Understanding Excited Baryon Resonances: Results from polarization experiments at CLAS

Volker Credé
Florida State University, Tallahassee, FL

JLab Users Group Workshop
Jefferson Lab
06/04/2014
Outline

1. Introduction
   - Quarks, QCD, and Confinement
   - Structure of Baryon Resonances

2. The Search for Undiscovered States
   - Electromagnetic Probes
   - Mission Goal: Complete Experiments

3. Results from Photoproduction Experiments
   - Photoproduction of $\pi^0$ and $\pi^+$ Mesons off the Proton
   - Observables in the Photoproduction of Two Pions

4. Summary and Outlook
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4. **Summary and Outlook**
QCD is the theory of the strong nuclear force which describes the interactions of quarks and gluons making up hadrons.

Strong processes at larger distances and at small (soft) momentum transfers belong to the realm of non-perturbative QCD.

Quarks are confined within hadrons.

Confinement of quarks and gluons within nucleons is a non-perturbative phenomenon, and QCD is extremely hard to solve in non-perturbative regimes: Knowledge of internal structure of nucleons is still limited.

This is particularly true for excited nucleons.
Non-Perturbative QCD

How does QCD give rise to excited hadrons?

1. What is the origin of confinement?
2. How are confinement and chiral symmetry breaking connected?
3. Would the answers to these questions explain the origin of $\sim 98\%$ of observed matter in the universe?

Excited Baryons: What are the fundamental degrees of freedom inside a proton or a neutron? How do they change with varying quark masses?
#### Spectrum of $N^*$ Resonances (PDG < 2012)

S. Capstick and N. Isgur, Phys. Rev. **D34** (1986) 2809

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1. Excitation Band: $(70, 1^-_1)$ ✓

2. Excitation Band: $(56, 0^+_2), (56, 2^+_2)$ ✓

$(70, 0^+_2), (70, 2^+_2)$ ✓

$(20, 1^+_2)$ ?

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**Theory**

**Experiment**

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Light Baryon Spectroscopy
Spectrum of $N^*$ Resonances (PDG < 2012)


Perhaps only the tip of the iceberg has been discovered?

1. Excitation Band:
   (70, $1_{1}^{-}$) ✓

2. Excitation Band:
   (56, $0_{2}^{+}$), (56, $2_{2}^{+}$) ✓
   (70, $0_{2}^{+}$), (70, $2_{2}^{+}$) ✓
   (20, $1_{2}^{+}$) ?

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Light Baryon Spectroscopy
The Search for Undiscovered States

Results from Photoproduction Experiments

Summary and Outlook

Quarks, QCD, and Confinement
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Spectrum of $N^*$ Resonances

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Light Baryon Spectroscopy
Introduction
The Search for Undiscovered States
Results from Photoproduction Experiments
Summary and Outlook

Quarks, QCD, and Confinement
Structure of Baryon Resonances

Polarization Transfer in $\gamma p \rightarrow K^+\Lambda$: $C_x$, $C_z$

\begin{align*}
C_x, C_z \quad \text{without } N(1900)P_{13} & \quad \text{with } N(1900)P_{13} \\
\text{without } N(1900)P_{13} & \quad \text{with } N(1900)P_{13}
\end{align*}


Bonn-Gatchina PWA requires $N(1900)P_{13}$
No quark-diquark oscillations!
$\Rightarrow$ Both oscillators need to be excited.
Complete Experiment for $K^+Y$: $1.65 < W < 2.2$ GeV

$W \in [1.90, 1.95]$ GeV

$\gamma p \rightarrow K^+\Lambda$

$K^+\Sigma^0$

$W \in [2.10, 2.15]$ GeV

$W \in [1.85, 1.90]$ GeV

$W \in [1.90, 1.95]$ GeV

$T_x$

$W \in [1.95, 2.00]$ GeV

$T_z$

$T_x$

BoGa

MAID

N. Walford et al. [CLAS Collaboration], FROST run group

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Light Baryon Spectroscopy
Exhibited-State Baryon Spectroscopy from Lattice QCD


Missing states?

\[ m_\pi = 396 \text{ MeV} \]

Exhibits broad features expected of \( SU(6) \otimes O(3) \) symmetry

\[ \rightarrow \text{Counting of levels consistent with non-rel. quark model, no parity doubling} \]
The mass scale is \( m - m_{\rho} \) for mesons and \( m - m_{N} \) for baryons.

