From Light Hadrons to Charm: Early Results From GlueX

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GlueX Physics Symposium
Jefferson Lab
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QCD and Hadron Spectroscopy

- Hadrons make up most of the visible mass of the universe.
- Bound states of quarks that interact via gluons.
- Quarks have “color charge” analogous to electric charge: red, green, blue.
- Quarks confined into color neutral (“color-singlet”) combinations. Example: $q\bar{q}$ mesons, $qqq$ baryons.
Quantum Chromodynamics (QCD) describes interaction of quarks and gluons.

- Predicts spectrum of bound states.
- Short-range “Coulombic” interaction.
- Long-range gluonic confinement

Charmonium
Bound Charm+Anticharm Quark States
“Hydrogen Atom” of QCD
Confined QCD States

What bound states of quarks and gluons do we know exist?

- **Mesons**
  - \( q \bar{q} \)

- **Baryons**
  - \( q q q \)

What bound states of quarks and gluons could exist in QCD?
Confined QCD States

What bound states of quarks and gluons do we know exist?

- mesons
- baryons

What bound states of quarks and gluons could exist in QCD?
Any color-singlet state!
What bound states of quarks and gluons do we know exist?

**Mesons**
- \( q \bar{q} \)

**Baryons**
- \( qqg \)

What bound states of quarks and gluons could exist in QCD?

**Tetraquark**
- \( q \bar{q} q \bar{q} \)

**Hadronic molecule**
- \( q \bar{q} \bar{q} q \)

**Pentaquark**
- \( \bar{q} q q q \)

**“Hybrid” meson**
- \( q \bar{q} g \)
Current State of Charmonium Spectrum

<table>
<thead>
<tr>
<th>Mass (MeV)</th>
<th>JPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>3000</td>
<td>0--</td>
</tr>
<tr>
<td>3500</td>
<td>1--</td>
</tr>
<tr>
<td>4000</td>
<td>1++</td>
</tr>
<tr>
<td>4500</td>
<td>2++</td>
</tr>
</tbody>
</table>

Expected

Unexpected

Calculated

R. Lebed, GHP 2017
Current State of Charmonium Spectrum

\[ <\text{Diagram with data points and theoretical model representations}> \]

**Expected**

**Unexpected**

**Calculated**

R. Lebed, GHP 2017
Current State of Charmonium Spectrum

\[ Z_c(3900) \]

\[ P_c(4450) \]

Expected

Unexpected

Calculated

R. Lebed, GHP 2017
Interesting hints! For deeper understanding, can look to light-quark meson spectrum. Idea: Look for excitations of gluonic field.
Confined QCD States

What bound states of quarks and gluons do we know exist?

- **Mesons**
  - Tetraquark
  - Hadronic molecule

- **Baryons**
  - Pentaquark
  - "Hybrid" meson
Light Meson Spectrum from Lattice QCD

Dudek, Edwards, Guo, Thomas, PRD 88, 094505 (2013)
Meson Quantum Numbers

\[ J = L + S \quad P = (-1)^{L+1} \quad C = (-1)^{L+S} \]

“Normal” Meson

Allowed \( J^{PC} \): \( 0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 2^{++}, \ldots \)

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

“Hybrid” Meson

Allowed \( J^{PC} \): \( 0^{-+}, 1^{-+}, 2^{+-}, \ldots \)

Hybrid–Meson mass splitting \( \sim 1.0 \text{ – } 1.5 \text{ GeV} \)

“constituent gluon” \( (J^{PC}) = 1^{-+} \)
Light Meson Spectrum from Lattice QCD

$S.~Dobbs~—~JLab~—~Feb.~16,~2017~—~From~Light~Hadrons~to~Charm:~Early~Results~from~GlueX$

Dudek, Edwards, Guo, Thomas, PRD 88, 094505 (2013)
Exotic QN mesons give a “smoking gun” to look for.

Need to measure a pattern of states to study their spectrum.
Meson Photoproduction

- Photon couples to exchanged QN via VMD, generates mesons with wide variety of $J^{PC}$
- Variety of hybrid decays expected, e.g.:
  - $\pi_1 \rightarrow \rho \pi, \pi b_1, \pi f_1$
  - $\eta_1 \rightarrow \eta f_2, \pi a_2, \eta f_1$
- Need to reconstruct charged and neutral particles
  - Neutral final states at these energies are mostly unexplored
- Photon polarization provides constraints on production processes
The GlueX Experiment in Hall D @ JLab

