Disentangling the Entanglement: 
Exploring the Excited States of the Nucleon

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Florida State University
Tallahassee, FL

Physics Department Colloquium
Tallahassee, February 18th, 2010
Outline

1. Introduction
   - QCD and Hadron Spectroscopy

2. Experimental Methods in Baryon Spectroscopy
   - Photoproduction

3. Experimental Efforts
   - CLAS and the Crystal Barrel Detector

4. Photoproduction of Mesons (off Protons)
   - Single-Meson Reactions: $\gamma N \rightarrow N\eta$
   - Double-Pion Photoproduction

5. Summary and Outlook
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5 Summary and Outlook
Quantum Chromodynamics (QCD)...

... is the theory of strong interactions; the strong force describes the interactions of quarks and gluons making up hadrons.

QCD enjoys two important properties:

1. Asymptotic Freedom
   In high-energy reactions, quarks and gluons interact very weakly.

The inside of the proton at high energies – a “dense soup” of quarks and gluons.
Quantum Chromodynamics (QCD) is the theory of strong interactions; the strong force describes the interactions of quarks and gluons making up hadrons.

QCD enjoys two important properties:

1. **Asymptotic Freedom**
   In high-energy reactions, quarks and gluons interact very weakly.

Good quantitative tests of perturbative QCD are:

- Running QCD coupling
- Scaling violation in (un)polarized DIS
- Jet cross sections in colliders
- Heavy-quark production in colliders
Quantum Chromodynamics (QCD)

... is the theory of strong interactions; the strong force describes the interactions of quarks and gluons making up hadrons.

QCD enjoys two important properties:

1. **Asymptotic Freedom**
   In high-energy reactions, quarks and gluons interact very weakly.

2. **Confinement**
   Force between quarks does not diminish as they are separated.

No free quarks!
Quantum Chromodynamics (QCD)

... is the theory of strong interactions; the strong force describes the interactions of quarks and gluons making up hadrons.

QCD enjoys two important properties:

1. **Asymptotic Freedom**
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Non-Perturbative QCD

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

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

How does QCD give rise to hadrons?

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

Courtesy of Craig Roberts, Argonne
What are the relevant degrees of freedom?

What are the corresponding effective interactions responsible for hadronic phenomena?
Why $N^*$’s (= Excited Nucleons)?

Why should we study excited baryons?
(Nathan Isgur, Workshop on Excited Nucleons (2000))

1. Nucleons are the stuff our world is made of.
2. Simplest system in which the nonabelian character of QCD is manifest.
3. Baryons are sufficiently complex to reveal physics hidden from us in the mesons.

→ In fact, baryons were at the roots of the development of the quark model.
The quark model for baryons (qqq):
- Fermions with baryon number $B = 1$
- All established baryons are consistent with qqq configuration

SU(6) Symmetry ($^{2S+1}$ multiplets; u, d, s, spin)

\[
\begin{align*}
6 \otimes 6 \otimes 6 &= 56_s \oplus 70_M \oplus 70_M \oplus 20_A \\
\Rightarrow 56 &= 4^{10} \oplus 8^{2} \text{ "ground states"} \\
70 &= 2^{10} \oplus 8^{4} \oplus 8^{2} \oplus 2^{1} \\
20 &= 8^{2} \oplus 4^{1}
\end{align*}
\]
One of the Goals of the $N^*$ Program ...

Search for *missing* or yet unobserved resonances

Quark models predict many more baryons than have been observed

<table>
<thead>
<tr>
<th>Spectrum</th>
<th>****</th>
<th>***</th>
<th>**</th>
<th>*</th>
</tr>
</thead>
<tbody>
<tr>
<td>N Spectrum</td>
<td>11</td>
<td>3</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>$\Delta$ Spectrum</td>
<td>7</td>
<td>3</td>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</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!!
Nucleon Resonances: Status of 2001


many predicted states missing

OGE Model: residual short-range interaction based on one-gluon exchange

V. Credé Exploring the Excited States of the Nucleon
Nucleon Resonances: Status of 2001


many predicted states missing

First Excitation Band:
(70, 1\(^{-}\)) ✓

2. Excitation Band:
(56, 0\(^{+}\)), (56, 2\(^{+}\)), (70, 0\(^{+}\)), (20, 1\(^{+}\)), (70, 2\(^{+}\))

Nucleon Resonances: Status of 2001

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Exploring the Excited States of the Nucleon
Resonances

Model: residual short-range interaction based on instanton-induced interactions

Mass [MeV]

