Status of and Prospects for N* Spectroscopy

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Lattice QCD and Experiment
Jefferson Laboratory, 11/21/2008
Outline

1. Introduction

2. Status
   - \( \eta (\eta') \) Photoproduction
   - Double-Pion
   - Hyperon Photoproduction

3. Towards Complete Experiment
   - Ingredients
   - Polarization

4. Summary and Outlook
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4. Summary and Outlook
What are the relevant degrees of freedom?

What are the corresponding effective interactions responsible for hadronic phenomena?
The excited baryon program has two main components:

- **Establish the systematics of the spectrum**
  - Provides information on the nature of effective degrees of freedom in strong QCD

- **Probe resonance transitions at different distance scales**
  - (electron beams are ideal to measure transition form factors)
  - Provides information on the confining forces of the 3-quark system
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4. Summary and Outlook
Search for *missing* resonances

Quark models predict many more baryons than have been observed

<table>
<thead>
<tr>
<th>N Spectrum</th>
<th>****</th>
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<tbody>
<tr>
<td></td>
<td>11</td>
<td>3</td>
<td>6</td>
<td>2</td>
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<tr>
<td>∆ Spectrum</td>
<td>7</td>
<td>3</td>
<td>6</td>
<td>6</td>
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</table>

⇒ according to PDG


⇒ little known

(many open questions left)

Possible solutions:

1. Quark-diquark structure

   one of the internal degrees of freedom is frozen

2. Have not been observed, yet

   Nearly all existing data result from $\pi N$ scattering experiments

   ⇒ If the missing resonances did not couple to $N\pi$, they would not have been discovered!!
Search for *missing* resonances

Quark models predict many more baryons than have been observed

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<td>11</td>
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<tr>
<td>Δ Spectrum</td>
<td>7</td>
<td>3</td>
<td>6</td>
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Possible solutions:

1. Quark-diquark structure
   - one of the internal degrees of freedom is frozen

2. Have not been observed, yet
   - Nearly all existing data result from \( \pi N \) scattering experiments
   - If the missing resonances did not couple to \( N\pi \), they would not have been discovered!!
 Possible Quark-Diquark Structure?

Regge trajectory for $\Delta^*$ states with intrinsic spin $S = 1/2$ and $S = 3/2$, and for $N^*$ states with spin $S = 3/2$ ($M^2$ versus $L$, not $J$)

1. Common Regge trajectory for $N/\Delta$ states with $S = 3/2$

2. Not shown, but slope of the Regge trajectory for meson and $\Delta$ excitations is identical

$\rightarrow$ Are baryons quark-diquark excitations?
Nucleon Resonances: Status – 2001


many predicted states missing

$P_{11}(1986)$

$S_{11}(1900)$

$D_{13}(1895)$ (CLAS: $m \approx 1910$)

OGE Model: residual short-range interaction based on one-gluon exchange
Analysis of $\gamma p \rightarrow p \eta$ (New Data from CB-ELSA/TAPS)

1. Full angular coverage
2. Absolute normalized

V.C. et al. [ CB-ELSA Collaboration ], PRL D94, 012004 (2005)
Analysis of $\gamma p \rightarrow p \eta$ (New Data from CB-ELSA/TAPS)

V.C. et al. [CB-ELSA Collaboration], PRL \textbf{D94}, 012004 (2005)
Analysis of $\gamma p \rightarrow p \eta$: Total Cross Section

Isospin Filter

$\rightarrow$ Only $N^*$ resonances can contribute!

Hint for $N^*$ resonance $N(2070)D_{15}$

Three resonances are dominantly contributing!

$N(1535)S_{11}$, $N(1720)P_{13}$, $N(2070)D_{15}$
## Partial Wave Analysis (PWA Center at ELSA)