- The GlueX experiment is located in Hall D, newly constructed as part of the Jefferson Lab 12 GeV upgrade.
  - Large acceptance solenoidal spectrometer
  - Linearly polarized photon beam peaking at 9 GeV
  - Detects all decay products from full hadronic photoproduction rate
  - 100+ Collaborators from 26 institutions
The GlueX Experiment: Photon Beamline

- Photon beam generated via coherent bremsstrahlung off thin diamond radiator
- Photon energies tagged by scattered electrons
  - Energy measurement precision < 25 MeV
- Photon linear polarization $P_\gamma \sim 40\%$ in peak
- Design intensity of $10^8 \gamma/s$ in peak
The GlueX Experiment: Photon Beam Spectrum

Calculated Spectrum

Measured Spectrum

Photon Flux (arb. units)

Photon Flux (arb. units)

Eγ (GeV)

Incoherent & coherent spectrum

40% polarization in peak

collimated

tagged with 0.1% resolution

12 GeV electrons

Photon Flux

Polarization

γ e+ → e+ e− e+

Measured Pair Spect. Flux

(a)

(b)

3% Syst. Uncert.
The GlueX Experiment: Detector

Photoproduction of Hybrids, Light quark mesons, Strangeonia, Baryons, J/ψ...
The GlueX Experiment: Detector

Acceptance: $\theta = 1-120^\circ$
Charged particles: $\sigma_p/p \sim 1-3\%$
Photons: $\sigma_E/E = 6\% / \sqrt{E} \oplus 2\%$
GlueX Detector, October 2014 (w/ Curtis Meyer, Spokesman)
GlueX Running

- **Fall 2014—Spring 2015:** Detector + beamline commissioning
- **Spring 2016:**
  - GlueX Engineering Run
  - Obtained initial physics data
  - Results shown today from ~80 hours of beam time
- **GlueX-I [low-intensity]: 2017-18**
  - Started last week, >half of 2016 data collected
  - 10x more data than 2016 planned
- **GlueX-II [high-intensity]: 2019+**
  - 100x current data with upgraded detector
Spectroscopy and Amplitude Analysis

- Detailed understanding of light-quark meson spectrum requires amplitude analysis.

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Experiment

Polarization Transfer

Opportunistic Measurements & New Ideas

Spin-density Matrix Elements

Measure Cross sections

Amplitude Analysis

Search for Exotics

Theoretical Models

Identify Known Mesons

Understand Photoproduction Mechanisms

Opportunistic Measurements & New Ideas

Measure Cross sections
Detailed understanding of light-quark meson spectrum requires amplitude analysis.

**Experiment**

- Polarization Transfer
- Opportunistic Measurements & New Ideas
- Understand Photoproduction Mechanisms
- Spin-density Matrix Elements
- Measure Cross sections

**Amplitude Analysis**

- Search for Exotics
- Theoretical Models
- Identify Known Mesons
Final State Survey: $\gamma p \rightarrow p + \pi^+ \pi^-$

- Using data from initial running in Spring 2016, we see signals ~100 times larger than previous experiments.
- Evidence for $\rho'$ from SLAC, production studies underway.

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

Final State Survey: $\gamma p \rightarrow p + 4\gamma$

- Early data illustrates reconstruction of neutral final states
- Several scalar and tensor mesons are seen, good spectroscopy prospects.
Final State Survey: $\gamma p \rightarrow p + 5\gamma$

- Reconstruction of $5\gamma$ final states is also seen:
  - $\gamma p \rightarrow p + b_1$, $b_1 \rightarrow \omega \pi^0$, $\omega \rightarrow \pi^0 \gamma$
  - $b_1\pi$ expected to be promising for exotic search.

S. Taylor (JLab)
• Understanding production mechanisms necessary to determine $J^{PC}$ of mesons in amplitude analyses

• Beam asymmetry $\Sigma$ yields information on production mechanisms
  - Measure azimuthal dependence with orthogonally polarized beams
  - Early measurements made with pseudoscalar $[\pi^0, \eta]$ and vector mesons $[\rho, \omega]$
Beam Asymmetries: $\gamma p \rightarrow p + \pi^0/\eta$

**Exchange $J^{PC}$**

$1^{--}$: $\omega, \rho$

$1^{+-}$: $b, h$

$$\sum = \frac{|\omega + \rho|^2 - |h + b|^2}{|\omega + \rho|^2 + |h + b|^2}$$

Mathieu et al., PRD 92, 074013

J. Stevens (W&M), D. Mack, S. Taylor (JLab), I. Strakovsky (GWU), Z. Zhang (Wuhan)
Beam Asymmetries: $\gamma p \rightarrow p + \pi^0/\eta$

\[ \frac{Y_\perp - F_R Y_\parallel}{Y_\perp + F_R Y_\parallel} = P_\gamma \sum \cos 2\phi_p \]
Beam Asymmetries: $\gamma p \rightarrow p + \pi^0/\eta$