Common scale of \( \sim 1.3 \) GeV for gluonic excitation, but hybrid baryons are difficult to identify experimentally.
Helicity Amplitudes for the “Roper” Resonance

Consistency between both channels ($N\pi\pi$, $N\pi$): sign change, magnitude, ...

- At short distances (high $Q^2$), Roper behaves like radial excitation.
- Low $Q^2$ behavior not well described by LF quark models: e.g. meson-baryon interactions missing

$\rightarrow$ Gluonic excitation likely ruled out!

Data from CLAS
$A_{1/2}$ and $S_{1/2}$ amplitudes: e.g. V. Mokeev et al., PRC 86, 035203 (2012); PRC 80, 045212 (2009).

Quark-model calculations:
- $q^3$ radial excitation
- $q^3G$ hybrid state

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**Electromagnetic Probes**
Mission Goal: Complete Experiments

**Reaction Thresholds**

\begin{align*}
\gamma p &\rightarrow p\eta\eta \\
\gamma p &\rightarrow p\pi^0\omega \\
\gamma p &\rightarrow p\pi^0\eta \\
\gamma p &\rightarrow p\eta \\
\gamma p &\rightarrow p\pi\pi \\
\gamma p &\rightarrow p\pi \\
\gamma p &\rightarrow p\pi \\
\gamma p &\rightarrow K\Lambda \\
\gamma p &\rightarrow K\Sigma \\
\end{align*}

**W [GeV]**

- **ELS A**
- **CLAS**
- **MAMI-C**
- **GRAAL**

**Common efforts at ELSA, JLab, and MAMI**
(Double-)polarization measurements, $\gamma p$ & $\gamma n$ reactions, etc.

**In addition:**
- SPring-8
- J-PARC

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Light Baryon Spectroscopy
The CLAS Spectrometer at Jefferson Laboratory

Electromagnetic Probes
Mission Goal: Complete Experiments

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Mission Goal: Complete Experiments

The CLAS Spectrometer at Jefferson Laboratory

Electron Beam

Electromagnetic Calorimeters

Torus

Drift Chambers

Cerenkov Counters

Time of Flight Scintillators

FROST
double polarization

\[ g_8b \]
linear beam polarization

Data for PERP 1.3GeV
Calculation

Polarization corresponding to calc
(Peaking at > 90%)

Target material

1K pot

Distillation chamber

4K pot

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Light Baryon Spectroscopy
Extraction of Resonance Parameters

- Double-polarization measurements

- Measurements off neutron and proton to resolve isospin contributions:
  1. \( A(\gamma N \rightarrow \pi, \eta, K)^{I=3/2} \Leftrightarrow \Delta^* \)
  2. \( A(\gamma N \rightarrow \pi, \eta, K)^{I=1/2} \Leftrightarrow N^* \)

- Re-scattering effects: Large number of measurements (and reaction channels) needed to extract full scattering amplitude.

Coupled Channels

Jülich, Gießen, EBAC, etc.
Why are Polarization Observables Important?

For single-meson production:

\[
\frac{d\sigma}{d\Omega} = \sigma_0 \left\{ 1 - \delta_\perp \Sigma \cos 2\phi \\
+ \Lambda_\chi \left( -\delta_\perp H \sin 2\phi + \delta_\odot F \right) \\
- \Lambda_\gamma \left( -T + \delta_\perp P \cos 2\phi \right) \\
- \Lambda_\zeta \left( -\delta_\perp G \sin 2\phi + \delta_\odot E \right) \right\}
\]

In order to determine the full scattering amplitude without ambiguities, one has to carry out eight carefully selected measurements: four double-spin observables along with four single-spin observables. Eight well-chosen measurements are needed to fully determine production amplitudes $F_1$, $F_2$, $F_3$, and $F_4$.

