Baryon Spectroscopy in Photoproduction: What have we learned about excited baryons?

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Xth Quark Confinement and the Hadron Spectrum
Munich, Germany, 10/08/2012
1. Introduction
   - Quarks, QCD, and Confinement

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

3. Results from Photoproduction Experiments
   - Photoproduction of $\pi$, $\eta$, and $\omega$ Mesons
   - Observables in the Photoproduction of Two Pions

4. Summary and Outlook
Outline

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4. Summary and Outlook
How does QCD give rise to hadrons?

Interaction between quarks fairly unknown throughout > 98% of a hadron’s volume.

Explaining the excitation spectrum of hadrons is central to our understanding of QCD in the low-energy regime (Hadron Models, Lattice QCD, etc.)

Complementary to Deep Inelastic Scattering (DIS) where information on collective degrees of freedom is lost.
Non-Perturbative QCD

How does QCD give rise to 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 $\sim 99\%$ of observed matter in the universe?

Baryons: What are the fundamental degrees of freedom inside a proton or a neutron? How do they change with varying quark masses?
Components of the Experimental $N^*$ Program

The excited baryon program has two main components:

- **Probe resonance transitions at different distance scales**
  
  Electron beams are ideal to measure resonance form factors and their corresponding $Q^2$ dependence.
  
  ➜ Provides information on the structure of excited nucleons and on the confining (effective) forces of the 3-quark system.

- **Establish the systematics of the spectrum**
  
  Current medium-energy experiments use photon beams to map out the baryon spectrum (JLab, ELSA, MAMI, SPring-8, etc.).
  
  ➜ Provides information on the nature of the effective degrees of freedom in strong QCD and also addresses the issue of previously unobserved or so-called *missing resonances*. 
Spectrum of Nucleon Resonances


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
Introduction

The Search for Undiscovered States

Results from Photoproduction Experiments

Summary and Outlook

Quarks, QCD, and Confinement

Spectrum of Nucleon Resonances


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1. Excitation Band: $(70, 1^-_1)$ ✓

2. Excitation Band:
   
   $\begin{align*}
   (56, 0^+_2), (56, 2^+_2) & \checkmark \\
   (70, 0^+_2), (70, 2^+_2) & \checkmark \\
   (20, 1^+_2) & ?
   \end{align*}$

Theory

Experiment

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Excited-State Baryon Spectroscopy from Lattice QCD


Missing states?

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

Counting of levels consistent with non-rel. quark model, no parity doubling

$m_\pi = 400$ MeV

$v_{\pi} = 400$ MeV
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0.00
1.0
2.0
3.0

W [GeV]

E_γ [GeV]

Reaction Thresholds

\[ γp \rightarrow p\eta\eta \]
\[ γp \rightarrow p\pi^0ω \]
\[ γp \rightarrow p\pi^0\eta \]
\[ γp \rightarrow p\eta \]
\[ γp \rightarrow p\pi\pi\pi \]
\[ γp \rightarrow p\pi\pi \]
\[ γp \rightarrow p\pi \]

In addition:

- LEGS
- SPring-8

Common efforts at ELSA, JLab, and MAMI
(Double-)polarization measurements, \( γp \) & \( γn \) reactions, etc.
Extraction of Resonance Parameters

- Double-polarization measurements
- Measurements off neutron and proton to resolve isospin contributions:
  1. \( A(\gamma N \rightarrow \pi, \eta, K)^{l=3/2} \Leftrightarrow \Delta^* \)
  2. \( A(\gamma N \rightarrow \pi, \eta, K)^{l=1/2} \Leftrightarrow N^* \)
- Re-scattering effects: Large number of measurements (and reaction channels) needed to extract full scattering amplitude.

Coupled Channels

Jülich, Gießen, EBAC, etc.

http://ebac-theory.jlab.org
Double-Polarization: Toward Complete Experiments

Calorimeter system at ELSA is optimized for neutral particles.

*Frozen-Spin Target:* Butanol ($C_4H_9OH$).

