The Study of Excited Baryons: What is next?

Volker Credé
Florida State University, Tallahassee, FL

Future Directions in Spectroscopy Analysis
Jefferson Laboratory
11/20/2014
Outline

1. The Spectrum of Baryons
   - Lattice Calculations
   - The Experimental Spectrum

2. Are we there yet?
   - Complete Experiments
   - Observables in Photoproduction
   - How do we publish and archive these data?

3. Spectroscopy of Cascade Baryons
   - Cascades at GlueX

4. Summary and Outlook
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Baryon Spectroscopy from Lattice QCD


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

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

$m_\pi = 396$ MeV

$N(938)$ $\Delta(1232)$ $\Delta(1620)$ $\Delta(1700)$

Missing states?
Evidence for *Missing* Strange Baryons

Comparison with two hadron resonance gas models:
- PDG-HRG
- QM-HRG

“These results do provide evidence for the existence of additional strange baryons and their thermodynamic importance.”

The Spectrum of Baryons
Are we there yet?
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Spectrum of $N^*$ Resonances (PDG < 2012)

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

2. Excitation Band:
   - $(56, 0^+_2)$, $(56, 2^+_2)$
   - $(70, 0^+_2)$, $(70, 2^+_2)$
   - $(20, 1^+_2)$

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The Study of Excited Baryons: What is next?
### Spectrum of $N^*$ Resonances

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<th>Jπ</th>
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<th>3/2+</th>
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#### $N^*$

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The Study of Excited Baryons: What is next?
The Experimental $N^*$ Spectrum: Recent Changes

Mass [GeV/c²]

PDG 2010  PDG 2014

J^p

1/2+  3/2+  5/2+  7/2+  9/2+  11/2+  1/2-  3/2-  5/2-  7/2-  9/2-  11/2-

939  1440  1680  1860  1900  1990  2040  2080  2090  2100  2120  2190  2200  2250  2300  2570  2600

PDG 2010
PDG 2014

Courtesy of Andrew Wilson, FSU & U. of Bonn (HISKP)
The Spectrum of Baryons
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Summary and Outlook

Lattice Calculations
The Experimental Spectrum

### Spectrum of $\Delta^*$ Resonances

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<th>$\Delta^*$</th>
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Reactions can serve as isospin filter:

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

$\gamma p \rightarrow \Delta \omega \rightarrow p \pi^0 \omega$
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For single-meson production:

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

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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How do we publish and archive these data?

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Table representing CLAS@JLab measurements.

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<th>Observables</th>
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Need more observables on:

$\gamma p \rightarrow p \pi\pi, p \pi\eta$

$\gamma p \rightarrow p \pi\omega, ...$
Observable $F$ in $\vec{\gamma} \vec{p} \rightarrow n \pi^+$ (CLAS FROST-g9b)

- MAID 07
- SAID 12
- BoGa not shown

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

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
Complete Experiment in $\gamma p \rightarrow p \omega$

$\gamma p \rightarrow p \omega \rightarrow p \pi^+ \pi^- \pi^0_{\text{miss}}$ ⇒ same final state as $\gamma p \rightarrow p \pi^+ \pi^-$

Analysis in basically three steps:

- Kinematics & Event Selection ($p \pi^+ \pi^-$)
  - lin. pol.: USC (✓)
  - circ. pol.: FSU ✓, CU (✓)

- Event-based background subtraction
  - $p \pi^+ (\pi^-)$, $p (\pi^+)\pi^-$, $p \pi^+ \pi^-$ ✓
  - $p \pi^+ \pi^- (\pi^0)$ ✓ $p \pi^+ \pi^- (\eta)$?

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

  published (+ SDME’s)

  in progress

  $E_\gamma \in [1.4, 1.5]$ GeV

  g9a: $\omega$

  Courtesy of Priyashree Roy (FSU)
Observation of new decay modes in the decay of $N^*$ resonances; weak at most in $\Delta^*$ decays.