1000

1500

2000

2500

3000

J π L2 T2J

1/2+ P3 1

3/2+ P3 3

5/2+ F3 5

7/2+ F3 7

9/2+ H3 9

11/2+ H3 11

13/2+ K3 13

15/2+ K3 15

1/2- S3 1

3/2- D3 3

5/2- D3 5

7/2- G3 7

9/2- G3 9

11/2- I3 11

13/2- I3 13

15/2-
Parity Doublets

Nucleons

<table>
<thead>
<tr>
<th>Mass [MeV]</th>
<th>J π</th>
</tr>
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<tbody>
<tr>
<td>939</td>
<td>1/2+</td>
</tr>
<tr>
<td>1000</td>
<td>1/2-</td>
</tr>
<tr>
<td>1385</td>
<td>3/2+</td>
</tr>
<tr>
<td>1440</td>
<td>3/2-</td>
</tr>
<tr>
<td>1500</td>
<td>5/2+</td>
</tr>
<tr>
<td>1535</td>
<td>5/2-</td>
</tr>
<tr>
<td>1630</td>
<td>7/2+</td>
</tr>
<tr>
<td>1710</td>
<td>7/2-</td>
</tr>
<tr>
<td>1720</td>
<td>9/2+</td>
</tr>
<tr>
<td>1895</td>
<td>9/2-</td>
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<tr>
<td>1900</td>
<td>11/2+</td>
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<tr>
<td>1986</td>
<td>11/2-</td>
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<tr>
<td>2080</td>
<td>13/2+</td>
</tr>
<tr>
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<td>13/2-</td>
</tr>
<tr>
<td>2100</td>
<td>1/2+</td>
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<tr>
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<tr>
<td>2600</td>
<td>13/2+</td>
</tr>
<tr>
<td>2620</td>
<td>13/2-</td>
</tr>
</tbody>
</table>

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Parity Doublets

Is this compelling empirical data?

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Exploring the Excited States of the Nucleon
Parity Doublets

Nucleons

Is this compelling empirical data?

- **Glozman**: “... and thus we have a complete and total, 100% ironclad proof that ...” (according to T. Cohen)
Is this compelling empirical data?

- **Glozman**: “… and thus we have a complete and total, 100% ironclad proof that …” (according to T. Cohen)
- **Cohen**: “… and thus we have a faint hint of a whisper of the suggestion of the possibility that perhaps …”
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Exploring the Excited States of the Nucleon
Hadron Beams: Pion- (Kaon-) Nucleon Scattering

First insight into experimental difficulties:
- The elastic cross section drops fast.
  ➜ The resonances decouple from elastic scattering amplitude.
- Gradual disappearance of resonant structures in the $\pi p$ cross sections
  ➜ For $\sqrt{s} > 1.7$ GeV, more and more inelastic channels open.

Knowledge on $N^*/\Delta^*$ in the PDG
Mostly 5 (reference) analyses based on (mainly) $\pi N \rightarrow \pi N$ and $\pi N \rightarrow N\pi\pi$ (Kent, Karlsruhe-Helsinki, Carnegie-Mellon, SAID, ...)

$\Delta_{3/2}^+(1232)$ dominates

$P_{33}^-$ found in $\pi N$ with ($L = 1$)
Baryon Spectroscopy at BES: $J/\psi \rightarrow p\pi^-\bar{n}$ \((p\pi^+ n)\)

Analysis identifies four peaks: (Li et al., 2009)

1. $N(1440)P_{11}$
2. Well-known 2nd resonance region around 1500 MeV
3. Well-known 3rd resonance region around 1700 MeV
4. Possible new state: \[ M = 2040^{+3}_{-4} \pm 25 \text{ MeV/c}^2 \]
   \[ \Gamma = 230 \pm 8 \pm 52 \text{ MeV/c}^2 \]
Photoproduction of Mesons (off Protons)

### Reaction Thresholds

<table>
<thead>
<tr>
<th>Reaction</th>
<th>W [GeV]</th>
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<tbody>
<tr>
<td>$\gamma p \rightarrow p\eta\eta$</td>
<td>1.66</td>
</tr>
<tr>
<td>$\gamma p \rightarrow p\pi^0\omega$</td>
<td>2.6*</td>
</tr>
<tr>
<td>$\gamma p \rightarrow p\pi^0\eta$</td>
<td>3.0</td>
</tr>
<tr>
<td>$\gamma p \rightarrow p\eta$</td>
<td>2.6</td>
</tr>
<tr>
<td>$\gamma p \rightarrow p\pi\pi\pi$</td>
<td>1.9</td>
</tr>
<tr>
<td>$\gamma p \rightarrow p\pi\pi\pi$</td>
<td></td>
</tr>
<tr>
<td>$\gamma p \rightarrow p\pi\pi$</td>
<td>1.7</td>
</tr>
</tbody>
</table>