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**Crystal Barrel Setup at ELSA**
- Crystal Barrel (1230 CsI crystals)
- Inner Detector (513 scintillating fibers)
- Forward Plug (90 CsI crystals with PM’s)
- MiniTAPS (216 $BaF_2$, $1^\circ - 12^\circ$)

Close to $4\pi$ coverage
The CLAS Spectrometer at Jefferson Laboratory

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The CLAS Spectrometer at Jefferson Laboratory

Electron Beam
Electromagnetic Calorimeters
Torus
Drift Chambers
Cerenkov Counters
Time of Flight Scintillators

FROST
double polarization

Data for PERP 1.3GeV Calculation

Polarization corresponding to calc (Peaking at > 90%)

Linear beam polarization

g8b

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Double-Polarization: Frozen Spin Targets

Horizontal cryostat with integrated solenoid to freeze the proton spin.

- DNP at high B-field (2.5 T), holding mode at 0.4 T
- Relaxation time at ELSA \( \sim 500 \) h

Longitudinally-Polarized Target \( (P_z \approx 80\%)\)

Transverse Target Polarization
(race-track coil - Dipole Magnet)

Butanol \( (C_4H_9OH)\)

“ELSA”

“CLAS”

Light Baryon Spectroscopy
Why are Polarization Observables Important?

1. From $\pi$ threshold up to $\Delta(1232)$ region
   - $s$- & $p$-wave approximation
   - Fermi-Watson Theorem
   - Two observables sufficient, e.g. $d\sigma/d\Omega$, $\Sigma$.

2. Above the $\pi\pi$ threshold
   - More observables needed.

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


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 $F_4$. 
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Example: Beam Asymmetry $\Sigma$ in $\vec{\gamma} p \rightarrow p \eta$

$$\frac{d\sigma}{d\Omega} = \sigma_0 \{ 1 - \delta_1 \Sigma \cos 2\phi \}$$

BoGa-PWA

$E_\gamma = 1250$ MeV

$D_{13}(1520)$

$P_{13}(1720)$

$\eta$-MAID

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Light Baryon Spectroscopy

D. Elsner et al. [CBELSA/TAPS], EPJ A 33, 147 (2007)
Example: Beam Asymmetry $\Sigma$ in $\vec{\gamma} p \rightarrow p \eta$

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

Normalization Discrepancy

$E_\gamma = 1250$ MeV

D. Elsner et al. [CBELSA/TAPS], EPJ A 33, 147 (2007)
Helicity-Dependent Cross Section for $\vec{\gamma}\vec{p} \rightarrow p\eta$

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

Very preliminary: Data are positive

M. Gottschall et al. [CBELSA/TAPS]

B. Morrison et al. [CLAS Collaboration]
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Isospin Filter: $\gamma p \rightarrow N^* (I = 1/2) \rightarrow p \omega$

A. Wilson et al. [CBELSA/TAPS], Ph.D. thesis

--- CBELSA/TAPS
--- CLAS (2009)

Good agreement between experiments
Excellent statistics

Great progress in our understanding of the differences between experiments.

Preliminary
Isospin Filter: $\gamma p \rightarrow N^* (l = 1/2) \rightarrow p \omega$

<table>
<thead>
<tr>
<th>$E_\gamma$ [GeV]</th>
<th>$d\sigma/d\Omega$ [$\mu$b/sr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>2.5</td>
<td>1.5</td>
</tr>
</tbody>
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</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>$-0.9 \rightarrow -0.8$</td>
</tr>
<tr>
<td>2</td>
<td>$-0.8 \rightarrow -0.7$</td>
</tr>
<tr>
<td>2.5</td>
<td>$-0.6 \rightarrow -0.5$</td>
</tr>
</tbody>
</table>

Discrepancy similar to $p\eta$

Great progress in our understanding of the differences between experiments.

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Light Baryon Spectroscopy
Isospin Filter: $\gamma p \rightarrow \Lambda^* (I = 1/2) \rightarrow p \omega$

Good agreement between experiments
Excellent statistics
New CBELSA/TAPS data extend the world database in the most forward direction.
Baryon Resonances in the Reaction $\gamma p \rightarrow p \omega$


Strong evidence for ($W < 2$ GeV):

$(3/2) - N(1700)$  
$(5/2) + N(1680)$

Only nucleon resonances can contribute (isospin filter)

- First-time PWA of $\omega$ photoproduction channel
- High statistics data sets are key to pull out signals.

