N* Transition Form Factors with CLAS at Jefferson Lab

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The N* spectrum and its Classification

Observed spectrum with supermultiplets $\rightarrow$ degrees of freedom $\rightarrow$ 3 quarks with SU(6)xO(3) symmetric interactions

Particle Data Group
- ****
- ***
- **
- 

$D_{13}(1520)$
$S_{11}(1535)$

$D_{33}(1700)$

$P_{33}(1232)$
$P_{11}(1440)$

$L_{3q}$

$0\omega$ $1\omega$ $2\omega$ $3\omega$ $N$

$P_{33}(1232)$
$P_{11}(1440)$

$D_{33}(1700)$

Missing states

$D_{13}(1520)$
$S_{11}(1535)$

$P_{33}(1232)$
$P_{11}(1440)$

$D_{33}(1700)$
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.
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

1. Measure different exclusive processes
2. Measure polarization observables
Exclusive Processes in N* Studies

\[ p(e,e')X \]

\[ p\pi^0 \]

\[ n\pi^+ \]

\[ p\pi^+\pi^- \]

\[ \Delta^{++}\pi^- \]

\[ p\omega \]
CEBAF at Jefferson Lab and CLAS

$E_{\text{max}} \sim 6 \text{ GeV}$

$I_{\text{max}} \sim 200 \, \mu\text{A}$

Duty Factor $\sim 100\%$

$\frac{\sigma_E}{E} \sim 2.5 \times 10^{-5}$

Beam $P \sim 80\%$

$E_{\gamma_p}^{\text{tagged}} \sim 0.8 - 5.5 \text{ GeV}$

$\vec{q} = \vec{e} - \vec{e}'$

$\vec{p}$
## Electroproduction data and analyses from CLAS

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$W$ (GeV)</th>
<th>$Q^2$ (GeV$^2$)</th>
<th>Observable</th>
<th>Physics extracted</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+p \rightarrow e^+p\pi^0$</td>
<td>1.1 - 1.4</td>
<td>0.4 - 1.8; 3 - 6</td>
<td>$\sigma_T, \sigma_L, \sigma_{TT}, \sigma_{LT}, d\sigma/d\Omega$</td>
<td>$\Delta (G_M, R_{EM}, R_{SM})$</td>
</tr>
<tr>
<td>$e^-p \rightarrow e^-p\pi^0$</td>
<td>1.1 - 1.4</td>
<td>0.4 - 0.65</td>
<td>$\sigma_{LT}$</td>
<td>$\Delta (G_M, R_{EM}, R_{SM})$</td>
</tr>
<tr>
<td>$e^-p \rightarrow e^-p\pi^0$</td>
<td>1.1 - 1.4; 1.1 - 1.7</td>
<td>0.5 - 1.5; 0.19 - 0.77</td>
<td>$A_t, A_{et}$</td>
<td>Comparison to models</td>
</tr>
<tr>
<td>$e^+p \rightarrow e^+n\pi^+$</td>
<td>1.1 - 1.6</td>
<td>0.25 - 0.65</td>
<td>$\sigma_T + \sigma_L, \sigma_{TT}, \sigma_{LT}$</td>
<td>$P_{11}(1440)$ ($A_{1/2}, S_{1/2}$), $D_{13}(1520)$ ($A_{1/2}, A_{3/2}, S_{1/2}$), $S_{11}(1535)$ ($A_{1/2}, S_{1/2}$)</td>
</tr>
<tr>
<td>$e^-p \rightarrow e^-n\pi^+$</td>