(a) \(\perp\) Polarization

(b) \(\parallel\) Polarization

(c) Yield Asymmetry

\[
\frac{Y_{\perp} - F_R Y_{\parallel}}{Y_{\perp} + F_R Y_{\parallel}} = P_{\gamma \Sigma} \cos 2\phi_p
\]
Beam Asymmetries: $\gamma p \rightarrow p + \pi^0/\eta$

- **Results submitted to PRL**  
  [arXiv:1701.08123]  
  First GlueX paper!

- First $\eta$ measurement at this energy

- Data compared to several theory calculations

- Dip at $-t = 0.5 \ (GeV/c)^2$ not observed

- Indicates vector exchange dominates at this energy

- Constrains background to baryon resonance production
Beam Asymmetries: $\gamma p \rightarrow p + \eta / \eta'$

$\eta \rightarrow \pi^+ \pi^- \pi^0$

$\eta' \rightarrow \eta \pi^+ \pi^-$

Good prospects with the full data set.

T. Beattie (Regina)
Beam Asymmetries: $\gamma p \rightarrow p + \pi^+ \pi^-$

J. Ballam et al.,
PRD 7, 3150 (1973)

- Full analysis of angular distributions under way.

A. Austregesilo (JLab)
Beam Asymmetries: $\gamma p \rightarrow p + \omega$

- Probe production mechanism with two different decays
- Assuming Vector Meson Dominance (VMD):

$$\frac{\Sigma(\pi^+ \pi^- \pi^0)}{\Sigma(\pi^0 \gamma)} = -2$$

M. Staib (CMU)
Beam Asymmetries: $\gamma p \rightarrow p + \omega$

Expected:

\[
\frac{\Sigma(\pi^+ \pi^- \pi^0)}{\Sigma(\pi^0 \gamma)} = -2
\]

Measured:

\[
\frac{\Sigma(\pi^+ \pi^- \pi^0)}{\Sigma(\pi^0 \gamma)} = -1.88 \pm 0.13
\]

Consistent with VMD expectations.

- Eventual goal: determine Spin Density Matrix Elements (SDMEs).
Transition Form Factors (TFF): $\eta^{(')} \rightarrow e^+e^-\gamma$

- EM decays of pseudoscalar mesons, $P \rightarrow e^+e^-\gamma$, probe internal structure of hadrons.

- Estimated rates for total approved GlueX running competitive with world data sets:
  - $\gamma p \rightarrow p \eta, \eta \rightarrow e^+e^-\gamma$: 15 k
    [compare to ~20k at MAMI]
  - $\gamma p \rightarrow p \eta', \eta' \rightarrow e^+e^-\gamma$: 1 k
    [compare to <1k at BES-III]
  - Other reactions may increase yield.
  - Signals for $\gamma p \rightarrow p e^+e^-\gamma$ seen in current data, bgkd. from photon conversions under study.

\[ \frac{d\Gamma(\eta' \rightarrow \gamma l^+l^-)}{dq^2\Gamma(\eta' \rightarrow \gamma\gamma)} = [\text{QED}(q^2)] \times |F(q^2)|^2 \]

Point-like TFF

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C. Fanelli (MIT)
• Threshold production is experimentally clean, ideal for studying $J/\psi+N$ interaction

• Probes gluon distributions in proton
  [Kharzeev et al., NPA 661, 568 (1999)]

• Also multiquark correlations
  [Brodsky et al., PLB 498, 23 (2001)]

J/ψ Photoproduction Near Threshold

leading-twist

higher-twist
J/ψ Photoproduction Near Threshold

• Threshold production is experimentally clean, ideal for studying J/ψ+N interaction

• Probes gluon distributions in proton
  [Kharzeev et al., NPA 661, 568 (1999)]

• Also multiquark correlations
  [Brodsky et al., PLB 498, 23 (2001)]

• Few existing measurements:
  • Cornell: \( E(\gamma) = 9 - 11.8 \) GeV
    \( \gamma + \text{Be} \rightarrow \text{Be} + e^+e^- \)
    [Gittelman et al., PRL 35, 1616 (1975)]

  • SLAC: \( E(\gamma) = 13 - 20 \) GeV
    \( \gamma + \text{LH}_2 \rightarrow p + (e^+e^-, \mu^+\mu^-) \)
    [Camirini et al., PRL 35, 389 (1975)]
Identifying $J/\psi$ in Photoproduction