Bonn-Gatchina PWA
V. Sokhoyan, E. Gutz, V.C. et al. @ELSA

Cross Section and Polarization Observables
(W. Roberts et al., PRC 71, 055201 (2005))

\[
I = I_0 \left\{ \left( 1 + \vec{\Lambda}_i \cdot \vec{P} \right) + \delta_\circ \left( I^\circ + \vec{\Lambda}_i \cdot \vec{P}^\circ \right) + \delta_1 \left[ \sin 2\beta \left( I^s + \vec{\Lambda}_i \cdot \vec{P}^s \right) + \cos 2\beta \left( I^c + \vec{\Lambda}_i \cdot \vec{P}^c \right) \right] \right\}
\]

Search for states in decay cascades!
Observation of Decay Cascades in $\gamma p \rightarrow p \pi^0 \pi^0$

F. Zehr et al., Eur. Phys. J. A 48, 98 (2012) @MAMI

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Search for states in decay cascades!
The Spectrum of Baryons
Are we there yet?
Spectroscopy of Cascade Baryons
Summary and Outlook

Observation of Decay Cascades in $\gamma p \rightarrow p \pi^0 \pi^0$

Nucleon states with $S = \frac{3}{2}$ require spatial wave functions of mixed symmetry. For $L = 2$ the wave functions do have equal admixtures of $M_S$ and

$$M_A = [\phi_0 p(\vec{\rho}) \times \phi_0 p(\vec{\lambda})]^{(L=2)},$$

a component in which both the $\rho$ and the $\lambda$ oscillator are excited simultaneously.

Observation of new decay modes in the decay of $N^*$ resonances; weak at most in $\Delta^*$ decays.

____ Bonn-Gatchina PWA

V. Sokhoyan, E. Gutz, V. C. et al. @ELSA
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High Statistics Study of the Reaction $\gamma p \rightarrow p \pi^0 \eta$


Dominant Isobars
$\Delta(1232)\eta, N(1535) \frac{1}{2}^- \pi, pa_0(980)$

Observation of some
$\Delta^* \rightarrow N(1535) \frac{1}{2}^- \pi \rightarrow p \pi \eta$

Bonn-Gatchina
$\Delta(1700) \frac{3}{2}^-$
$\Delta(1600) \frac{3}{2}^+$
$\Delta(1920) \frac{3}{2}^+$
$\Delta(1940) \frac{3}{2}^-$
$\Delta(1905) \frac{5}{2}^+$
$\Delta(2360) \frac{3}{2}^-$
$N(1880) \frac{1}{2}^+$
$N(2200) \frac{3}{2}^+$

V. L. Kashevarov et al., EPJ A 42, 141 (2009) @MAMI

V. Credé
The Study of Excited Baryons: What is next?
High Statistics Study of the Reaction $\gamma p \rightarrow p \pi^0 \eta$


Linear Beam Polarization

Bonn-Gatchina
A. Fix et al.
M. Döring et al.
**Isospin Filter:** \( \gamma p \rightarrow \Delta^* (I = 3/2) \rightarrow \Delta \omega \rightarrow p \pi^0 \omega \)

**Preliminary Differential Cross Sections for** \( \gamma p \rightarrow p \pi^0 \omega \)**

<table>
<thead>
<tr>
<th>Inv Mass [MeV]</th>
<th>Preliminary Differential Cross Sections</th>
<th>( \omega \rightarrow \pi^0 \gamma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1300-1350</td>
<td></td>
<td>( \sim 18,000 ) events</td>
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<td>1500-1550</td>
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<td>2500-2550</td>
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</tbody>
</table>

A. Wilson, Florida State University, PhD thesis (2013)
The Spectrum of Baryons
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Complete Experiments
Observables in Photoproduction
How do we publish and archive these data?

