Light-Meson Spectroscopy at Jefferson Lab

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PANDA Collaboration Meeting

Uppsala, Sweden

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Outline

1. Introduction
2. The GlueX Experiment
   - Detector and Commissioning Status
   - Light-Meson Spectroscopy
3. Gluonic Excitations
   - Lattice QCD and Hybrid Mesons
   - Experimental Evidence
4. Other Physics (at GlueX)
5. Summary and Outlook
Non-Perturbative Quantum Chromodynamics (QCD)

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 hadrons is a non-perturbative phenomenon, and QCD is extremely hard to solve in non-perturbative regimes: Knowledge of internal structure of hadrons is still limited.
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?

Hadron Spectroscopy: (Baryons) What are the effective degrees of freedom inside the nucleon? (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.
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Hadron Spectroscopy

- $\pi + \text{Nucleus}$
- $\gamma p$ *Photoproduction*
- $e^+ e^-$
- $\bar{p} p$

The GlueX Collaboration

- 110 members, 21 institutions
  (USA, Canada, Chile, Armenia, Greece, Russia, UK)
- Commissioning in full swing
- First physics in 2016
Search for exotic mesons:

- Linearly-polarized photons; coherent edge at 9 GeV.
  Goal: $5 \times 10^7 \gamma/s$ (coh. peak)
- Sophisticated analysis tools.
  ➔ Partial Wave Analysis (PWA)
Jefferson Lab Upgrade to 12 GeV

- 10.1 GeV achieved, Fall 2014
- Hall D complete

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First Round of Experiments in Hall D
The GlueX Experiment

Gluonic Excitations

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Summary and Outlook

Detector and Commissioning Status

Light-Meson Spectroscopy

Coh. Peak: 8.4 - 9.0 GeV

\[ \gamma \sigma E/E \sim 0.1\%, \mathcal{P} \sim 40\% \]

\[ h^\pm \sigma p/p \sim 1-3\% \]

\[ \gamma \sigma E/E \sim 6\%/\sqrt{E} \pm 2\% \]

Barrel CALorimeter (BCAL):
48 4-m long modules

2.0 T superconducting solenoid

FCAL: 2800 lead glass blocks

Goniometer:
20 \( \mu \)m diamond

TOF: two planes of 2.5 cm scintillator bars

CDC: 28-layer straw-tube chamber

FDC: four six-plane forward drift chambers

First Round of Experiments in Hall D

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GlueX Upgrade: Focusing DIRC Detector

**DIRC Detector**
- Detection of Internally Reflected Cherenkov light
- Use 48 of BaBar DIRC quartz bars
- Separation of $\pi/K$ up to 4 GeV
- Installation in FY 2018

**Physics Motivation** A study of decays to strange final states with GlueX in Hall D using components of the BaBar DIRC. arXiv:1408.0215 [physics.ins-det].

First Round of Experiments in Hall D
Commissioning: Fall 2014 and Spring 2015

**Vertex reconstruction from tracking**

**Data from all subsystems**

**Signal coincidence & hit correlation between detectors**

**TOF: positive tracks**

**Particle ID**

- **p**
- **π**

**dE/dx [a.u.]**

**z Vertex [cm]**

- **30 cm H₂ target**
- **Vacuum chamber exit window**
- **Solid plastic target**

**p [GeV/c]**

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First Round of Experiments in Hall D
Quark-Model Classification: Ordinary & Exotic Mesons

Quantum Numbers $J^{PC} \equiv 2S+1L_J$

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

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

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

Forbidden States (Exotics):
$J^{PC} = 0^{+-}, 0^{--}, 1^{+-}, 2^{+-}, \ldots$

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.”

Excited flux-tube $m=1$
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Hybrid Meson Decays and Interesting Channels

Ideas on Hybrid-Meson Decays:
(angular momentum in the flux tube stays in one of the daughter mesons)

Evidence for $J^{PC} = 1^{-+}$ wave

→ Interpretation controversial ...

