Highlights in Light-Baryon Spectroscopy and Searches for Gluonic Excitations

Volker Credé

Florida State University, Tallahassee, FL

Xlth Quark Confinement and the Hadron Spectrum

St. Petersburg, Russia

09/11/2014
Outline

1. Introduction
   - The Hadron Spectrum: Baryons and Mesons

2. Spectroscopy of Baryon Resonances
   - Complete Experiments
   - Polarization Observables in $\gamma p \rightarrow N\pi$
   - Decay Cascades of Excited Baryons

3. Meson Spectroscopy
   - Search for Gluonic Excitations
   - Hybrid Mesons in Photoproduction

4. Summary and Outlook
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Light-Flavor Hadron Spectroscopy
Strong-Coupling Quantum Chromodynamics (QCD)

\[ \mathcal{L}_{\text{QCD}} = \sum_q \bar{q} \left( i \gamma_\mu D_\mu - m_q \right) q - \frac{1}{4} F_{\mu\nu}^\mu F_{\mu\nu}^\nu \]

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.

Asymptotic Freedom

Confinement

“Strong QCD”

“pQCD”

Asymptotic Freedom
The strong coupling confines quarks and breaks chiral symmetry, and so defines the world of light hadrons. Baryons are special because

- their structure is most obviously related to the color degree of freedom, e.g. \(|\Delta^{++}\rangle = |u^\uparrow u^\uparrow u^\uparrow\rangle\).
- they are the stuff of which our world is made.
The strong coupling confines quarks and breaks chiral symmetry, and so defines the world of light hadrons.

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\[\begin{array}{c}
P_{33}(1232) \\
P_{31}(1620) \\
S_1(1535) \\
D_{13}(1520) \\
P_{13}(1440) \\
S_{11}(1650) \\
D_{13}(1675) \\
F_{15}(1680) \\
F_{33}(1905) \\
P_{33}(1910) \\
\end{array}\]

- \(\pi^+ p \rightarrow X\)
- \(\pi^- p \rightarrow X\)

\[\begin{array}{c}
P_{33}(1232) \\
P_{31}(1620) \\
S_1(1535) \\
D_{13}(1520) \\
P_{13}(1440) \\
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F_{15}(1680) \\
F_{33}(1905) \\
P_{33}(1910) \\
\end{array}\]

\[\begin{array}{c}
\rightarrow \gamma N \ & \pi N \ data\end{array}\]
Hadrons: Baryons & Mesons

The strong coupling confines quarks and breaks chiral symmetry, and so defines the world of light hadrons.

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- their structure is most obviously related to the color degree of freedom, e.g. \( |\Delta^{++}\rangle = |u^\uparrow u^\uparrow u^\uparrow\rangle \).

Many \( Y^* \) QN not measured:
(Quark model assignments)
\( \rightarrow \) many \( \Xi^* \) and \( \Omega^* \), etc.
Spin and Parity Measurement of the \( \Lambda(1405) \) Baryon


Data for \( \gamma p \rightarrow K^+ \Lambda(1405) \) support \( J^P = \frac{1}{2}^- \)

- Decay distribution of \( \Lambda(1405) \rightarrow \Sigma^+ \pi^- \) consistent with \( J = \frac{1}{2} \).
- Polarization transfer, \( \vec{Q} \), in \( Y^* \rightarrow Y \pi \):
  - S-wave decay: \( \vec{Q} \) independent of \( \theta_Y \)

\[
\begin{align*}
\text{S-wave:} & \quad J^P = \frac{1}{2}^- \\
\text{P-wave:} & \quad J^P = \frac{1}{2}^+ \end{align*}
\]
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. What role do gluonic excitations play in the spectroscopy of light mesons, and can they help explain quark confinement?

Baryons: What are the fundamental degrees of freedom inside a nucleon? Constituent quarks? How do degrees change with varying quark masses?
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. What role do gluonic excitations play in the spectroscopy of light mesons, and can they help explain quark confinement?

Mesons: What are the properties of the predicted states beyond simple quark-antiquark systems (hybrid mesons, glueballs, ...)?