Example: Ambiguities in $\gamma p \rightarrow p \pi^0$

- Bonn-Gatchina (2011-02)
- SAID (SN11, CM12)
- MAID

Example:

\[ E = -\frac{1}{2\Lambda_z \delta} \frac{N \rightarrow \Rightarrow - N \rightarrow \Leftarrow}{N \rightarrow \Rightarrow + N \rightarrow \Leftarrow} \]

\[ \sigma_1/2 \]

\[ \sigma_3/2 \]
Helicity Asymmetry $E$ in $\bar{\gamma} \bar{p} \rightarrow p \pi^0$ @ ELSA

$E = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$

$E_{\gamma} \in [0.6, 2.2] \text{ GeV}$

- CBELSA/TAPS
  - Maid
  - Said (CM12)
  - BoGa (2011_2)

Angular distributions sensitive to interference between resonances.


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Asymmetry $G$ in $\gamma \vec{p} \rightarrow p \pi^0$ @ ELSA

$$\frac{d\sigma}{d\Omega} = \sigma_0 \left\{ 1 - \delta_1 \Sigma \cos 2\phi ight. + \Lambda_x \left( -\delta_1 H \sin 2\phi + \delta_\odot F \right)
- \Lambda_y \left( -T + \delta_1 P \cos 2\phi \right)
- \Lambda_z \left( -\delta_1 G \sin 2\phi + \delta_\odot E \right) \left\} \right.$$ 

Surprisingly, $\pi$ production also not well understood at lower energies:
- BoGa
- SAID
- MAID

Asymmetry $G$ in $\vec{\gamma} \vec{p} \rightarrow p \pi^0$ @ ELSA

\[ \frac{d\sigma}{d\Omega} = \sigma_0 \left\{ 1 - \delta_1 \Sigma \cos 2\phi \right. \]
\[ + \Lambda_x \left( -\delta_1 H \sin 2\phi + \delta_\odot F \right) \]
\[ - \Lambda_y \left( -T + \delta_1 P \cos 2\phi \right) \]
\[ - \Lambda_z \left( -\delta_1 G \sin 2\phi + \delta_\odot E \right) \]

$\theta_\pi = 90 \pm 5^\circ$ Surprisingly, $\pi$ production also not well understood at lower energies.

$\theta_\pi = 130 \pm 5^\circ$

Below 1 GeV, discrepancies can be traced to the $E_{0+}$ and $E_{2-}$ multipoles, which are related to certain resonances:

$E_{0+}: N(1535) \frac{1}{2}^-, N(1650) \frac{1}{2}^-, \Delta(1620) \frac{1}{2}^-$

$E_{2-}: N(1520) \frac{3}{2}^-, \Delta(1700) \frac{3}{2}^-$

Beam Asymmetry $\Sigma$ in $\vec{\gamma} p \rightarrow p \pi^0$ @ CLAS (g8b)

\[
\frac{d\sigma}{d\Omega} = \sigma_0 \left\{ 1 - \delta_1 \Sigma \cos 2\phi \right\}
\]

Beam Asymmetry $\Sigma$ in $\vec{\gamma} p \rightarrow p \pi^0$ @ CLAS (g8b)

Largest changes in SAID DU13

- Improved mapping of dip near 60°
- Couplings of
  - $\Delta(1700)^{3/2}^-$
  - $\Delta(1905)^{5/2}^+$

Beam Asymmetry \( \Sigma \) in \( \vec{\gamma} p \rightarrow n \pi^+ \) @ CLAS (g8b)

\[
\frac{d\sigma}{d\Omega} = \sigma_0 \left\{ 1 - \delta I \Sigma \cos 2\phi \right\}
\]

Helicity Difference $E$ in $\vec{\gamma} \vec{p} \rightarrow n \pi^+$ @ CLAS (FROST)

\begin{align*}
\Delta^+ & \quad N^* \\
\rho_{\pi^0} & : \sqrt{\frac{2}{3}} | l = \frac{3}{2}, l_3 = \frac{1}{2} \rangle - \sqrt{\frac{1}{3}} | l = \frac{1}{2}, l_3 = \frac{1}{2} \rangle \\
n_{\pi^+} & : \sqrt{\frac{1}{3}} | l = \frac{3}{2}, l_3 = \frac{1}{2} \rangle + \sqrt{\frac{2}{3}} | l = \frac{1}{2}, l_3 = \frac{1}{2} \rangle
\end{align*}