<td>1.3 - 1.5; 1.15 - 1.7</td>
<td>0.4 - 0.65; 1.72 - 4.16</td>
<td>$\sigma_{LT}; \sigma_T + \sigma_L, \sigma_{TT}, \sigma_{LT}, \sigma_{LT'}$</td>
<td>$P_{11}(1440)$ ($A_{1/2}, S_{1/2}$), $D_{13}(1520)$ ($A_{1/2}, A_{3/2}, S_{1/2}$), $S_{11}(1535)$ ($A_{1/2}, S_{1/2}$)</td>
</tr>
<tr>
<td>$e^-p \rightarrow e^-n\pi^+$</td>
<td>1.12 - 1.84</td>
<td>0.35 - 1.5</td>
<td>$(A_1 + \eta A_2)/(1 + \varepsilon R)$</td>
<td>Comparison to models</td>
</tr>
<tr>
<td>$e^+p \rightarrow e^+n\eta$</td>
<td>1.5 - 1.86</td>
<td>0.25 - 1.5</td>
<td>$\sigma, d\sigma/d\Omega \rightarrow$ Legendre coeff. in $\sigma_T + \sigma_L, \sigma_{TT}, \sigma_{LT}$</td>
<td>$S_{11}(1535)$ ($A_{1/2}, S_{1/2}$)</td>
</tr>
<tr>
<td>$e^+p \rightarrow e^+n\eta$</td>
<td>1.5 - 2.3</td>
<td>0.13 - 3.3</td>
<td>$\sigma, d\sigma/d\Omega \rightarrow$ Legendre coeff. in $\sigma_T + \sigma_L, \sigma_{TT}, \sigma_{LT} + \sigma_{LT}/\sigma, \sigma_{LT}/\sigma$</td>
<td>$S_{11}(1535)$ ($A_{1/2}, S_{1/2}$) + further PWA</td>
</tr>
<tr>
<td>$e^+p \rightarrow e^+n\pi^+\pi^-$</td>
<td>1.4 - 2.1; 1.3 - 1.57</td>
<td>0.5 - 1.5; 0.2 - 0.6</td>
<td>Simultaneous fit of $d\sigma/d\theta$ and $d\sigma/dM$</td>
<td>$P_{13}(1440), D_{13}(1520), P_{13}(1720), D_{33}(1700)$</td>
</tr>
<tr>
<td>$e^-p \rightarrow e^-K^+\Lambda$</td>
<td>1.6 - 2.15</td>
<td>0.3 - 1.5</td>
<td>$\Lambda$ transferred pol. $P'<em>{x'}, P'</em>{y'}$</td>
<td>Comparison to models</td>
</tr>
<tr>
<td>$e^-p \rightarrow e^-K^+\Lambda, K^+\Sigma^0$</td>
<td>1.6 - 2.4</td>
<td>0.5 - 2.8</td>
<td>$\sigma_T, \sigma_L, \sigma_{TT}, \sigma_{LT}$</td>
<td>Comparison to models</td>
</tr>
<tr>
<td>$e^-p \rightarrow e^-K^+\Lambda$</td>
<td>1.65 - 2.05</td>
<td>0.65, 1</td>
<td>$\sigma_{LT}$</td>
<td>Comparison to models</td>
</tr>
</tbody>
</table>
CLAS $\pi^0$ electroproduction data

Complete angular distributions in $\Theta_\pi$ and $\phi_\pi$, in wide $W$ & $Q^2$ range.

$\cos\Theta_\pi$

$Q^2=3\text{GeV}^2$

$\phi$
CLAS $\pi^+$ electroproduction data

$$\frac{d\sigma}{d\Omega_{\text{lab}}^\text{lab} \, dE \, d\Omega_{\pi}^\text{CM}} = \Gamma_v \left( \sigma_T + \epsilon_L \sigma_L + \epsilon_{TT} \cos 2\phi + \sqrt{2\epsilon_L (1+\epsilon)} \sigma_{LT} \cos \phi + \sqrt{2\epsilon_L (1-\epsilon)} \sigma_{LT} \sin \phi \right)$$