- **CLAS**
- **ELSA**
- **MAMI-C**
- **GRAAL**

### In addition:

- **LEGS**
- **SPring-8**

- **Partially complementary**
  - **All facilities have started polarization programs**

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Exploring the Excited States of the Nucleon
Components and goals of the $N^*$ program:

- **How many baryon resonances are known?**
  - The PDG gives a large number of 1-star to 4-star resonances.

- **How many baryon resonances are expected?**
  - What about quark-model (lattice) predictions?

- **What is the structure of baryons?**
  - Electroproduction
Total Photoproduction Cross Sections

No peak hunting

- Decays into neutral and charged particles
- Broad resonances
Total Photoproduction Cross Sections

- No peak hunting
- Decays into neutral and charged particles
- Broad resonances


total photoproduction cross sections

E_{\gamma}(GeV) vs \sigma(mb)
Ingredients in the Study of Excited Baryons

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

- Re-scattering effects: Large number of measurements (and also final states) needed to define the full scattering amplitude

- Double-polarization measurements

**Chiang & Tabakin, Phys. Rev. C55, 2054 (1997)**

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 the four single-spin observables.
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CLAS/Crystal Barrel – Complementary Detectors

Photoproduction at ELSA with the Crystal-Barrel Detector

Great to measure neutral particles:
\[ \pi^0, \eta \rightarrow \gamma\gamma, \eta \rightarrow \pi^0\pi^0\pi^0, \text{etc.} \]

Photo/Electroproduction at CLAS

Great for charged particles:
\[ \pi^\pm, \text{etc.} \]
The CBELSA/TAPS Experiment

  - (un)polarized beam
  - liquid $\text{H}_2$, deuterium
  - solid targets

TAPS
- 512 BaF Crystals
- Forward detector
  - High Granularity
  - Fast Trigger

Goniometer
- amorphous radiators
- screen
- empty position
- wires for determination of beam profiles
- diamond crystal
CLAS Spectrometer

Electron Coverage: $\theta : 15−50^\circ$

Hadron Coverage:
$\theta : 15−140^\circ$, $\phi : 80\% \ 2\pi$

Resolution :
$\Delta p/p \sim 1−2\%$
$\Delta \theta, \Delta \phi \sim 2 \text{ mrad}$

$\mathcal{L} = 1 \times 10^{34} \ cm^{-2} \text{sec}^{-1}$
$\mathcal{F}_\gamma = 1 \times 10^7 /s$
CLAS Spectrometer

- **Torus**
- **Tagger**
- **Drift Chambers**
- **Cerenkov**
- **Calorimeters**

**CHARACTERISTICS:**

- **Electron Coverage:** \( \theta : 15-50^\circ \)
- **Hadron Coverage:** \( \theta : 15-140^\circ, \phi : 80\% \ 2\pi \)
- **Resolution:** \( \Delta p/p \sim 1-2\% \)
- \( \Delta \theta, \Delta \phi \sim 2\ mrad \)

- \( \mathcal{L} = 1 \times 10^{34} \ cm^{-2}sec^{-1} \)
- \( \mathcal{F}_\gamma = 1 \times 10^{7}/s \)
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Isospin Filter: $\gamma p \rightarrow N^* \ (I = 1/2) \rightarrow p\eta$

$\eta \rightarrow \gamma\gamma$

$\eta \rightarrow 3\pi^0$

Only nucleon resonances can contribute

- $N(1535)S_{11}$, $N(1520)D_{13}$, $N(1650)S_{11}$, $N(1680)F_{15}$, $N(1720)P_{13}$, ... $\rho$- and $\omega$-$t$-channel exchange
- New resonance $N(2070)D_{15}$: $m = (2068 \pm 22) \text{ MeV}/c^2$, $\Gamma = (295 \pm 40) \text{ MeV}/c^2$
  (needs confirmation in polarization experiments)
Photoproduction of $\eta$ Mesons off the Proton


Photoproduction of $\eta$ Mesons off the Proton


Exploring the Excited States of the Nucleon
Photoproduction of $\eta$ Mesons off the Proton