$L = 1$

$L = 0$

Lattice calculations:
(lightest hybrid) $M_{1^{-+}} \approx (1.9 \pm 0.2)$ GeV/c$^2$

$0^{+-}$

$h_0 \rightarrow b_1 \pi \rightarrow \pi^+ \pi^- \pi^0 \pi^0 \pi^0; \ h_1 \eta$

$b_0 \rightarrow \pi(1300)\pi; \ h_1 \pi$

$1^{-+}$

$\eta_1 \rightarrow a_1 \pi \rightarrow 2\pi^+ 2\pi^-; \ \pi(1300)\pi$

$\pi_1 \rightarrow f_1 \pi \rightarrow \eta \pi \pi \pi; \ b_1 \pi, \ \pi \rho, \ \eta a_1$

$2^{+-}$

$h_2 \rightarrow \rho \pi \rightarrow \pi \pi \pi; \ b_1 \pi, \ \omega \eta$

$b_2 \rightarrow a_2 \pi; \ a_1 \pi, \ h_1 \pi, \ \omega \pi$

→ Multi-particle final states with neutral and charged particles!
Hybrid Meson Decays and Interesting Channels

Ideas on Hybrid-Meson Decays:
(angular momentum in the flux tube stays in one of the daughter mesons)

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\[
\begin{align*}
0^{+-} & \quad h_0 \to b_1 \pi \to \pi^+ \pi^- \pi^0 \pi^0 \pi^0; \quad h_1 \eta \\
& \quad b_0 \to \pi(1300) \pi; \quad h_1 \pi \\
1^{-+} & \quad \eta_1 \to a_1 \pi \to 2\pi^+ 2\pi^-; \quad \pi(1300) \pi \\
& \quad \pi_1 \to f_1 \pi \to \eta \pi \pi \pi; \quad b_1 \pi, \pi \rho, \eta a_1 \\
2^{+-} & \quad h_2 \to \rho \pi \to \pi \pi \pi; \quad b_1 \pi, \omega \eta \\
& \quad b_2 \to a_2 \pi; \quad a_1 \pi, h_1 \pi, \omega \pi
\end{align*}
\]

$\rightarrow$ Multi-particle final states with neutral and charged particles!

Lattice calculations:
(lightest hybrid) $M_{1^{-+}} \approx (1.9 \pm 0.2)$ GeV/c$^2$
Meson Spectroscopy on the Lattice

negative parity → positive parity


\( m_\pi = 396 \text{ MeV} \)

\( m_\eta = 396 \text{ MeV} \)

→ isoscalar

→ isovector

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First Round of Experiments in Hall D
Meson Spectroscopy on the Lattice

**Lattice QCD Predictions**

Constituent glue with $J^{PC} = 1^{-+}$

→ Lightest nonet: $1^{--}$, $(0^{-+}, 1^{++}, 2^{--})$

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**J. J. Dudek et al., PRD 84, 074023 (2011)**

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First Round of Experiments in Hall D
Experimental Searches for Hybrid Mesons

There is convincing evidence for an exotic $J^{PC} = 1^{--}$ wave. ➔ The interpretation remains controversial.

Exotic waves are (all) observed in diffraction-like reactions. ➔ Observation of $\pi_1(1400) \rightarrow \eta \pi$ in $p\bar{p}$ remains exception.

1. $\pi_1(1400) \rightarrow \eta \pi$ ➔ Tetraquark? Nothing? (too low in mass for hybrid)
2. $\pi_1(1600)$ Appears to be robust signal.

Diffractive Production Process

- Natural parity exchange: $J^P = 0^+, 1^-, 2^+$, ...
- Unnatural parity exchange: $J^P = 0^-, 1^+, 2^-$, ...
- Same production mechanism, $M^\epsilon$, expected for all decay modes.

The $J^{PC} = 1^{-+}$ Exotic Wave: E852 Experiment

There is convincing evidence for an exotic $J^{PC} = 1^{-+}$ wave.