$W \in [1.74; 1.77] \text{ GeV}, \cos \Theta_{\text{c.m.}}^\rho > 0.5$

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

Data of unprecedented statistical quality

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

Charles Hanretty (FSU), approved by CLAS collaboration

V. Credé

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Priyashree Roy (Florida State), CLAS g9b (FROST)
How do we publish these results?

The interpretation of many observables is far behind the experimental analysis, in particular for 2-meson reactions. How do we proceed?

- Wait?
- Publish results without any direct physics conclusion? Reviewers usually ask what the impact of the new data is.

How do we preserve the data for future analysis?

- Events? Simple projections are not suitable for $p\pi\pi$, $p\pi\eta$ (5-dim.)

What else is needed for future analyses?

- Polarized cross sections? Requires Monte Carlo simulations (also for event-based PWA), which is not a standard tool for the people doing “baryon” polarization experiments.
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1. The Spectrum of Baryons
   - Lattice Calculations
   - The Experimental Spectrum

2. Are we there yet?
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   - How do we publish and archive these data?

3. Spectroscopy of Cascade Baryons
   - Cascades at GlueX

4. Summary and Outlook
Cascade Resonances: Status of 2001


Many predicted states missing

Instanton Model: residual short-range interaction based on instanton interactions
CLAS g12 (prel.): Total Cross Section of $\Xi^{-}$

Johann Goetz (CLAS Collaboration), UCLA, Ph.D. Thesis

Upper Limits (integrated over 3.5-5.4 GeV):

1. $\Xi(1620)$: 0.78 nb
2. $\Xi(1690)$: 0.97 nb
3. $\Xi(1820)$: 1.09 nb
1. Only $\Xi(1530)$ statistically significant

2. $\Xi(1620)$ signal "plausible", but simulated $K^{*0}$ events also peak in 1600 MeV/$c^2$ region ($\gamma p \rightarrow K^+ K^{*0} \Xi^0, \ K^{*0} \rightarrow K^+ \pi^-$)

"... it is not possible to determine its exact nature without a full PWA."

Need high-statistics, high-energy data from an experiment designed to see $\Xi$ states

- 3- or 4-track trigger
- Reconstruction of full decay chain
- Higher photon energy
- Improved detectors

$\rightarrow$ GlueX, CLAS12, ...
Possible Production Mechanisms

a) $K^+(\Xi^- K^+), \ K^+(\Xi^0 K^0), \ K^0(\Xi^0 K^+)$$

→ Cross sections, beam asymmetries
(similar to $p\pi\pi$ & $pKK^*$)

Production of excited states via a

1. forward-going $K^0$ meson
   → $K^0(\Xi^- \pi^+) K^+$, etc.

2. forward-going $K^+$ meson
   → $K^+(\Xi^- \pi^+) K^0$, $K^+(\Xi^0 \pi^-) K^+$, etc.

Efficiency should be adequate for conducting a study of excited $\Xi$ states with the baseline detector:

- Detailed studies of the production, especially of the ground state $\Xi$'s, and a parity measurement \(^*\) will likely require enhanced kaon identification in the forward direction  \(\Rightarrow\)  Components of the BaBar DIRC for GlueX.

\(^*\) e.g. Nakayama et al., Phys. Rev. C 85, 042201 (2012)
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Baryon Spectroscopy: Are we there, yet? Certainly not ...

Data-taking in low-energy photoproduction is almost over
(polarization experiments for “complete experiments”)

- The job to extract (and study) baryon resonances has only just begun.
- The experimental (data analysis) community slowly moves on.
  How do we archive the data for later analysis?

Example 2-meson channels: Extraction of observables is happening now, but the extraction of physics will likely happen years later.

New era in the spectroscopy of strange baryons (GlueX, LHCb, PANDA, ...)

- Mapping out the spectrum of Ξ baryons is the primary motivation (including parity measurements); some hope for peak hunting.
- Ground-state Ξ in $\gamma p \rightarrow KK\Xi$ will allow the spectroscopy of $\Sigma^* / \Lambda^*$ states.