$\Rightarrow$ CLAS at JLab can provide statistics, but there are also limitations in the acceptance.
Baryon Resonances in the Reaction $\gamma p \rightarrow p \omega$


Strong evidence for ($W > 2$ GeV):

- $(5/2)+ N(1680) \ast \ast \ast$
- $(5/2)+ N(1950) \ast \ast$
- $(7/2)− N(2190) \ast \ast \ast$
Polarization Observables in $\gamma p \rightarrow p \omega$

Strong evidence for $(W > 2 \text{ GeV)}$:

(5/2)$^+$ $N(1680)$ $^{***}$

(5/2)$^+$ $N(1950)$ $^{**}$

(7/2)$^-$ $N(2190)$ $^{***}$

Asymmetry $\Sigma$ for $\gamma p \rightarrow p \omega$ (P. Collins et al., CUA)

- Oh et al.
- Paris et al.
- Sarantsev et al.
Photoproduction of $\pi^0$ Mesons from the Proton

Reaction $\gamma p \rightarrow p \pi^0$ remains important for our understanding of baryons.

- At ELSA, excellent data with good statistics in the forward direction.
- Forward region is very sensitive to higher-spin resonances:
  - Observation of $N(2190)G_{17}$ within the Bonn-Gatchina PWA framework
    (Important to confirm high-mass states first observed in $\pi N$ scattering)

Beam Asymmetry $\Sigma$ in $\vec{\gamma} p \rightarrow p \pi^0$

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

- SAID  
- MAID  
- CLAS

$(E_\gamma < 2 \text{ GeV}, -0.85 < \cos \theta_\pi < -0.35)$

$\rightarrow$ Serious discrepancies between models and data above 1.4 GeV.

Photoproduction of $\pi$ mesons still not very well understood.

M. Dugger (ASU), CLAS g8b run group, to be published
Beam Asymmetry $\Sigma$ in $\gamma p \rightarrow p \pi^0$

\[ \gamma p \rightarrow p \pi^0 \]

- SAID
- MAID
- CLAS

(\(E_{\gamma} < 2 \text{ GeV}, \ 0.35 < \cos \theta_{\pi} < 0.85\))

Combination of $p \pi^0$ and $n \pi^+$ final states can help distinguish between $\Delta$ and $N^*$ resonances:

\[
\begin{align*}
\pi^0 + p & : \sqrt{2/3} \left| I = \frac{3}{2}, I_3 = \frac{1}{2} \right> - \sqrt{1/3} \left| I = \frac{1}{2}, I_3 = \frac{1}{2} \right> \\
\pi^+ + n & : \sqrt{1/3} \left| I = \frac{3}{2}, I_3 = \frac{1}{2} \right> + \sqrt{2/3} \left| I = \frac{1}{2}, I_3 = \frac{1}{2} \right>
\end{align*}
\]

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Beam Asymmetry $\Sigma$ in $\vec{\gamma}p \rightarrow p\pi^0$ and $\vec{\gamma}p \rightarrow n\pi^+$

$\gamma p \rightarrow p\pi^0$

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

M. Dugger (ASU), CLAS g8b run group, to be published

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Asymmetry $G$ in $\gamma \bar{p} \rightarrow p \pi^0$ (Results from ELSA)

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

Surprisingly, $\pi$ production also not well understood at lower energies:

- BoGa
- SAID
- MAID

A. Thiel et al. [CBELSA/TAPS], PRL 109, 102001 (2012)
**Asymmetry $G$ in $\vec{\gamma} \vec{p} \rightarrow p \pi^0$ (Results from ELSA)**

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

\[\theta_\pi = 90 \pm 5^\circ\]

\[\theta_\pi = 130 \pm 5^\circ\]

Surprisingly, $\pi$ production also not well understood at lower energies.

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

A. Thiel et al. [CBELSA/TAPS], PRL 109, 102001 (2012)
Transverse Target Polarization: Target Asymmetry $T$

$$\Delta N(\phi) = \frac{1}{f P_{\text{target}}} \cdot \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$

$$= T \cdot \sin (\phi - \beta)$$

$\rightarrow$ Unprecedented statistical quality.