- CBELSA/TAPS
- CB-ELSA
- CLAS
- SAID
- BoGa Fit

\[ \gamma N \rightarrow N\eta \]

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

Isospin Filter

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

Bonn-Gatchina (PWA) group:
Hints for $N^*$ resonance $N(2070)D_{15}$
(Phys. Rev. Lett. 94, 012004 (2005))

Three resonances are dominantly contributing:

$N(1535)S_{11}$, $N(1720)P_{13}$, $N(2070)D_{15}$
Single-Meson Reactions: $\gamma N \rightarrow N\eta$

**Photoproduction of Mesons (off Protons)**

### Isospin Filter

- Only $N^*$ resonances can contribute!

**Bonn-Gatchina (PWA) group:**

- Hint for $N^*$ resonance $(2070)D_{15}$
  - Confirmed in 2009 analysis!
- $N(1720)P_{13} \rightarrow p\eta$?
  - $N(1710)P_{11} \rightarrow p\eta$ significant!

**Resonances dominantly contributing:**

$N(1535)S_{11}$, $(N(1720)P_{13})^?$, $N(2070)D_{15}$

---

**Analysis of $\gamma p \rightarrow p\eta$: Total Cross Section**
Photoproduction of \( \eta \) Mesons at CLAS (Jefferson Lab)

- g11a
- CB-ELSA ('05)
- CLAS ('02)
- GRAAL ('02)
- LNS ('06)
- SAID

Big discrepancies at high energies and in the forward direction ➔ CLAS PWA in the works

V.C. et al. [CB-ELSA Collaboration],

M. Williams et al. [CLAS Collaboration],
Beam Asymmetry $\Sigma$ in the Reaction $\bar{\gamma}p \rightarrow p\eta$

Higher sensitivity due to interference effects: $\Sigma \sim A_{1/2}(S_{11}) \times A_{1/2}(P_{13}) + \ldots$

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

Further spin observables available:

- $E$ and $G$ from FROST run with longitudinal target polarization (2007/2008)
- $T$, $F$, $H$, and $P$ from FROST with transverse target polarization (Spring 2010)

P. Collins, CLAS g8b run group, to be published
Beam Asymmetry $\Sigma$ in the Reaction $\gamma p \rightarrow p \eta$

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

Further spin observables available

- E and G from FROST run with longitudinal target polarization (2007/2008)
- T, F, H, and P from FROST with transverse target polarization (Spring 2010)
Predictions for E “Helicity Difference”

\[
\frac{d\sigma_{(3/2-1/2)}}{d\Omega} = \frac{d\sigma_{3/2}}{d\Omega} - \frac{d\sigma_{1/2}}{d\Omega}
\]

\(\eta\)-MAID / BoGa-PWA

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Online spectra: circularly polarised beam, longitudinally polarised target

First asymmetries observed at ELSA

Single-Meson Reactions: $\gamma N \rightarrow N\eta$

Double-Pion Photoproduction

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Exploring the Excited States of the Nucleon
Count rate differences plotted:

\[ N_{1/2} - N_{3/2} \]

\[ S_{11}(1535) \]

Clear asymmetries observed!

\[ \sim \text{complete angular coverage} \]

\[ \Rightarrow \text{New and important information for the PWA} \]
\[ \gamma p \rightarrow p \eta: \]

\[ E_\gamma = 950 \pm 50 \text{ MeV} \]

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

\[ \Sigma: \]

\[ G: \]

- MAID
- BnGa
- SAID

\[ \leftrightarrow \text{preliminary dilution factor included} \]
Single-Meson Reactions: $\gamma N \rightarrow N \eta$

Double-Pion Photoproduction

– MAID – BnGa – SAID

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

$E_\gamma = 950 \pm 50$ MeV

$E_\gamma = 1050 \pm 50$ MeV

$\Sigma$:

$\theta_\eta$

$G$:

$\theta_\eta$

CBELSA/TAPS

CB/TAPS (D.Elsner et al)

$E_\gamma = 950 \pm 50$ MeV

$E_\gamma = 1050 \pm 50$ MeV

$\leftrightarrow$ preliminary dilution factor included
Study of $\gamma n \rightarrow n \eta$


- ▲ quasi-free proton
- ● quasi-free neutron

$\gamma\eta$ fits

$-1 -0.5 0 0.5 1 -0.5 0 0.5 1 -0.5 0 0.5 1$
Study of \( \gamma n \rightarrow n \eta \)


Event-by-event correction of Fermi motion

\[ \frac{d\sigma}{d\Omega_{\text{acc}}}[\text{\mu b/sr}] \]

- ▲ quasi-free proton
- ● quasi-free neutron

Excitation functions for \( \cos \theta_\eta < -0.1 \)

\[ W_B[\text{MeV}] \] vs. \[ W_R[\text{MeV}] \]
Study of $\gamma n \rightarrow n \eta$


Event-by-event correction of Fermi motion

Is there a narrow $P_{11}$ state?

