Electroexcitation of Nucleon Resonances

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Why N*’s are important

(Nathan Isgur, N*2000 Conference, Jlab)

- Nucleons represent the real world, they must be at the center of any discussion on

  "why the world is the way it is"
Why Excitations of the Nucleon?

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- Nucleons represent the simplest system where

  “the non-abelian character of QCD is manifest”
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- Nucleons represent the simplest system where
  
  “the non-abelian character of QCD is manifest”

- Nucleons/baryons are complex enough to
  
  “reveal physics hidden from us in mesons”

Gell-Mann & Zweig - Quark Model

O. Greenberg - The $\Delta^{++}$ problem/color
OUTLINE

- Why electroproduction?

- Experimental results
  - Quadrupole deformation in the N-Δ transition
  - The Roper resonance - N’(1440)1/2^+
  - Eta production and the N*(1535)1/2^-
  - SQT.M and higher mass states
  - Resonances in multi-pion, and KY^* channels?

- Summary/Outlook
Why N* Electroproduction?

- Light quark baryon spectrum for $N^* \rightarrow N\pi$

- Internal structure of baryons
  Helicity amplitudes vs $Q^2$ \(\Rightarrow\) Relevant degrees of freedom vs distance scale

- Meson production mechanism
Lowest Supermultiplets in SU(6)O(3) Symmetry Group

\[ D_{13}(1520), S_{11}(1535) \]

\[ \Delta(1232) \]

Roper \( P_{11}(1440) \)

Particle Data Group

\[ (56,0+), (70,0+) \]

\[ (56,2+), (70,2+) \]

\[ (56,3-), (70,3-) \]

\[ (20,3-) \]

“missing”

\[ P_{13}(1910) \]

Capstick & Rol

\[ 0 \omega, 1\omega, 2\omega, 3\omega \]

\[ 0\omega \ (1135 \text{ MeV}), 1\omega \ (1545 \text{ MeV}), 2\omega \ (1839 \text{ MeV}), 3\omega \ (2130 \text{ MeV}), N \ (\text{Mass}) \]
**CLAS**: ep $\rightarrow$ epX, $E=4\text{GeV}$
N-$\Delta$(1232) Quadrupole Transition

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

(A. Buchmann, E. Henley, 2000)
Multipole Ratios $R_{EM}$, $R_{SM}$ - before 2001
Kinematics for $ep \rightarrow ep\pi^0$

$$\frac{d\sigma}{d\Omega_e dE'_e d\Omega_\pi} = \Gamma_t \left( \sigma_t + \varepsilon \sigma_1 + \varepsilon \sigma_t t \cos 2\phi_\pi + \sqrt{2\varepsilon (\varepsilon + 1)} \cdot \sigma_t l \cos \phi_\pi \right)$$
Multipole Analysis for $\gamma^* p \rightarrow p\pi^0$

$Q^2 = 0.9$ GeV$^2$

$|M_{1+}|^2$

Re($E_{1+}M_{1+}^* )$

L.C. Smith

$\sigma_t + \varepsilon \sigma_l$

$\sigma_{\pi\pi}$

$\sigma_{\ell\ell}$

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Multipole Ratios $R_{EM}, R_{SM}$ - before 2001
Multipole Ratios $R_{EM}$, $R_{SM}$ - 2002
Multipole Ratios $R_{EM}(Q^2)$, $R_{SM}(Q^2)$

![Graph showing multipole ratios](image)

- **Sato**
- **Ernst**
Multipole Ratios $R_{EM}(Q^2)$, $R_{SM}(Q^2)$

LQCD 1993
Multipole Ratios $R_{EM}(Q^2)$, $R_{SM}(Q^2)$

LQCD 2002? (Moore’s law)
Polarized Beam Observable

\[ e^+ p \longrightarrow e^- p \pi^0 \quad \sigma_{LT}, \text{ response function} / \text{CLAS} \]

Beam spin asymmetry

Mami/A2

Joo Botto Kuhn
The 2nd Resonance Region

The Roper \( N'(1440) P_{11} \)

- In CQM assigned as a \( N=2 \) radial excitation of the nucleon

- Poor description of properties such as mass, photocouplings, \( Q^2 \) evolution

- Strong gluonic component?
- Quark core with meson cloud?
- \( N\sigma \) molecule?
The 2nd Resonance Region

CLAS $e p \rightarrow e n \pi^+$ UnitaryIsobar fit

$W$, GeV/c$^2$

$\mu / \text{sr}$

$\theta^*$, deg
The 2nd Resonance Region

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\[ CLAS \text{ (preliminary)} \]
\[ \sigma(\pi^0,\pi^+), A_c(\pi^0,\pi^+), \text{ unitary isobar fit} \]

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\[ H. \ Egiyan \]
The 2nd Resonance Region