→ Gluonic Excitations provide a measurement of the excited QCD potential. Hybrid baryons are possible but do not carry “exotic” quantum numbers.
**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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V. Credé
Light-Flavor Hadron Spectroscopy
The Hadron Spectrum: Baryons and Mesons

Spectrum of \( N^* \) Resonances

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<th>Mass [MeV]</th>
<th>( J^P ) (L_{2I,2J})</th>
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\( N^* \)

- \( N(1440) \quad 1/2^+ \quad (P_{11}) \quad * * * *\)
- \( N(1520) \quad 3/2^- \quad (D_{13}) \quad * * * *\)
- \( N(1535) \quad 1/2^- \quad (S_{11}) \quad * * * *\)
- \( N(1650) \quad 1/2^- \quad (S_{11}) \quad * * * *\)
- \( N(1675) \quad 5/2^- \quad (D_{15}) \quad * * * *\)
- \( N(1680) \quad 5/2^+ \quad (F_{15}) \quad * * * *\)
- \( N(1685) \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \woo
### Spectrum of $N^*$ Resonances

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<td>$N(2220)$</td>
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**Light-Flavor Hadron Spectroscopy**
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V. Credé  Light-Flavor Hadron Spectroscopy
Polarization Transfer in $\gamma p \rightarrow K^+ \Lambda$ : $C_x$, $C_z$

without $N(1900)P_{13}$

with $N(1900)P_{13}$


Bonn-Gatchina PWA requires $N(1900)P_{13}$
No quark-diquark oscillations!
$\Rightarrow$ Both oscillators need to be excited.


* * $N(1900)P_{13}$, $N(2000)F_{15}$, $N(1990)F_{17}$
Baryon Spectroscopy from Lattice QCD


Missing states?

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

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

$m_\pi = 396$ MeV

$\Delta(1700)$

$\Delta(1620)$

$m_\pi = 396$ MeV

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

$\rightarrow$ Counting of levels consistent with non-rel. quark model, no parity doubling
Why are Polarization Observables Important?

Atomic Spectrum of Hydrogen

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

\[ E_\gamma \text{[MeV]} \]

\[ \sigma \text{[\mu b]} \]

ELS \n
MAMI \n
GRAAL \n
SPRING-8 \n
CLAS@JLab

V. Credé  

Light-Flavor Hadron Spectroscopy
Why are Polarization Observables Important?

For single-meson production:

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

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 \(F_4.\)
Example: Ambiguities in $\gamma p \rightarrow p \pi^0$

Helicity Difference:

$$E = -\frac{1}{2 \Lambda_z \delta_c} \left( \frac{N \rightarrow \Rightarrow - N \rightarrow \Leftarrow}{N \rightarrow \Rightarrow + N \rightarrow \Leftarrow} \right)$$

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

V. Credé  
Light-Flavor Hadron Spectroscopy
Helicity Asymmetry $E$ in $\gamma p \rightarrow p \pi^0 @ ELSA$

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

$E_\gamma \in [0.6, 2.2]$ GeV

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

Angular distributions sensitive to interference between resonances.

M. Gottschall et al., PRL 112, 012003 (2014)
Asymmetry $G$ in $\gamma \vec{p} \rightarrow p \pi^0$ @ ELSA

J. Hartmann, Parallel III: B10 “Light Quarks” (more results from ELSA)

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

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

- BoGa
- SAID
- MAID

A. Thiel et al., PRL 109, 102001 (2012)
Asymmetry $G$ in $\gamma \vec{p} \rightarrow p \pi^0$ @ ELSA

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

\[\theta_{\pi} = 90 \pm 5^\circ\] 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:

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

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

A. Thiel et al., PRL 109, 102001 (2012)
Beam Asymmetry $\Sigma$ in $\vec{\gamma} p \rightarrow p \pi^0$ @ CLAS (g8b)

- SAID DU13
- SAID CM12
- MAID 07
- BoGa 2011-02

Largest changes in SAID DU13

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

M. Dugger et al. [CLAS Collaboration], PRC 88, 065203 (2013)
**Observation of Decay Cascades in $\gamma p \rightarrow p \pi^0\pi^0$**