Absolutely no evidence for such a peak off the proton
Study of $\gamma n \rightarrow n\eta$


Is there a narrow $P_{11}$ state?

- Absolutely no evidence for such a peak off the proton
- Most natural solution: interference within $S_{11}$-wave

![Graph showing the total cross-section for $\gamma n \rightarrow n\eta$]
Study of $\gamma n \rightarrow n\eta$


Event-by-event correction of Fermi motion

- ▲ quasi-free proton
- ● quasi-free neutron

Is there a narrow $P_{11}$ state?

- Absolutely no evidence for such a peak off the proton
- Most natural solution: interference within $S_{11}$-wave
- Other interpretations cannot be ruled out
Brief Summary of Further Experimental Efforts

\[ \gamma p \rightarrow p \eta' \]

\((d\sigma/d\Omega, \Sigma \text{ from CLAS})\)

\[ V. C., A. McVeigh \text{ et al., Phys. Rev. C 80, 055202 (2009)} \]
Brief Summary of Further Experimental Efforts

- $\gamma p \rightarrow p \eta'$
- $\gamma p \rightarrow p \pi^0$ (in full swing) ($d\sigma/d\Omega$, $\Sigma$, etc.)

N. Sparks et al., to be submitted to Phys. Rev. C
Brief Summary of Further Experimental Efforts

- $\gamma p \rightarrow p\eta'$
- $\gamma p \rightarrow p\pi^0$
- $\vec{\gamma}p \rightarrow n\pi^+$ (Evan McClellan, “Honors Thesis”)
- $\gamma p \rightarrow p\omega$
- $\vec{\gamma}p \rightarrow p\pi^0\pi^0, p\pi^0\omega, p\pi^0\eta$ (Crystal Barrel)
- Proposal ELSA/7-2005, Approval Rating “A−”
  ➜ A. Wilson, M. Szmaida
  (A. Woodard, “Honors Thesis”)
- $\vec{\gamma}p \rightarrow p\pi^+\pi^−$ (CLAS)
  ➜ S. Park, C. Hanretty
- Whole industry on strangeness channels: $\gamma p \rightarrow \Sigma K$ and $\gamma p \rightarrow \Lambda K$
  ➜ Possibility of a complete experiment!
- Measurements off the neutron ($\vec{\gamma}n \rightarrow$) planned for this year at CLAS
### Proposed (New) Baryon Resonances

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Resonances</th>
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<tbody>
<tr>
<td>$\gamma p \rightarrow N\pi$</td>
<td>$\Delta(1232)P_{33}$, $N(1520)D_{13}$, $N(1680)F_{15}$, $N(1535)S_{11}$</td>
</tr>
<tr>
<td>$\gamma p \rightarrow p\eta$</td>
<td>$N(1535)S_{11}$, $N(1720)P_{13}$, $N(2070)D_{15}$, $N(1650)S_{11}$</td>
</tr>
<tr>
<td>$\gamma p \rightarrow p\pi^0\pi^0$</td>
<td>$\Delta(1700)D_{33}$, $N(1520)D_{13}$, $N(1680)F_{15}$</td>
</tr>
<tr>
<td>$\gamma p \rightarrow p\pi^0\eta$</td>
<td>$\Delta(1940)D_{33}$, $\Delta(1920)P_{33}$, $N(2200)P_{13}$, $\Delta(1700)D_{33}$</td>
</tr>
<tr>
<td>$\gamma p \rightarrow \Lambda K^+$</td>
<td>$S_{11}$ – wave, $N(1720)P_{13}$, $N(1900)P_{13}$, $N(1840)P_{11}$</td>
</tr>
<tr>
<td>$\gamma p \rightarrow \Sigma K$</td>
<td>$S_{11}$ – wave, $N(1900)P_{13}$, $N(1840)P_{11}$</td>
</tr>
<tr>
<td>$\pi^- p \rightarrow n\pi^0\pi^0$</td>
<td>$N(1440)P_{11}$, $N(1520)D_{13}$, $S_{11}$ – wave</td>
</tr>
</tbody>
</table>