$N^*(1535)S_{11}$

- CQM assigns state to the $[70,1^-]$ multiplet
- Speculation if it is not a $|q^3>$ state but a $|K\Sigma>$ molecule
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- LQCD indicates clear $|q3>$ behavior
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The 2nd Resonance Region

N*(1535)S_{11}

- Consistent $Q^2$ evolution from $\eta$ production

H. Denizli
The 2nd Resonance Region

**Photocoupling amplitude $A_{1/2}$**

- **$N^*(1535)S_{11}$**
  - Consistent $Q^2$ evolution from $\eta$ production

![Graph showing photocoupling amplitude $A_{1/2}$ vs. $Q^2$ (GeV$^2$)]

- Li and Close (NR)
- Konen and Weber (Rel)
- Capstick and Keister (NR)
- Capstick and Keister (Rel)
- Dipole form factor
- Old data
- Armstrong et al. [11]
- CLAS published
- New CLAS data

Giannini and Santopinto
The 2nd Resonance Region

Photocoupling amplitude $A_{1/2}$

$N^*(1535)S_{11}$

- Consistent $Q^2$ evolution from $\eta$ production
- Discrepancy with $N\pi$ analysis
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Photocoupling amplitude $A_{1/2}$

$N^*(1535)S_{11}$

- Consistent $Q^2$ evolution from $\eta$ production
- Discrepancy with $N\pi$ analysis
- **CLAS** $p\eta$ and $N\pi$ data consistent
Transition $[56,0^+] \rightarrow [70,1^-]$ described by 3 amplitudes, e.g. determined from $S_{11}$, $D_{13}$
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Predicts all other amplitudes in same supermultiplet.
Test of the Single Quark Transition Model

- Transition \([56,0^+] \rightarrow [70,1^-]\) described by 3 amplitudes, e.g. determined from \(S_{11}, D_{13}\)

- Predicts all other amplitudes in same supermultiplet

- Tests model in the large \(N_c\) limit

- Good description of \(Q^2=0\)

- Insufficient \(Q^2 \neq 0\) data
Higher mass and “missing states”

- Higher mass states tend to couple strongly to $N\pi\pi$

<table>
<thead>
<tr>
<th>State</th>
<th>$\pi N$</th>
<th>$\eta N$</th>
<th>$\pi N$ wave</th>
<th>$\pi\pi N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{1/2-}(1535)$</td>
<td>40</td>
<td>45</td>
<td>$S_{11}$</td>
<td>5</td>
</tr>
<tr>
<td>$N_{1/2+}(1440)$</td>
<td>65</td>
<td></td>
<td>$P_{11}$</td>
<td>35</td>
</tr>
<tr>
<td>$N_{1/2+}(1710)$</td>
<td>15</td>
<td></td>
<td>$P_{11}$</td>
<td>40 - 90</td>
</tr>
<tr>
<td>$N_{3/2+}(1720)$</td>
<td>15</td>
<td></td>
<td>$P_{13}$</td>
<td>70</td>
</tr>
<tr>
<td>$N_{3/2-}(1520)$</td>
<td>55</td>
<td></td>
<td>$D_{13}$</td>
<td>45</td>
</tr>
<tr>
<td>$N_{3/2-}(1700)$</td>
<td>10</td>
<td></td>
<td>$D_{13}$</td>
<td>90</td>
</tr>
<tr>
<td>$N_{5/2-}(1675)$</td>
<td>45</td>
<td></td>
<td>$D_{15}$</td>
<td>55</td>
</tr>
<tr>
<td>$N_{5/2+}(1680)$</td>
<td>65</td>
<td></td>
<td>$F_{15}$</td>
<td>35</td>
</tr>
<tr>
<td>$\Delta_{1/2-}(1620)$</td>
<td>25</td>
<td>-</td>
<td>$S_{31}$</td>
<td>75</td>
</tr>
<tr>
<td>$\Delta_{3/2+}(1232)$</td>
<td>100</td>
<td>-</td>
<td>$P_{33}$</td>
<td></td>
</tr>
<tr>
<td>$\Delta_{3/2+}(1600)$</td>
<td>15</td>
<td>-</td>
<td>$P_{33}$</td>
<td>~80</td>
</tr>
<tr>
<td>$\Delta_{3/2-}(1700)$</td>
<td>15</td>
<td>-</td>
<td>$D_{33}$</td>
<td>85</td>
</tr>
<tr>
<td>$\Delta_{7/2+}(1950)$</td>
<td>40</td>
<td>-</td>
<td>$F_{37}$</td>
<td>35</td>
</tr>
</tbody>
</table>
“Missing” Resonances?