$\sigma_T + \epsilon_L \sigma_L (\mu b/sr)$

Bold solid line: UIM fit

MAID00 (thin dashed), MAID03 (bold dash-dotted), Sato-Lee (bold dotted), Sato-Lee04 (thin dash-dotted)
Legendre Moments of $\sigma_T + \epsilon\sigma_L$

$$\sigma_T + \epsilon\sigma_L = \sum_{l=0}^{N} D_l^{T+L} P_l(\cos \theta^*_\pi)$$

Delta disappears rapidly with $Q^2$, other structures and features remain strong.
$P_{11}(1440)$ contributions to Leg. Mom. of $\sigma_T + \varepsilon\sigma_L$

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

- $D_0 (\mu b/sr)$
  - $W(\text{GeV})$
  - Peaks in $\Delta$, $D_{13}/S_{11}$ region, broad enhancement from $P_{11}$

- $D_1 (\mu b/sr)$
  - $W(\text{GeV})$
  - $\sim\cos\theta$

- $D_2 (\mu b/sr)$
  - $W(\text{GeV})$
  - DR w/o $P_{11}(1440)$

- DR

- Broad structure from 1.2 to 1.5 GeV due to s-p interference terms.

preliminary
The asymmetries are integrated over $\theta^*$ and $\phi^*$ in the $Q^2$ range from 0.187 to 0.770 GeV$^2$ and will further reduce the model dependence of the extracted resonance parameters.
How N* electrocouplings can be accessed

- Isolate the resonant part of production amplitudes by fitting the measured observables within the framework of reaction models, which are rigorously tested against data.
- These N* electrocouplings can then be determined from resonant amplitudes under minimal model assumptions.

Used Dispersion relations (DR) and Unitary Isobar Model (UIM) Fits
\( \gamma^* p \rightarrow \Delta(1232) P_{33}(1232): R_{EM} \text{ and } R_{SM} \)

\[
R_{EM} = \frac{E_{1+/M_{1+}}}{R_{SM} = \frac{S_{1+/M_{1+}}}{< 0} \text{ favors oblate shape of the } \Delta, \text{ prolate shape of the nucleon at large distances} \\
\text{Scattering off massless fermions: Helicity is conserved, thus} \\
A_{3/2} = 0 \Rightarrow R_{EM} \rightarrow 1, R_{SM} \rightarrow \text{const} \\
\text{We are still far from pQCD asymptotia} \\
\]

(not shown here)
LQCD calculations: encouraging, work in progress…
$\gamma^* p \rightarrow \text{Roper } P_{11}(1440) \text{ Helicity amplitudes}$

- Sign change of $A_{1/2}$
- Gluonic excitation ruled out due to $Q^2$ dependence of both amplitudes.
- High $Q^2$ behavior consistent with radial excitation of the nucleon as in CQM
**S_{11}(1520) Helicity amplitudes**

- Hard $A_{1/2}$ form factor confirmed *(Slow fall-off as Q^2)*
- First measurement of $S_{1/2}$. Sign inconsistent with CQM.
Helicity Amplitudes for $\gamma^* p \rightarrow D_{13}(1520)$

$$A_{\text{hel}} = \frac{A^{2}_{1/2} - A^{2}_{3/2}}{A^{2}_{1/2} + A^{2}_{3/2}}$$

CQM predictions: $A_{1/2}$ dominance with increasing $Q^2$.

Also from helicity conservation.

- Rapid switch of helicity structure from $A_{3/2}$ dominance to $A_{1/2}$ dominance at $Q^2 > 0.6$ GeV$^2$
CLAS12 - Detector
Projections for $N^*$ Transition Amplitudes @ 12 GeV

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

$P_{11}(1440)$

$D_{13}(1520)$

CLAS12 projected
Summary

- New accurate measurements on $Q^2$ dependence of transition form factors of low lying excited states of the nucleon.

- More analysis results on transition form factors of higher mass states.

- Extensive program is underway with polarized photon beams and polarized targets to search for new baryon states.

- Approved proposal for a transition form factor program at high $Q_2$ at the Jlab 12 GeV upgrade with CLAS12.