The available data sets comprising various high-statistics differential cross sections, beam, target, recoil asymmetries, double polarization observables, and also data resolving isospin contributions are not yet sufficient to converge into a unique solution.
Beam-Target Polarization Observables

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

At higher excitation energies:
Multi-meson final states play an increasingly important role

⇒ Single-Meson Final States
(7 Observables)

⇒ Search for states in cascades!
Beam-Target Polarization Observables

\[ \frac{d\sigma}{d\Omega} = \sigma_0 \left\{ 1 - \delta_I \sum \cos 2\phi \right. \\
\left. + \lambda_x ( -\delta_I H \sin 2\phi + \delta_\odot F ) \right. \\
- \lambda_y ( -T + \delta_I P \cos 2\phi ) \\
- \lambda_z ( -\delta_I G \sin 2\phi + \delta_\odot E ) \right\} \]

\( \Leftarrow \) Single-Meson Final States
(7 Observables)

Two-Meson Final States ⇒
(15 Observables)

\[ I = I_0 \left\{ (1 + \vec{\Lambda}_i \cdot \vec{P}) \right. \\
\left. + \delta_\odot (I^c + \vec{\Lambda}_i \cdot \vec{P}^c) \right. \\
+ \delta_I \left[ \sin 2\beta (I^s + \vec{\Lambda}_i \cdot \vec{P}^s) \right. \\
\left. \cos 2\beta (I^c + \vec{\Lambda}_i \cdot \vec{P}^c) \right] \right\} \]
Photoproduction of $\pi^+\pi^-$ 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:
→ p-meson system in the reaction plane

Two-meson reactions:
→ Reaction and decay plane form angle $\phi$
Photoproduction of $\pi^+\pi^-$: Beam Asymmetry $I_s$ (new)

Two mesons in the final state require 5 independent variables

- Here: integrated over 2 variables (a mass, further angle)
- Linearly-polarized photons on unpolarized target
  $$ I = I_0 \left\{ 1 + \delta_I I_s \sin 2\beta + \delta_I I_c \cos 2\beta \right\} $$
- $E_\gamma \in [1.10, 2.10]$ GeV in 50-MeV wide bins
- $\theta$ and $\phi$ describe $\pi^+$ in the rest frame of the two mesons

C. Hanretty (FSU), CLAS g8b run group, to be published
Photoproduction of $\pi^+\pi^-$: Beam Asymmetry $I_s$ (new)

$E_\gamma \in [1.25, 1.30]$ GeV

Preliminary

C. Hanretty (FSU), CLAS g8b run group, to be published
Photoproduction of $\pi^+\pi^-$: Beam Asymmetry $I_c (= \Sigma)$

C. Hanretty (FSU), CLAS g8b run group, to be published

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V. Credé

Exploring the Excited States of the Nucleon
The Frozen-Spin (FROST) Target

Production Data

- **Target (Butanol)**
  Longitudinally-polarized target
  Average polarization $\sim 80\%$
  Additional targets: $^{12}\text{C}$, CH$_2$

- **PhotonBeam**
  Circular and linear Polarization
  Excellent degrees of polarization

\[ \Delta B/B \approx 3 \cdot 10^{-3} \text{ at } 0.5 \text{ T} \]

\[ B \approx 0.5 \text{ T} \]

\[ T \approx 0.05 \text{ K} \]
Two mesons in the final state require 5 independent variables

- Here: integrated over 2 variables (a mass, further angle)
- Circularly-polarized photons on long.-polarized target
  \[ I = I_0 \{ 1 + \Lambda_z P_z + \delta_\odot (I_\odot + \Lambda_z P_z^\odot) \} \]
- \( E_\gamma \in [0.70, 2.10] \) GeV in 100-MeV wide bins
- \( \theta \) and \( \phi \) describe \( \pi^+ \) in the rest frame of the two mesons
Photoproduction of $\pi^+\pi^-$: Helicity Difference $P_z^\gamma (= E)$