1. $\pi_1(1400) \rightarrow \eta \pi$
2. $\pi_1(1600) \rightarrow \eta' \pi$; $f_1(1285)\pi$  $\Rightarrow$ Natural-parity exchange.
   $\pi_1(1600) \rightarrow b_1 \pi$  $\Rightarrow$ Unnatural-parity exchange dominates.
   $\pi_1(1600) \rightarrow \rho \pi$

$\pi(1600) \rightarrow \rho \pi$
(E852: $\pi^- p \rightarrow \pi^+ 2\pi^- p$)

$M = 1598 \pm 8^{+29}_{-47}$ MeV
$\Gamma = 168 \pm 20^{+150}_{-12}$ MeV

$M^\epsilon = 0^-, 1^-$

$M^\epsilon = 1^+$

更好理解需要一个混合介子的光谱。
There is convincing evidence for an exotic $J^{PC} = 1^{-+}$ wave.

1. $\pi_1(1400) \rightarrow \eta \pi$
2. $\pi_1(1600) \rightarrow \eta' \pi; f_1(1285) \pi$ → Natural-parity exchange.
   $\pi_1(1600) \rightarrow b_1 \pi$ → Unnatural-parity exchange dominates.
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$\pi(1600) \rightarrow \rho \pi$
(E852: $\pi^- p \rightarrow \pi^+ 2\pi^- p$)

$M = 1598 \pm 8^{+29}_{-47}$ MeV
$\Gamma = 168 \pm 20^{+150}_{-12}$ MeV

→ Better understanding requires a spectrum of hybrid mesons.
The GlueX Experiment
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Lattice QCD and Hybrid Mesons
Experimental Evidence

COMPASS Experiment (1): $\pi^- Pb \rightarrow \pi^- \pi^- \pi^+ (Pb)$

M. Alekseev et al., PRL 104, 241803 (2010)

$1^{-+}$ Exotic Wave

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

$\pi_1(1600)$: $M = 1660$ MeV \hspace{1cm} $\pi_2(1670)$: $M = 1658$ MeV

$\Gamma = 269$ MeV \hspace{1cm} $\Gamma = 271$ MeV

$\rightarrow$ Exotic $1^{-+}$ wave dominantly produced in natural-parity ($M^\epsilon = 1^+$) exchange.
COMPASS Experiment (2): $\pi^- p \rightarrow \eta(\prime) \pi^- (p)$

C. Adolph et al., PLB 740, 303 (2015)

1$^{-+}$ Exotic 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 $8 \otimes 8$ ($\eta\pi$) & $1 \otimes 8$ ($\eta'(\pi)$) nature of $SU(3)$ flavor configurations $\rightarrow gq\bar{q}$ and $q\bar{q}q\bar{q}$ configurations predicted to have $1 \otimes 8$ character.

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 $8 \otimes 8$ ($\eta\pi$) & $1 \otimes 8$ ($\eta'(\pi)$) nature of $SU(3)$ flavor configurations $\rightarrow gq\bar{q}$ and $q\bar{q}q\bar{q}$ configurations predicted to have $1 \otimes 8$ 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.
Meson Spectroscopy in Photoproduction: CLAS

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))

A $J^{PC} = 1^{--}$ gluonic hybrid should be photo-produced at the same rate as the $a_2(1320)$, whereas in pion production it should be suppressed by a factor of 10.

- Upper limit for the $\pi_1(1600)$ of 13.5 nb, less than 2% of the $a_2(1320)$.
- Recent CLAS-g12 data have an order of magnitude more statistics.

$\rightarrow$ e.g. $\gamma p \rightarrow n \pi^+\pi^+\pi^-$, $\gamma p \rightarrow p \pi^+\pi^-\pi^0$ ($J^{PC} = 1^{--}$ isoscalar production?)
First GlueX “Physics”: Observation of vector mesons

\[ \gamma p \rightarrow \pi^+\pi^-\pi^0 (p) \]

Proton PID based on dE/dx

Exclusive process (missing mass cut)

\[ \pi \rightarrow \gamma\gamma: \text{reconstructed from forward calorimeter} \]

(\sigma \sim 11 \text{ MeV, calibration ongoing})
First GlueX “Physics”: Observation of $K_S$ and $\Lambda$

No direct $K^\pm$ meson ID, yet. But
- $K_S \rightarrow \pi^+\pi^-$
- $\Lambda \rightarrow p\pi^-$

clearly observed.

Reconstruction
- $p$ & $\pi^\pm$ PID based on dE/dx, $\beta$
- Detached vertices
Studies of diamond radiator in beam confirmed understanding and control of photon polarization and diamond orientation.