### PWA: Operator (Tensor) Formalism (Rarita–Schwinger)

- Datasets

<table>
<thead>
<tr>
<th>Observables</th>
<th>Reference</th>
<th>$N_{data}$</th>
<th>$\chi^2/N$</th>
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</thead>
<tbody>
<tr>
<td>$\sigma(\gamma p \rightarrow p\eta)$</td>
<td>CB-ELSA</td>
<td>667</td>
<td>0.91</td>
</tr>
<tr>
<td>$\sigma(\gamma p \rightarrow p\eta)$</td>
<td>TAPS</td>
<td>100</td>
<td>1.6</td>
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<tr>
<td>$\Sigma(\gamma p \rightarrow p\eta)$</td>
<td>GRAAL 04</td>
<td>100</td>
<td>1.75</td>
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<tr>
<td>$\Sigma(\gamma p \rightarrow p\eta)$</td>
<td>GRAAL 04</td>
<td>1106</td>
<td>1.50</td>
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<tr>
<td>$\Sigma(\gamma p \rightarrow p\pi^0)$</td>
<td>CB-ELSA</td>
<td>469</td>
<td>3.43</td>
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<tr>
<td>$\Sigma(\gamma p \rightarrow p\pi^0)$</td>
<td>SAID</td>
<td>593</td>
<td>2.87</td>
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<tr>
<td>$\sigma(\gamma p \rightarrow n\pi^+)$</td>
<td>SAID</td>
<td>1583</td>
<td>2.86</td>
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<table>
<thead>
<tr>
<th>Resonance</th>
<th>$M$ (MeV)</th>
<th>$\Gamma$ (MeV)</th>
<th>Fraction</th>
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<tbody>
<tr>
<td>N(1520)D$_{13}$</td>
<td>1523 ± 4</td>
<td>105$^{+6}_{-18}$</td>
<td>0.020</td>
</tr>
<tr>
<td>PDG</td>
<td>1520$^{+10}_{-5}$</td>
<td>120$^{+15}_{-10}$</td>
<td></td>
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<tr>
<td>N(1535)S$_{11}$</td>
<td>1501 ± 5</td>
<td>215 ± 25</td>
<td>0.430</td>
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<tr>
<td>PDG</td>
<td>1505 ± 10</td>
<td>170 ± 80</td>
<td></td>
</tr>
<tr>
<td>N(1650)S$_{11}$</td>
<td>1610 ± 10</td>
<td>190 ± 20</td>
<td></td>
</tr>
<tr>
<td>PDG</td>
<td>1660 ± 20</td>
<td>160 ± 10</td>
<td></td>
</tr>
<tr>
<td>N(1675)D$_{15}$</td>
<td>1690 ± 12</td>
<td>125 ± 20</td>
<td>0.001</td>
</tr>
<tr>
<td>PDG</td>
<td>1675$^{+10}_{-5}$</td>
<td>150$^{+30}_{-10}$</td>
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<tr>
<td>N(1680)F$_{15}$</td>
<td>1669 ± 6</td>
<td>85 ± 10</td>
<td>0.005</td>
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<tr>
<td>PDG</td>
<td>1680$^{+10}_{-5}$</td>
<td>130 ± 10</td>
<td></td>
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<tr>
<td>N(1700)D$_{13}$</td>
<td>1740 ± 12</td>
<td>84 ± 16</td>
<td>0.004</td>
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<tr>
<td>PDG</td>
<td>1700 ± 50</td>
<td>100 ± 50</td>
<td></td>
</tr>
<tr>
<td>N(1720)P$_{13}$</td>
<td>1775 ± 18</td>
<td>325 ± 25</td>
<td>0.300</td>
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<tr>
<td>PDG</td>
<td>1720$^{+30}_{-70}$</td>
<td>250 ± 50</td>
<td></td>
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<tr>
<td>N(2000)F$_{15}$</td>
<td>1950 ± 25</td>
<td>230 ± 45</td>
<td>0.007</td>
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<tr>
<td>N(2070)D$_{15}$</td>
<td>2068 ± 22</td>
<td>295 ± 40</td>
<td>0.171</td>
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<tr>
<td>N(2080)D$_{13}$</td>
<td>1943 ± 17</td>
<td>82 ± 20</td>
<td>0.011</td>
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<tr>
<td>N(2200)P$_{13}$</td>
<td>2214 ± 28</td>
<td>360 ± 55</td>
<td>0.051</td>
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* K-Matrix Fit, Fraction for the total K-matrix contribution

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Analysis of $\gamma p \rightarrow p\eta$: Total Cross Section

- **Isospin Filter**
  - Only $N^*$ resonances can contribute!