$E_\gamma \in [1.1, 1.2]$ GeV

Preliminary

S. Park (FSU), CLAS g9a (FROST) run group
Photoproduction of $\pi^+\pi^-$: Helicity Difference $P_z^\circ (= E)$

$E_\gamma \in [1.2, 1.3]$ GeV

Preliminary

S. Park (FSU), CLAS g9a (FROST) run group
Photoproduction of $\pi^+\pi^-$: Helicity Difference $P_z^\circ (= E)$

$E_\gamma \in [1.3, 1.4] \text{ GeV}$

S. Park (FSU), CLAS g9a (FROST) run group

V. Credé
Exploring the Excited States of the Nucleon
Outline

1. Introduction
   - QCD and Hadron Spectroscopy

2. Experimental Methods in Baryon Spectroscopy
   - Photoproduction

3. Experimental Efforts
   - CLAS and the Crystal Barrel Detector

4. Photoproduction of Mesons (off Protons)
   - Single-Meson Reactions: $\gamma N \rightarrow N\eta$
   - Double-Pion Photoproduction

5. Summary and Outlook

V. Credé
Exploring the Excited States of the Nucleon
Summary

Many high-statistics (photoproduction) data samples available with excellent energy and angular coverage:

- Several analyses provide good description of $\pi$, $\eta$, $\pi\pi$, and hyperon data
  - (New) baryon resonances have been confirmed (proposed)
    - Studies do not always agree, ambiguities!
- Polarization measurements have started at all facilities
  - First asymmetries in double-polarization have been observed
  - Complete experiment in hyperon photoproduction possible
- New FROST run starting next month using CLAS at JLab with transverse target polarization
Transverse Holding Magnet: Dipole \textit{(Race-Track Coils)}

Homogeneity: \( \Delta B/B \approx 5 \cdot 10^{-3} \) at 0.5 T
Transverse Holding Magnet: Dipole \((\text{Race-Track Coils})\)

Homogeneity: \(\Delta B/B \approx 5 \cdot 10^{-3} \text{ at } 0.5 \text{ T}\)
Photoproduction of $\pi^0$ Mesons off the Proton

M. Dugger et al. [CLAS Collaboration], PRC 76, 025211 (2007)
Photoproduction of $\pi^0$ Mesons off the Proton

- Strong excitation of $N(1720)P_{13}$ consistent with analysis of $\pi^+\pi^-$ electro-couplings
- No new nucleon resonances needed!

- CLAS
- CB-ELSA
- SAID SM02

\[\begin{array}{|c|c|c|c|}
\hline
\text{Resonance} & \pi N \text{ SAID} & A_{1/2} & A_{3/2} \\
\hline
N(1535)S_{11} & W_R=1547 \text{ MeV} & 91.0 \pm 2.2 & 90 \pm 30 \\
& \Gamma=188 \text{ MeV} & & \\
& \Gamma_{\pi}/\Gamma=0.36 & & \\
\hline
N(1650)S_{11} & W_R=1635 \text{ MeV} & 22.2 \pm 7.2 & 53 \pm 16 \\
& \Gamma=115 \text{ MeV} & & \\
& \Gamma_{\pi}/\Gamma=1.00 & & \\
\hline
N(1440)P_{11} & W_R=1485 \text{ MeV} & -50.6 \pm 1.9 & -65 \pm 4 \\
& \Gamma=284 \text{ MeV} & & \\
& \Gamma_{\pi}/\Gamma=0.79 & & \\
\hline
N(1720)P_{13} & W_R=1764 \text{ MeV} & 96.6 \pm 3.4 & -39.0 \pm 3.2 \\
& \Gamma=210 \text{ MeV} & 18 \pm 30 & -19 \pm 20 \\
& \Gamma_{\pi}/\Gamma=0.09 & & \\
\hline
N(1520)D_{13} & W_R=1515 \text{ MeV} & -28.0 \pm 1.9 & 143.1 \pm 2.0 \\
& \Gamma=104 \text{ MeV} & -24 \pm 9 & 166 \pm 5 \\
& \Gamma_{\pi}/\Gamma=0.63 & & \\
\hline
N(1675)D_{15} & W_R=1674 \text{ MeV} & 18.0 \pm 2.3 & 21.2 \pm 1.4 \\
& \Gamma=147 \text{ MeV} & 19 \pm 8 & 15 \pm 9 \\
& \Gamma_{\pi}/\Gamma=0.39 & & \\
\hline
N(1680)F_{15} & W_R=1680 \text{ MeV} & -17.3 \pm 1.4 & 133.6 \pm 1.6 \\
& \Gamma=128 \text{ MeV} & -15 \pm 6 & 133 \pm 12 \\
& \Gamma_{\pi}/\Gamma=0.70 & & \\
\hline
\Delta(1620)S_{31} & W_R=1615 \text{ MeV} & 49.6 \pm 2.2 & 27 \pm 11 \\
& \Gamma=147 \text{ MeV} & 27 \pm 11 & 27 \pm 11 \\
& \Gamma_{\pi}/\Gamma=0.32 & & \\
\hline
\Delta(1232)P_{33} & W_R=1233 \text{ MeV} & -139.1 \pm 3.6 & -257.6 \pm 4.6 \\
& \Gamma=119 \text{ MeV} & -135 \pm 6 & -250 \pm 8 \\
& \Gamma_{\pi}/\Gamma=1.00 & & \\
\hline
\Delta(1700)D_{33} & W_R=1695 \text{ MeV} & 125.4 \pm 3.0 & 105.0 \pm 3.2 \\
& \Gamma=376 \text{ MeV} & 104 \pm 15 & 85 \pm 22 \\
& \Gamma_{\pi}/\Gamma=0.16 & & \\
\hline
\Delta(1905)F_{35} & W_R=1858 \text{ MeV} & 21.3 \pm 3.6 & -45.6 \pm 4.7 \\
& \Gamma=321 \text{ MeV} & 26 \pm 11 & -45 \pm 20 \\
& \Gamma_{\pi}/\Gamma=0.12 & & \\
\hline
\end{array}\]

