Electroexcitation of Nucleon Resonances

Volker D. Burkert
Jefferson Lab

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Why Excitations of the Nucleon?

(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”

- 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 Δ++ 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^-
  - SQTM 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 $Q^2$ => Relevant degrees of freedom vs distance scale

- Meson production mechanism

![Diagram](image-url)
Lowest Supermultiplets in SU(6)O(3) Symmetry Group

- \( D_{13}(1520), S_{11}(1535) \)
- \( L_{3q} \)
- \( \Delta(1232) \)
- Roper \( P_{11}(1440) \)
- "missing" \( P_{13}(1910) \)

Capstick & Rol

Volker D. Burkert
BARYONS 02
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**CLAS:** $ep \rightarrow epX, \ E=4\text{GeV}$
N-$\Delta(1232)$ Quadrupole Transition

\[ \gamma \rightarrow M_{1+} \]

\[ SU(6): E_{1+} = S_{1+} = 0 \]

\begin{align*}
&\text{E/M} & \text{S/M} \\
&\sim 0.03 & \sim 0.1 \\
&\sim 0.01 & \text{+1 const.}
\end{align*}

(A. Buchmann, E. Henley, 2000)
Multipole Ratios $R_{EM}$, $R_{SM}$ - before 2001

[Graph showing data points and error bars for $E_{1+} / M_{1+}$ and $S_{1+} / M_{1+}$ as functions of $Q^2(\text{GeV}/c)^2$.]
Kinematics for $ep \rightarrow ep\pi^0$

$$\frac{d\sigma}{d\Omega_e dE'_e d\Omega_\pi} = \Gamma_t ( \sigma_t + \varepsilon\sigma_l + \varepsilon\sigma_{tt} \cos 2\phi_\pi + \sqrt{2\varepsilon (\varepsilon + 1)} \cdot \sigma_{tl} \cos \phi_\pi )$$
Multipole Analysis for $\gamma^* p \rightarrow p\pi^0$

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

$|M_{1+}|^2$

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

$|M_{1+}|^2$

$\text{Re}(S_{1+}M_{1+}^*)$
Multipole Ratios $R_{EM}, R_{SM} - 2002$
Multipole Ratios $R_{EM}(Q^2), R_{SM}(Q^2)$

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

\[ \vec{e}p \rightarrow e p \pi^0 \quad \sigma_{lt}, \text{ response function} / \text{CLAS} \]

Beam spin asymmetry

\( \rho_{lt} (\%) \)

\[ \rho_{lt} (\%) \]

\( W (\text{MeV}) \)

\[ W = 1.1 \text{ GeV} \quad W = 1.14 \text{ GeV} \quad W = 1.18 \text{ GeV} \]

\[ W = 1.22 \text{ GeV} \quad W = 1.26 \text{ GeV} \quad W = 1.3 \text{ GeV} \]

Mami/A2

Joo Botto Kuhn

CLAS Data (Q^2 = 0.65 GeV^2)

L-2 Legendre Fit

MAID2001

Sato–Lee
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?
  - No $\sigma$ molecule?

![Graph showing $A_{1/2}$ vs. $Q^2$ (GeV/c)^2 with lines for LCM, q^3G, nrCQM, rCQM]
The 2nd Resonance Region

**CLAS**  \( ep \rightarrow en\pi^+ \)  Unitary Isobar fit

\[ W, \text{GeV/c}^2 \]
\[ \theta^*, \text{deg} \]
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?

$\sigma(\pi^0,\pi^+), A_\epsilon(\pi^0,\pi^+)$, unitary isobar fit

$CLAS$ (preliminary)

$H.\ Egiyan$
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
- Hard e.m. formfactor
- LQCD indicates clear $|q^3>$ behavior
- Strong coupling to $p\eta$
The 2nd Resonance Region

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

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

Photocoupling amplitude $A_{1/2}$

H. Denizli
The 2nd Resonance Region

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

- Consistent $Q^2$ evolution from $\eta$ production
The 2nd Resonance Region

\[ N^{*}(1535)S_{11} \]

- Consistent Q^2 evolution from \( \eta \) production
- Discrepancy with N\( \pi \) analysis
- CLAS \( p\eta \) and N\( \pi \) data consistent
Single Quark Transition Model

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

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

- Predicts all other amplitudes in same supermultiplet
Test of the Single Quark Transition Model

- Transition \([56,0^+] -> [70,1^-]\) 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 $N\pi\pi$

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

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

$|q^3\rangle$ => predicted to couple to $N\pi\pi (\Delta\pi, N\rho), N\omega, KY$

which model is closer to reality?

$|q^2q\rangle$ => fewer excitation degrees of freedom, fewer states

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Klempt, Vijande
Resonances in $\gamma^* p \rightarrow p\pi^+\pi^-$

Total cross section

CLAS

Genova-Moscow Isobar model fit

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

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

missing resonance strength

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

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

$Q^2 = 1.30 \text{ GeV}^2$
Isobar fit to $D_{13}(1700)$ and new $P_{13}$

**CLAS**

Genova-Moscow
Isobar model fit

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

Total cross section

- $Q^2 = 0.65$ GeV$^2$
- $Q^2 = 0.95$ GeV$^2$
- $Q^2 = 1.30$ GeV$^2$

$P_{13}$

$D_{13}(1700)$
Isobar fit - A new state?

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

\[ \begin{align*}
\frac{d\sigma}{dM} \text{ (\(\text{mb/GeV}\))} & \quad \text{\(M_{\pi^+p}\)} \\
\frac{d\sigma}{dM} \text{ (\(\text{mb/GeV}\))} & \quad \text{\(M_{\pi^+\pi^-}\)} \\
\theta_{\pi^-} \text{ (deg)} & \quad \text{\(\theta_{\pi^-}\)}
\end{align*} \]

- Data described best by \textbf{new P}_{13}
  \[ M = 1.72 \pm 0.02 \text{ GeV} \]
  \[ \Gamma_T = 88 \pm 17 \text{ MeV} \]
  \[ \Delta\pi : 0.41 \pm 0.13 \]
  \[ \mathcal{N}_\rho : 0.17 \pm 0.10 \]

- consistent with “missing” \textbf{P}_{13} state, but mass low

\[ \begin{align*}
\text{1650-1750} & \quad \text{100-200} \\
\sim 0 & \quad \text{0.8 - 0.9}
\end{align*} \]

\[ \text{known P}_{13} \quad \text{F. Klein} \]
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**

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

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**preliminary**

**Niculescu/Feuerbach**

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

above resonance region

$\sigma$

$\gamma$ $\omega$

$p$ $p$

$\gamma$ $N^*$ $\omega$

$p$ $p$

CLAS

in resonance region

$\cos\theta_{p\omega}$

$+1$

$-1$

$F.\ Klein$

$\frac{d\sigma}{d\cos\theta}$ [mb/ rad]

$1.85 < W < 1.95 \text{ GeV}$

$1.0 < Q^2 < 1.5 \text{ GeV}^2$

$1.5 < Q^2 < 2.0 \text{ GeV}^2$

$2.05 < W < 2.15 \text{ GeV}$

$1.0 < Q^2 < 1.5 \text{ GeV}^2$

$1.5 < Q^2 < 2.0 \text{ GeV}^2$
Resonances in Virtual Compton Scattering

**Hall A - E93-50**

ep → epγ

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

→ Fonvieveille
→ Todor
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

- 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!

It is an exciting time to work in this field!