S. Strauch SC, under CLAS collaboration review

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S. Strauch SC, under CLAS collaboration review
Target Asymmetry $T$ in $\gamma \vec{p} \rightarrow n \pi^+$ (CLAS FROST)

- MAID 07
- SAID
- BoGA 12

Early-stage results (g9b)

- Transverse Target Polarization

M. Dugger (ASU), CLAS g9b run group
Observable $F$ in $\vec{\gamma} \vec{p} \rightarrow n \pi^+$ (CLAS FROST-g9b)

$\frac{d\sigma}{d\Omega} = \sigma_0 \{ 1 - \delta_I \Sigma \cos 2\phi$

$\quad + \Lambda_x (-\delta_I H \sin 2\phi + \delta_\odot F)$

$\quad - \Lambda_y (-T + \delta_I P \cos 2\phi)$

$\quad - \Lambda_z (-\delta_I G \sin 2\phi + \delta_\odot E) \}$

Transv. target pol. & circ. beam pol.

- Early-stage analysis
- Reasonable agreement among predictions for $W < 1.7$ GeV
  $\Rightarrow$ Much to learn at the higher energies

M. Dugger (ASU), CLAS g9b run group

M. Dugger (ASU), CLAS g9b run group
Overview of CLAS Polarization Measurements

Measurements off the proton

- $\gamma p \rightarrow p \pi^0, n \pi^+$
- $\gamma p \rightarrow p \eta, p \eta'$ (I. Senderovich, R. Tucker et al.)
- $\gamma p \rightarrow p \pi^+\pi^-, p \phi, p \omega$ (CMU, CU, Florida State)

Measurements off the neutron

- $\gamma n \rightarrow p \pi^-$
- $\gamma n \rightarrow n \pi^+\pi^-$

“Complete” experiment possible in Strangeness Photoproduction (S. Fegan, N. Walford et al.)

- $\gamma p \rightarrow K Y \ (Y = \Lambda, \Sigma^0, \Sigma^+)$
- $\gamma n \rightarrow K^+ \Sigma^-, K^0 \Lambda$

Frozen-Spin Target (FROST)

HD Ice Target

“Complete” experiment possible in Strangeness Photoproduction (S. Fegan, N. Walford et al.)

- $\gamma p \rightarrow K Y \ (Y = \Lambda, \Sigma^0, \Sigma^+)$
- $\gamma n \rightarrow K^+ \Sigma^-, K^0 \Lambda$

Cross sections (K. Moriya, 2:30 PM)
(Also $\Lambda(1405), \Lambda(1520)$)
Beam-Target Polarization Observables in $\gamma p \rightarrow p \pi\pi$

\[ I = I_0 \left\{ \left( 1 + \vec{\Lambda}_i \cdot \vec{P} \right) + \delta_{\odot} \left( I^\odot + \vec{\Lambda}_i \cdot \vec{P}^\odot \right) + \delta_I \left[ \sin 2\beta \left( I^s + \vec{\Lambda}_i \cdot \vec{P}^s \right) + \cos 2\beta \left( I^c + \vec{\Lambda}_i \cdot \vec{P}^c \right) \right] \right\} \]


At higher excitation energies:
Multi-meson final states important.

At higher excitation energies:
Multi-meson final states important.