- 2.5h of pol. beam (∼10 nA), $P_{\text{max}} = 65\%$, $P_{\text{ave}} = 47\%$

Enhanced "Polarized" Photon Spectrum

8-fold peaking (symmetries):
- Lattice planes: [022], [022], [004], [040]
- Each plane: $\phi$, $\phi + \pi$
First GlueX “Physics”: Polarized $\rho$ Photoproduction

\[ \gamma p \rightarrow \rho^0 p \rightarrow \pi^+ \pi^- p \]

\[ \frac{d\sigma}{d\psi} \propto (1 + P \cos 2\psi) \]

Energy of Beam with Different Radiators for $\gamma p \rightarrow \rho p$ Events

Polarization $P$ is preserved in $\rho$ production.
First GlueX “Physics”: Initial Analyses

\[ \gamma p \rightarrow \rho^0 p \rightarrow \pi^+ \pi^- p \]

Detector Understanding:
- \( \gamma p \rightarrow p \pi^0 \)
- \( \gamma p \rightarrow p \eta \)
- \( \gamma p \rightarrow p \rho \)
- \( \gamma p \rightarrow p \omega \)
- \( \gamma p \rightarrow p \phi \)

Initial Exotic Hybrid Searches
- \( \gamma p \rightarrow \eta \pi (n, p) \)
- \( \gamma p \rightarrow \eta' \pi (n, p) \)
- \( \gamma p \rightarrow \rho \pi (n, p) \)
- \( \gamma p \rightarrow \omega \pi (n, p) \)
- \( \gamma p \rightarrow \omega \pi \pi (n, p) \)
- \( \gamma p \rightarrow \eta \pi \pi (n, p) \)

Strange Baryons: \( \gamma p \rightarrow K^+ \Lambda, K \Sigma, KK \Xi \)
Gluonic Excitations on the Lattice


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.
Gluonic Excitations on the Lattice


The mass scale is $m - m_\rho$ for mesons and $m - m_N$ for baryons.

Letter of Intent to JLab PAC 43

Search for Hybrid Baryons with CLAS 12 in Hall B
Opportunities for Baryon Spectroscopy at GlueX

Spectroscopy of $|ssn\rangle$ $\Xi$ baryons:
- Very few established states
- Hardly any $J^P$ measured
- Possibly narrow resonances

The multi-strange baryons provide a missing link between light-flavor and heavy-flavor baryons.

Program on Cascades involves:
- Measurement of $\Xi^- - \Xi^0$ splittings.
- $J^P$ measurements.
- Search for new states.
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Planned Experiments at Jefferson Lab

Broad and rich physics program in Hall D using the GlueX detector:

- Mapping the Spectrum of Light-Quark Mesons and Gluonic Excitations with Linearly-Polarized Photons. (arXiv:)
  A study of decays to strange final states with GlueX in Hall D using components of the BaBar DIRC. (arXiv:1408.0215)
- Precision Measurement of $\eta$ Radiative Decay Width via Primakoff Effect.
- Measuring the Charged-$\pi$ Polarizibility in the $\gamma\gamma \rightarrow \pi^+\pi^-$ Reaction.
- Symmetry Tests of Rare $\eta$ Decays to All-Neutral Final States.

Spectroscopy Program in Hall B with CLAS 12:

- Search for hybrid mesons.
- Study of very (doubly) strange baryons; hybrid baryon program.
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Summary

The GlueX experiment is ideally suited to study the spectrum of light-flavor mesons up to $M \approx 2.8$ GeV and – if existing – the pattern of the gluonic excitations produced in $\gamma p$ collisions:

- It is important to establish the existence and the nonet nature of the $1^{-+}$ state (and of $0^{+-}$, $2^{+-}$)
- For a given produced resonance, linear polarization will allow us to distinguish between naturalities of exchanged particles.
- About 70% of the photoproduction cross section in the energy region $E_\gamma \sim 7 – 12$ GeV has multiple neutrals and is completely unexplored.

→ Many opportunities for GlueX to make key experimental advances in our knowledge of excited mesons and baryons.

Advances in both theory and experiment will allow us to finally understand QCD and confinement.