (CLAS), arXiv:080447 [nucl-ex]
Transverse amplitudes for $\gamma^* p \rightarrow D_{13}(1520)$
CLAS Single Pion Electro-production Data

Data in the $\Delta(1232)$ region up to $W = 1.4$ GeV

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Collaboration</th>
<th>Year</th>
<th>Reaction</th>
<th>$Q^2$ Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>JLab/Hall C</td>
<td>Frolov</td>
<td>1999</td>
<td>$p\pi^0$</td>
<td>$Q^2 = 2.5 - 4.3$ GeV$^2$</td>
</tr>
<tr>
<td>Bates</td>
<td>Mertz et al.</td>
<td>2001</td>
<td>$p\pi^0$</td>
<td>$Q^2 = 0.127$ GeV$^2$</td>
</tr>
<tr>
<td>Mainz</td>
<td>Pospischil et al.</td>
<td>2001</td>
<td>$p\pi^0$</td>
<td>$Q^2 = 0.127$ GeV$^2$</td>
</tr>
<tr>
<td>JLab/CLAS</td>
<td>Joo et al.</td>
<td>2002</td>
<td>$p\pi^0$</td>
<td>$Q^2 = 0.4 - 1.8$ GeV$^2$</td>
</tr>
<tr>
<td>Bonn</td>
<td>Bantes, Gothe</td>
<td>2002</td>
<td>$p\pi^0$</td>
<td>$Q^2 = 0.6$ GeV$^2$</td>
</tr>
<tr>
<td>JLab/CLAS</td>
<td>Egiyan et al.</td>
<td>2006</td>
<td>$n\pi^+$</td>
<td>$Q^2 = 0.3 - 0.6$ GeV$^2$</td>
</tr>
<tr>
<td>Mainz</td>
<td>Elsner et al. / Stave et al.</td>
<td>2006</td>
<td>$p\pi^0$</td>
<td>$Q^2 = 0.05 - 0.2$ GeV$^2$</td>
</tr>
<tr>
<td>JLab/CLAS</td>
<td>Ungaro et al.</td>
<td>2006</td>
<td>$p\pi^0$</td>
<td>$Q^2 = 3.0 - 6.0$ GeV$^2$</td>
</tr>
<tr>
<td>JLab/Hall A</td>
<td>Kelly et al.</td>
<td>2007</td>
<td>$p\pi^0$</td>
<td>$Q^2 = 1.0$ GeV$^2$</td>
</tr>
<tr>
<td>JLab/CLAS</td>
<td>Park et al.</td>
<td>2008</td>
<td>$n\pi^+$</td>
<td>$Q^2 = 3.0 - 6.0$ GeV$^2$</td>
</tr>
</tbody>
</table>
## CLAS Single Pion Electro-production Data

Data up to the 3rd resonance region up to $W = 1.7$ GeV

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Collaboration</th>
<th>Year</th>
<th>Mode</th>
<th>$Q^2$ Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>JLab/CLAS</td>
<td>Joo et al. ($A_e$ only)</td>
<td>2003</td>
<td>$p\pi^0$</td>
<td>$0.4 - 0.65$ GeV$^2$</td>
</tr>
<tr>
<td>JLab/CLAS</td>
<td>Joo et al. ($A_e$ only)</td>
<td>2004</td>
<td>$n\pi^+$</td>
<td>$0.4 - 0.65$ GeV$^2$</td>
</tr>
<tr>
<td>JLab/Hall A</td>
<td>Laveissiere et al.</td>
<td>2004</td>
<td>$p\pi^0$</td>
<td>$1.0$ GeV$^2$</td>
</tr>
<tr>
<td>JLab/CLAS</td>
<td>Egiyan et al.</td>
<td>2006</td>
<td>$n\pi^+$</td>
<td>$0.3 - 0.6$ GeV$^2$</td>
</tr>
<tr>
<td>JLab/CLAS</td>
<td>Park et al.</td>
<td>2008</td>
<td>$n\pi^+$</td>
<td>$1.7 - 4.5$ GeV$^2$</td>
</tr>
</tbody>
</table>
CLAS Single $\pi^0$ Electro-production Data Analysis

- **E1E:**
  - Beam Energy: 1 GeV and 2 GeV
  - Low $Q^2$ up to 1.5 GeV, and $W$ up to 1.7 GeV