**Cross Sections**

**Beam Asymmetry, $I^\odot$**

**Search for states in decay cascades!**

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

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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**Introduction**

**Spectroscopy of Baryon Resonances**

**Meson Spectroscopy**

**Summary and Outlook**

**Complete Experiments**

**Polarization Observables in $\gamma p \rightarrow N\pi$**

**Decay Cascades of Excited Baryons**
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

$$\mathcal{M}_A = [\phi_0\rho(\vec{\rho}) \times \phi_0\lambda(\vec{\lambda})]^{(L=2)},$$

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.

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Bonn-Gatchina PWA

V. Sokhoyan, E. Gutz, V. C. et al. @ELSA
Decays observed in PWA into, e.g.

\[
\begin{aligned}
N(1880) & \ 1/2^+ & N(1520) & \pi \\
N(1900) & \ 3/2^+ & N(1535) & \pi \\
N(2000) & \ 5/2^+ & N(1680) & \pi \\
N(1990) & \ 7/2^+ & N(1880) & \pi \\
N(1990) & \ 1/2^+ & N(1900) & \pi \\
N(2000) & \ 5/2^+ & N(2000) & \pi \\
N(2000) & \ 7/2^+ & N(2000) & \pi \\
\rightarrow \text{Quartet of } (70, \ 2^+) \text{ with } S = \frac{3}{2}.
\end{aligned}
\]

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

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Bonn-Gatchina PWA

V. Sokhoyan, E. Gutz, V. C. et al. @ELSA

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 $\mathcal{M}_S$ and

\[
\mathcal{M}_A = [\phi_{0\rho}(\vec{\rho}) \times \phi_{0\rho}(\vec{\lambda})]^{(L=2)},
\]

a component in which both the $\rho$ and the $\lambda$ oscillator are excited simultaneously.
M. Battaglieri, Parallel II: B5 “Light Quarks”
V. Crede, Parallel III: B10 “Light Quarks”
(more results from CLAS@JLab)

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Proton targets

Tensor polarization, SDME

Neutron targets

Need more observables on:
\[ \gamma p \rightarrow p \pi \pi, p \pi \eta \]
\[ \gamma p \rightarrow p \pi \omega, \ldots \]
### Introduction

**Spectroscopy of Baryon Resonances**

**Meson Spectroscopy**

**Summary and Outlook**

---

**Complete Experiments**

**Polarization Observables in $\gamma p \rightarrow N\pi$ Decay Cascades of Excited Baryons**

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### Table representing CLAS@JLab measurements.

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**V. Credé**

**Light-Flavor Hadron Spectroscopy**

---

**Much to learn, you still have.**

---

**Proton targets**

**Tensor polarization, SDME**

---

**Need more observables on:**

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

$\gamma p \rightarrow p\pi\omega, ...$
Outline

1. Introduction
   - The Hadron Spectrum: Baryons and Mesons

2. Spectroscopy of Baryon Resonances
   - Complete Experiments
   - Polarization Observables in $\gamma p \rightarrow N\pi$
   - Decay Cascades of Excited Baryons

3. Meson Spectroscopy
   - Search for Gluonic Excitations
   - Hybrid Mesons in Photoproduction

4. Summary and Outlook

V. Credé
Light-Flavor Hadron Spectroscopy
Introduction
Spectroscopy of Baryon Resonances
Meson Spectroscopy
Summary and Outlook

Search for Gluonic Excitations
Hybrid Mesons in Photoproduction

Quark-Model Classification: Ordinary Mesons

Quantum Numbers \([q\bar{q}]\) \((J^{PC} \equiv 2S+1L_J)\)

- **Parity:** \(P = (-1)^{L+1}\)
- **Charge Conjugation:** \(C = (-1)^{L+S}\) (defined for neutral mesons)
- **G parity:** \(G = C (-1)^I\)

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<td>(\rho, \omega, \phi (J^{PC} = 1^{--}))</td>
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<td>(h_1, b_1 (J^{PC} = 1^{+-}))</td>
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ground-state flux-tube \(m=0\)
Introduction
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Quark-Model Classification: Ordinary & Exotic Mesons