Search for states in decay cascades!
$W \in [1.74; 1.77] \text{ GeV}, \cos \Theta_{c.m.}^\rho > 0.5$

Data of unprecedented statistical quality

$I = I_0 \{ (1 + \vec{\Lambda}_i \cdot \vec{P}) + \delta_\odot (I^\odot + \vec{\Lambda}_i \cdot \vec{P}^\odot) + \delta_l \left[ \sin 2\beta \left( I^s + \vec{\Lambda}_i \cdot \vec{P}^s \right) + \cos 2\beta \left( I^c + \vec{\Lambda}_i \cdot \vec{P}^c \right) \right] \}$
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$W \in [1.716; 1.770]$ GeV

Priyashree Roy (Florida State), CLAS g9b (FROST)
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Data of unprecedented statistical quality

$$l = l_0 \left\{ (1 + \vec{\lambda}_i \cdot \vec{P}) + \delta_\circ \left( l_\circ + \vec{\lambda}_i \cdot \vec{P}_\circ \right) \\ + \delta_l \left[ \sin 2\beta \left( l^s + \vec{\lambda}_i \cdot \vec{P}^s \right) + \cos 2\beta \left( l^c + \vec{\lambda}_i \cdot \vec{P}^c \right) \right] \right\}$$

Sungkyun Park (FSU), under collaboration review
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Data of unprecedented statistical quality

\[
I = I_0 \left\{ (1 + \vec{\Lambda}_i \cdot \vec{P}) + \delta_\odot \left( I_\odot + \vec{\Lambda}_i \cdot \vec{P}_\odot \right) \right. \\
\left. + \delta_I \left[ \sin 2\beta \left( I^s + \vec{\Lambda}_i \cdot \vec{P}^s \right) + \cos 2\beta \left( I^c + \vec{\Lambda}_i \cdot \vec{P}^c \right) \right] \right\}
\]

Sungkyun Park (FSU), under collaboration review

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V. Credé
Light Baryon Spectroscopy
Preliminary Data of unprecedented statistical quality

\[ I = I_0 \left\{ (1 + \vec{\Lambda}_i \cdot \vec{P}) + \delta_\odot (I_\odot^0 + \vec{\Lambda}_i \cdot \vec{P}_\odot^0) \\
+ \delta_I \left[ \sin 2\beta (I_s + \vec{\Lambda}_i \cdot \vec{P}_s) + \cos 2\beta (I_c + \vec{\Lambda}_i \cdot \vec{P}_c) \right] \right\} \]

V. Credé
Light Baryon Spectroscopy
Outline

1. Introduction
   - Quarks, QCD, and Confinement
   - Structure of Baryon Resonances

2. The Search for Undiscovered States
   - Electromagnetic Probes
   - Mission Goal: Complete Experiments

3. Results from Photoproduction Experiments
   - Photoproduction of $\pi^0$ and $\pi^+$ Mesons off the Proton
   - Observables in the Photoproduction of Two Pions

4. Summary and Outlook
Summary and Outlook

Our understanding of baryon resonances has made great leaps forward. There is good evidence that most of the known states (listed in the PDG) will also be confirmed in photoproduction and that new states will be revealed:

- Goal of performing (almost) complete experiments has been (almost) achieved; significant contributions from (double-)polarization experiments.
- Still too early to nail down relevant degrees of freedom in excited baryons. ➔ Some states might be generated dynamically ...

\[
\begin{align*}
N(1860)^+ & \quad \frac{5}{2}^+ \quad \ast \ast \quad \pi N \quad \gamma N \\
N(1875) & \quad \frac{3}{2}^- \quad \ast \ast \ast \quad \pi N \quad \gamma N \quad \Lambda K \quad \Sigma K \\
N(1880) & \quad \frac{3}{2}^+ \quad \ast \ast \quad \pi N \quad \gamma N \quad \Lambda K \quad \Sigma K \\
N(1895) & \quad \frac{1}{2}^- \quad \ast \ast \ast \quad \pi N \quad \gamma N \quad \eta N \quad \Lambda K \quad \Sigma K \\
N(1900) & \quad \frac{3}{2}^+ \quad \ast \ast \ast \quad \pi N \quad \gamma N \quad \eta N \quad \Lambda K \quad \Sigma K \quad \Delta \pi \\
N(2060) & \quad \frac{5}{2}^- \quad \ast \ast \ast \quad \pi N \quad \gamma N \quad \eta N \quad \Sigma K \\
\Delta(1940) & \quad \frac{3}{2}^- \quad \ast \rightarrow \ast \ast \quad \pi N \quad \gamma N \\
\end{align*}
\]

New States in PDG 2012.