- **E1-6:**
  - Beam Energy: 5.75 GeV
  - Low $Q^2$, up to 4.5 GeV and $W$ up to 2.0 GeV

- Beam polarization: $\sim 70 – 80 \%$

- Target: Liquid Hydrogen
CEBAF at Jefferson Lab

- $E_{\text{max}} \approx 6 \text{ GeV}$
- $I_{\text{max}} \approx 200 \mu \text{A}$
- Duty Factor $\approx 100\%$
- $\sigma_{E/E} \approx 2.5 \times 10^{-5}$
- Beam $P \approx 80\%$
- $E_{\gamma_p}(\text{tagged}) \approx 0.8 - 5.5 \text{ GeV}$
CEBAF Large Acceptance Spectrometer (CLAS)

- Six identical sectors
- 5 T toroidal B-field
- $\Delta \theta = 15-140$ degrees
- $\Delta \varphi = 0-50$ degrees
- $\Delta p/p = 10^{-2}-10^{-3}$
Electron PID

- Number of photo-electrons ($nphe$) in the Čerenkov detector
- EC Threshold
- EC Sampling Fraction
- Track Coordinates in the EC plane
- Minimum Ionizing Particles rejection
- Electromagnetic Shower Shape
Electron PID

10 \times \text{Number of photo-electrons}

- cc / no cc: 58.7% → no cuts
- nphe cut / cc: 57.8% → calorimeter cuts
- calorimeter / cc: 51.0% → calorimeter negative cuts
- nphe ≥ 0 / calorimeter: 53.6% → all cuts applied
- all cuts / cc: 27.3% → all cuts applied
Proton PID

Use TOF timing and DC momentum of positive tracks

\[ \beta \text{ versus } p \text{ for positives} \]
$\pi^0$ selection

$e + p \rightarrow e' + p + X$ on $\Delta(1232)$ resonance region from 5.7 GeV

$M_X^2$ from $e + p \rightarrow e' + p + X$ on $\Delta(1232)$ resonance region from 2.0 GeV
\( \pi^0 \) selection (E1-6)

\[ M_X^2 \text{ from } e + p \rightarrow e' + p + X \]
for \( 1.1 < W < 2.0 \text{ GeV} \)

Currently working on bench-mark studies on \( \Delta(1232) \) region
with/without tagging \( \pi^0 \)
Typical $ep \rightarrow e'p\pi^0$ cross sections vs $\cos \theta^*$ and $\phi^*$

$Q^2 = 0.2 \text{ GeV}^2$  $W=1.22 \text{ GeV}$

![Graph showing cross sections vs. cos \( \theta^* \) and \( \phi^* \)]
π⁺ electroproduction at $Q^2=0.20$ GeV$^2$ using CLAS
Differential Cross section from 2.0 GeV

$0.6 < Q^2 < 0.7, 1.3 < W < 1.35$
Legendre Moment

\[ \sigma_T + \varepsilon \sigma_L = \sum_{i=0}^{i=2} A_i P_i (\cos \theta) \]

\[ 0.6 < Q^2 < 0.7 \]

Very preliminary
E1+/M1+ and S1+/M1+

CLAS e1e UIM Fit

- $p\pi^0$ only
- $n\pi^+$ only
- $p\pi^0$ and $n\pi^+$

$E_{t+} / M_{t+}$ (%)

$S_{t+} / M_{t+}$ (%)

$Q^2$ (GeV$^2$)
\*NΔ Multipole Ratios $R_{EM}, R_{SM}$ with JLab

- $R_{EM}$ = -2 to -4% at $0 \leq Q^2 \leq 6$ GeV$^2$.
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CLAS12 - Detector
Projections for N* Transition Amplitudes @ 12 GeV

Prove the transition from effective degrees of freedom, e.g. constituent quarks, to elementary quarks, with characteristic Q^2 dependence.
Summary

- Single $\pi^0$ electro-production analysis is under way for low and high $Q^2$ range up to 2.0 GeV in $W$.

- Able to perform combined analysis with $n\pi^+$ and two pion channels.

- $p\pi^0$ channel is an important part of 12 GeV $N^*$ program with CLAS12.

- Current $p\pi^0$ analysis measuring all final states will provide an important step for 12 GeV $N^*$ program.