Quantum Numbers \([q \bar{q}] (J^{PC} \equiv 2S+1L_J)\)

- Parity: \(P = (-1)^{L+1}\)
- Charge Conjugation: \(C = (-1)^{L+S}\) (defined for neutral mesons)
- G parity: \(G = C (-1)^I\)

\(L = 0, S = 0:\)
- e.g. \(\pi, \eta (J^{PC} = 0^{-+})\)

\(L = 0, S = 1:\)
- e.g. \(\rho, \omega, \phi (J^{PC} = 1^{--})\)

12 GeV CEBAF upgrade has high priority (DOE Office of Science, Long Range Plan)
“[key area] is experimental verification of the powerful force fields (flux tubes) believed to be responsible for quark confinement.”

Forbidden States (Exotics):
\(J^{PC} = 0^{+-}, 0^{--}, 1^{--}, 2^{+-} \ldots\)
Meson Spectroscopy on the Lattice

- Negative parity
- Positive parity
- Exotics

$m_{\pi} = 396$ MeV

→ isoscalar

→ isovector

Meson Spectroscopy on the Lattice

Lattice QCD Predictions
Constituent glue with $J^{PC} = 1^{+-}$
→ Lightest nonet: $1^{--}$, $(0^{--}, 1^{+-}, 2^{++})$

J. J. Dudek et al., PRD 83, 111502 (2011)
**COMPASS Experiment (1):** $\pi^- Pb \rightarrow \pi^- \pi^- \pi^+(Pb)$


1$^{-+}$ Exotic Wave

Based on $\sim 420,000$ events using a 180 GeV $\pi$ beam:

$\pi_1(1600): \quad M = 1660 \text{ MeV} \quad \Gamma = 269 \text{ MeV}$

$\pi_2(1670): \quad M = 1658 \text{ MeV} \quad \Gamma = 271 \text{ MeV}$

$\rightarrow$ Exotic $1^{-+}$ wave dominantly produced in natural-parity ($M^\epsilon = 1^+$) exchange.
Collaboration refrains from proposing resonance parameters for exotic $P$ wave.

- Odd partial waves with $L = 1, 3, 5$ (non-$q\bar{q}$ QN) suppressed in $\eta\pi^-$ with respect to $\eta'\pi^-$. Even partial waves similar (intensity & phase behavior).

- Dominant $\mathbf{8} \otimes \mathbf{8}$ ($\eta\pi$) & $\mathbf{1} \otimes \mathbf{8}$ ($\eta'\pi$) nature of $SU(3)$ flavor configurations $gq\bar{q}$ and $q\bar{q}q\bar{q}$ configurations predicted to have $\mathbf{1} \otimes \mathbf{8}$ character.
Results on light mesons from CLAS at Jefferson Lab

Search for the photo-excitation of exotic mesons in the $\pi^+\pi^+\pi^-$ system:
(M. Nozar et al., Phys. Rev. Lett. 102, 102002 (2009))

CLAS does not observe a resonant structure in the $1^{−+}$ $(\rho\pi)_P$ partial wave in charge exchange (confirmed with higher statistics, PhD 2012).

$\rightarrow$ Consistent with $\pi_1(1600)$ photoproduction via Pomeron exchange.
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V. Credé
Light-Flavor Hadron Spectroscopy
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 degrees of freedom in excited baryons? Well, is any of the different approaches THE correct one? Or, do they just represent different legitimate views?

I think we are moving toward a new exciting era in meson spectroscopy (COMPASS@CERN, BES III, PANDA, etc.):

- GlueX in Hall-D at JLab will start to commission in about three weeks ...

Advances in both theory and experiment will allow us to finally understand QCD and confinement.
Search for exotic mesons:
- Linearly-polarized photons; coherent edge at 9 GeV.
- High intensity ($\sim 10^8 \gamma/s$).
- Sophisticated analysis tools.
  ➔ Partial Wave Analysis (PWA).

➔ M. Shepherd, Plenary 2