- Symmetric CQM predicts many more states than observed in elastic \( \pi N \) scattering analysis

\[ |q^3> \Rightarrow \text{predicted to couple to} \]

\( \Lambda\pi\pi (\Delta\pi, N\rho), N\omega, KY \)

which model is closer to reality?

\[ |q^2q> \Rightarrow \text{fewer excitation degrees of freedom} \]

fewer states

\[ \text{Klempt, Vijande} \]
Resonances in $\gamma^* p \rightarrow p \pi^+ \pi^-$

**CLAS**

Genova-Moscow Isobar model fit

$\Gamma_{N\pi\pi}$ PDG

$\Gamma_{N\gamma}$ AO/SQTM

Total cross section

$Q^2 = 0.65 \text{ GeV}^2$

$Q^2 = 0.95 \text{ GeV}^2$

$Q^2 = 1.30 \text{ GeV}^2$

missing resonance strength
Isobar fit to $D_{13}(1700)$ and new $P_{13}$

**CLAS**

Genova-Moscow Isobar model fit

$\Gamma_{N\pi\pi}$ PDG

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Total cross section

- $Q^2 = 0.65$ GeV$^2$
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---

$P_{13}$

$D_{13}(1700)$
Isobar fit - hadronic decays

\[ W = 1.74 \text{GeV} \]

\[ \text{CLAS} \]

\[ \theta_{\pi^-} \text{(deg)} \]

\[ \theta_{\pi} \text{(deg)} \]

Data described best by new \( P_{13} \)

\[ M = 1.72 \pm 0.02 \text{ GeV} \]

\[ \Gamma_T = 88 \pm 17 \text{ MeV} \]

\[ \Delta\pi : 0.41 \pm 0.13 \]

\[ N\rho : 0.17 \pm 0.10 \]
Isobar fit - A new state?

$W = 1.74 \text{GeV}$

**CLAS**

- $P_{13}$
- $D_{13}(1700)$

- Data described best by new $P_{13}$
  - $M = 1.72 \pm 0.02 \text{ GeV}$
  - $\Gamma_T = 88 \pm 17 \text{ MeV}$
  - $\Delta\pi : 0.41 \pm 0.13$
  - $N_{\rho} : 0.17 \pm 0.10$

- Consistent with “missing” $P_{13}$ state, but mass low

Known $P_{13}$

- 1650-1750
- 100-200
- $\sim 0$
- 0.8 - 0.9

F. Klein
Search for resonances in hyperon production

**CLAS** \( \gamma^*p \rightarrow K^+Y \)

**forward hemisphere**

\[
0. < \cos(\Theta_K) < 1., \quad Q^2 = 0.7 \text{ (GeV/c)}^2
\]

**backward hemisphere**

\[
-1. < \cos(\Theta_K) < 0., \quad Q^2 = 0.7 \text{ (GeV/c)}^2
\]

\[\Lambda \quad \sigma_T + \varepsilon_L \sigma_L\]

\[\Lambda \quad \sigma_T + \varepsilon_L \sigma_L\]

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Niculescu/Feuerbach

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Resonances in $\gamma^* p \rightarrow p \omega$?

above resonance region

CLAS

in resonance region

$\sigma$ vs $\cos\theta_{p\omega}$

$\gamma$ $\rightarrow$ $p$ $\rightarrow$ $N^*$ $\rightarrow$ $\omega$

$\gamma$ $\rightarrow$ $p$ $\rightarrow$ $p$ $\rightarrow$ $\omega$

$\gamma$ $\rightarrow$ $N^*$ $\rightarrow$ $p$ $\rightarrow$ $p$ $\rightarrow$ $\omega$

$\gamma$ $\rightarrow$ $p$ $\rightarrow$ $p$ $\rightarrow$ $N^*$ $\rightarrow$ $\omega$

$\gamma$ $\rightarrow$ $p$ $\rightarrow$ $p$ $\rightarrow$ $\omega$

F. Klein
Resonances in Virtual Compton Scattering

**Hall A - E93-50**

\[ e^+ p \rightarrow e^+ p \gamma \]

- First measurement through entire resonance region
- Advantage over mesons, the lack of final state interaction
- Strong resonance excitations

\[ \Delta(1232) \]
\[ N^*(1520) \]
\[ N^*(1650) \]

Fonvieille  
Todor

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Summary

- Accurate results on transition amplitudes for several states give a consistent picture, and allow stringent test of theory
  - $\Delta(1232)$, $N^*(1535)$, (Roper)

- Searches in various final states suggest excitations of states not seen before
  - $p\pi^+\pi^-$, $p\omega$, $K^+\Lambda$, ....

- $N^*$ electroexcitation has become a major tool in studying the complex regime of strong QCD and confinement
Outlook

- Transition amplitudes for several states under study
  CLAS, Hall A/C, OOPS

- New instrumentation/facilities - BLAST, MAMI upgrade
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- The $\Delta(1232)$ is the only resonance so far seen first
  in electron scattering experiments.

  Perhaps, this long drought is over soon.

  The potential is there!
Outlook

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  CLAS, Hall A/C, OOPS

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It is an exciting time to work in this field!