- **Hint for $N^*$ resonance $N(2070)D_{15}$**
  - **1** Confirmed in new analysis!
  - **2** $N(1720)P_{13} \rightarrow \eta p$ unexpected
    - $\eta$-MAID: $N(1710)P_{11} \rightarrow \eta p$ significant!

- **Three resonances are dominantly contributing!**
  - $N(1535)S_{11}$, $N(1720)P_{13}$, $N(2070)D_{15}$
Linearly-Polarized Beam at JLab: $\Sigma(\gamma p \rightarrow p \eta)$

Good agreement with other data
- Interpretation of Bonn (PWA) and CLAS data (SAID) different: $P_{13}(1720) \leftrightarrow P_{11}(1710)$

Preliminary analysis of $\gamma p \rightarrow p\eta$
- $P_\gamma$ estimated at 0.8
- SAID prediction
- Data with statistical errors (no systematic)
Linearly-Polarized Beam at JLab: g8b Run Group

Set IV
N(1535)S_{11}, N(2090)S_{11}
N(1710)P_{11}, N(2100)P_{11}
N(1700)D_{13}, N(2080)D_{13}

Similar to \( \eta \) analysis:
N(1535)S_{11} and N(1710)P_{11} dominant (SAID, MAID)!

Analysis of \( \gamma p \rightarrow p\eta' \)
Linearily-Polarized Beam at JLab: g8b Run Group

\[ \frac{d\sigma}{d\Omega} \text{ for } \gamma p \rightarrow \eta' p \]

Raw asymmetry for \( \eta' \) photoproduction (\( P = 0.8 \) assumed)

- Set IV
  - \( 2 \times S_{11} \)
  - \( 2 \times P_{11} \)
  - \( 2 \times D_{13} \)

Analysis of \( \gamma p \rightarrow p\eta' \)


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Status of and Prospects for \( N^* \) Spectroscopy
Resonances in $\gamma(*)p \rightarrow p\pi^+\pi^-$

- $2\pi$ channel sensitive to N*’s heavier than 1.4 GeV
- Provides complementary information to the $1\pi$ channel
- Many higher lying N*’s decay preferably to $N\pi\pi$ final states via intermediate states

Solid curves are from fits using the recent JM06 model with and without a new $\rho(1720)P_{33}$ state
Resonances in $\gamma(\ast)p \rightarrow p\pi^+\pi^-$

- **Background**
- **Resonances**

Combined analysis of preliminary real (M. Bellis) and also published virtual photon data (M. Ripani):

Fit needs both the candidate $(1720)P_{33}$ and the $N(1720)P_{13}$ state.

Authors claim that combined fit of various single differential cross sections allowed to establish all significant mechanisms.
Reasonable Description of $N\pi/N\pi\pi$ Electroproduction

The CLAS-Collaboration phenomenological models (UIM/DR/JM) reproduce reasonably well comprehensive CLAS/world data on all observables in $N\pi/N\pi\pi$ electroproduction:

- Isobars used in $N\pi\pi$ electroproduction
  1. All well-established $N^* \rightarrow \pi^- \Delta^{++}$ decays + $3/2^+(1720)$
  2. All well-established $N^* \rightarrow \rho \pi$ decays + $3/2^+(1720)$
  3. Observed for the first time in CLAS data: $\pi^+ D_{13}^0 (1520)$, $\pi^+ F_{15}^0 (1685)$, and $\pi^- P_{33}^{++} (1640)$

- Models can be used to evaluate $N^*$ electrocouplings
  ➔ Information on contributing mechanisms will be used by EBAC for $N^*$ studies in advanced coupled channel analysis (Julia-Diaz, Lee, Phys. Rev. C76, 065201 (2007))
Total Cross Section for $\gamma p \rightarrow p\pi^0\pi^0$ (CB-ELSA)

Event-based Maximum Likelihood Fit

- $N(1440)P_{11}$, $N(1520)D_{13}$, $N(1680)F_{15}$
- $\Delta(1700)D_{33}$, $\Delta(1920)P_{33}$, $\Delta(1940)D_{33}$
- ... + Background amplitudes

$\rightarrow$ Not compatible with $N(1440)P_{11} \rightarrow p\sigma$ dominance!
Baryon Resonances in Hyperon Photoproduction
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