M. Dugger et al. [CLAS Collaboration], PRC 76, 025211 (2007)
Photoproduction of $\pi^0$ Mesons: Beam Asymmetry $\Sigma$

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

V. Credé
Exploring the Excited States of the Nucleon
Photoproduction of $\pi^+$ Mesons: $\gamma p \rightarrow n \pi^+$

M. Dugger et al. (CLAS g1c), PRC 76, 065206 (2009)
Photoproduction of $\pi^+$ Mesons: $\gamma p \rightarrow n \pi^+$

SAID FA07  MAID07  —  ?  SAID FA08

- No new resonances needed (multipole fit to all available data)
- New SAID solution more satisfactory at higher energies
- Resonance couplings have not changed significantly
- Changes in high-energy behavior of cross-section predictions and amplitudes

M. Dugger et al. (CLAS g1c), PRC 76, 065206 (2009)
Photoproduction of $\pi^+$ Mesons: $\Sigma$ in $\gamma p \rightarrow n \pi^+$

CLAS g8b run group, ASU analysis, to be published (▲)

V. Credé  Exploring the Excited States of the Nucleon
Photoproduction of $\pi^+$ Mesons: Helicity Difference $E$

circ.-pol. beam on long.-pol. target: good agreement with SAID & MAID for $W < 1.7 \text{ GeV}$

CLAS g9a (FROST) run group, USC analysis
Refrigeration below 4.2 K

Evaporative Cooling

In order to evaporate 1 mole of $^4$He, heater must supply: $L \approx 80 \text{ J/mol}$ (L is latent heat of vaporazation)

⇒ In absence of a heater, liquid will absorb heat from surroundings and temperature will drop ($T \approx 1.5 \text{ K}$)
Refrigeration below 4.2 K

Evaporative Cooling

In order to evaporate 1 mole of $^4$He, heater must supply:

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$\Rightarrow$ In absence of a heater, liquid will absorb heat from surroundings and temperature will drop ($T \approx 1.5 \text{ K}$)

$\Rightarrow$ Insufficient for freezing the spin!
Refrigeration below 4.2 K

1. **Evaporative Cooling**
   In order to evaporate 1 mole of $^4\text{He}$, heater must supply:
   \[ L \approx 80 \text{ J/mol} \] (L is latent heat of vaporization)
   \[ \Rightarrow \text{In absence of a heater, liquid will absorb heat from surroundings and temperature will drop (} T \approx 1.5 \text{ K)} \]
   \[ \Rightarrow \text{Insufficient for freezing the spin!} \]

2. **$^3\text{He}/^4\text{He}$ Dilution Refrigeration**
   Below 0.8 K, a $^3\text{He}/^4\text{He}$ mixture will separate into two phases:
   1. Lighter *concentrated phase* rich in $^3\text{He}$
   2. Heavier *dilute phase* rich in $^4\text{He}$ (concentration of $^3\text{He} \geq 6\%$)
   \[ \Rightarrow \text{Thus, } ^3\text{He will absorb energy when it dissolves (evaporates) into the dilute phase providing highly-effective cooling} \]
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Thus, $^3\text{He}$ will absorb energy when it dissolves (*evaporates*) into the dilute phase providing highly-effective cooling.