$\gamma \vec{p} \rightarrow p\pi^0$

$\gamma \vec{p} \rightarrow p\eta$

700 < $E_\gamma$ < 800 MeV

800 < $E_\gamma$ < 900 MeV

$\chi^2$/ndf 23.25/17

$T$ -0.2444 ± 0.0029

$\chi^2$/ndf 19.97/17

$T$ 0.1668 ± 0.0091

Direction of target pol.: $\beta = 99^\circ$

$\Delta N$ vs $\phi_{\pi^0}$ for $700 < E_\gamma < 800$ MeV

$\Delta N$ vs $\phi_{\pi^0}$ for $800 < E_\gamma < 900$ MeV

Preliminary

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Target Asymmetry $T$ in $\gamma \vec{p} \rightarrow p \pi^0$ (Data from ELSA)

$600 < E_\gamma < 1000$ MeV in bins of $\Delta E = 25$ MeV

- CBELSA/TAPS
- Maid
- Said
- Bonn Gatchina

$\Rightarrow$ Good agreement of experimental data. (improved statistics)

J. Hartmann et al. [CBELSA/TAPS]
Target Asymmetry $T$ in $\gamma \vec{p} \to p \pi^0$ (Data from ELSA)

1000 $< E_\gamma < 1500$ MeV

- CBELSA/TAPS
- Daresbury (1977)

→ Good agreement of experimental data.

Model disagreement toward 3rd resonance region: $W > 1.6$ GeV ($E_{0^+}, E_{2^-}$ multipoles?)

J. Hartmann et al. [CBELSA/TAPS]
Target Asymmetry $T$ in $\gamma \vec{p} \rightarrow p \eta$ (Data from ELSA)

708 < $E_\gamma$ < 933 MeV
in bins of $\Delta E = 25$ MeV

- CBELSA/TAPS
- PHOENICS (1998)
- Maid
- Said
- Bonn Gatchina

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J. Hartmann et al. [CBELSA/TAPS]
Beam-Target Polarization Observables in $\gamma p \rightarrow p \pi \pi$

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


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

$\gamma \rightarrow N^*, \Delta^*$

$\pi^0 \rightarrow N^*, \Delta^*$

Search for states in decay cascades!
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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 be confirmed in photoproduction and that new states will be revealed:

- Goal of performing (almost) complete experiments has been (almost) achieved; program on neutron ongoing.
- Spectroscopy will continue at ELSA, MAMI and JLab in the 12 GeV era (e.g. $\Xi$, $\Omega$ states): GlueX and CLAS12.

### New States in PDG 2012.

- $N(1860)_{\frac{5}{2}^+}^{**}$
- $N(1875)_{\frac{3}{2}^-}^{***}$
- $N(1880)_{\frac{1}{2}^+}^{**}$
- $N(1895)_{\frac{1}{2}^-}^{**}$
- $N(1900)_{\frac{3}{2}^+}^{***}$
- $N(2060)_{\frac{5}{2}^-}^{**}$
- $\Delta(1940)_{\frac{3}{2}^-}^{* \rightarrow **}$
Photoproduction of $\pi\pi$ Pairs off the Proton: Kinematics

Two mesons in the final state require 5 independent variables!

For example: $E_\gamma, \Theta_{c.m.,} \phi^*, \theta^*, M_{p+\text{meson}_1}$

Single-meson reactions:
$\rightarrow$ p-meson system in the reaction plane

Two-meson reactions:
$\rightarrow$ Reaction and decay plane form angle $\phi$
Beam Asymmetries $I^s, I^c$ in $\gamma p \rightarrow p \pi^0 \pi^0$

First measurements of beam asymmetries $I^s$ and $I^c$ using linearly-polarized photons in the reaction $\gamma p \rightarrow p \pi^0 \pi^0$.

Among other things, study of decays into $\Delta \pi$:

--- BoGa-PWA solution with a dominant $\Delta(1700)D_{33} \rightarrow \Delta \pi$ $D$-wave

----- BoGa-PWA solution with a dominant $\Delta(1700)D_{33} \rightarrow \Delta \pi$ $S$-wave

- Direct measurements
- From mirror operation $I^s(\Phi^*) \rightarrow I^s(2\pi - \Phi^*)$

V. Sokhoyan et al. [CBELSA/TAPS], to be published

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Data of unprecedented stat. quality

Here: 3-dim. phasespace $(E_\gamma, \theta_{\pi^+}^*, \phi_{\pi^+}^*)$
Analysis of butanol target challenging:

- Determination of dilution factor $\rightarrow$
  (event-based dilution factors possible)

The interpretation of these $\pi\pi$ data has only just begun.

S. Park et al., CLAS (FROST), to be published