- We select fully reconstructed, kinematically fitted $\gamma + p \rightarrow p + J/\psi$, $J/\psi \rightarrow e^+e^-$ events using the taken in Spring 2016 with:
  - At least 3 tracks in the event; matched to tagged beam photon, $E_\gamma > 8$ GeV
  - Electron ID using calorimeter information: reduces background by $\sim 10^4$

SD, L. Robison, T. Xiao, K. Seth (NU), L. Pentchev (JLab)
Example J/ψ Candidate Event
$N(J/\psi) = 66 \pm 9 \quad M(J/\psi) = 3099.3 \pm 1.8 \text{ MeV} \quad \sigma = 11.2 \pm 1.6 \text{ MeV}$
For initial GlueX running, expect 10x current data, ~700 J/ψ.
- Allows first detailed look at cross sections near threshold [L. Robison Ph.D. project]
- First searches for resonant states in this region.

![Projected J/ψ Cross sections at GlueX](image)
GlueX Experimental Program

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Description</th>
<th>Beam Time (PAC days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GlueX-I</td>
<td>Spectroscopy of light and hybrid mesons (low-intensity)</td>
<td>80</td>
</tr>
<tr>
<td>GlueX-II</td>
<td>Spectroscopy of hadrons with strange quark decays (high-intensity)</td>
<td>220+</td>
</tr>
<tr>
<td>PrimEx-eta</td>
<td>Eta radiative decay width</td>
<td>79</td>
</tr>
<tr>
<td>CPP</td>
<td>Charged pion polarizability</td>
<td>25</td>
</tr>
<tr>
<td>JEF</td>
<td>Rare eta decays</td>
<td>42 (conditional)</td>
</tr>
</tbody>
</table>

- Detector upgrades underway: DIRC for enhanced π/K separation to be installed starting this summer.
- Software trigger to be added for high-intensity running
- Workshops: $K_L$ beam, $\omega$-photoproduction in nuclei
The GlueX Experiment: Future Detector Upgrades

DIRC
Muon detector

Not shown: Software Trigger Farm
The GlueX Experiment: Future Detector Upgrades

DIRC Detector
Improves $\pi/K$ separation
Installation: 2017-2018
Available: 2018+

Enables detailed studies of strange-quark hadrons
Summary

• A rich spectrum of hadronic states is seen in nature. Studying them will yield fresh insight into the nature of quark confinement.

• Photoproduction allows for the production of a wide variety of hadrons, normal and “exotic”.

• The GlueX experiment has just started its first physics run!
  • Commissioning data show rich prospects for spectroscopy and other physics measurements
  • Initial running will focus on spectroscopy of up/down quark states and provide enough data for initial studies of J/ψ and other rare processes
  • High-luminosity running will focus on strange-quark states.
  • A rich physics program is underway!
Backup Slides
\( \alpha_s \) — Strong Force Coupling Constant

Strong interaction strength
Numerical lattice calculations
Bound states

Weak interaction strength
“asymptotic freedom”
Perturbative calculations OK

\[ \alpha_s(Q) \]

July 2009

- Deep Inelastic Scattering
- \( e^+e^- \) Annihilation
- Heavy Quarkonia

\[ QCD \quad \alpha_s(M_Z) = 0.1184 \pm 0.0007 \]
“Charmed” Tetraquark Candidates

\[ e^+ e^- \rightarrow \pi^+ Z_c^\pm \]

\( Z_c(3900) \)

\[ e^+ e^- \rightarrow \pi^0 Z_c^0 \]

Identification of neutral partner confirms isospin-1 nature

NU w/ CLEO data

BESIII Collaboration, PRL 110, 252001 (2013)
“Charmed” Pentaquark Candidate from LHCb

$B \rightarrow pK J/\psi$

$p+J/\psi$ decay implies 5-quark structure

$P_c(4450)$

LHCb Collaboration, PRL 115, 072001 (2015)
Evidence for exotic light-quark mesons

\( \pi_1 \rightarrow \eta' \pi \)

**E852: 18 GeV \( \pi \) on \( p \)**

- **P**
- **D**

PRL 86, 3977 (2001)

**COMPASS: 190 GeV \( \pi \) on \( Pb \)**

- \( a_2(1320) \)
- \( a_1(1260) \)
- \( \pi_2(1670) \)

PRL 104, 241803 (2010)
• Light Meson Spectroscopy: First Results from GlueX — Matthew Shepherd
• Single Meson Photoproduction at JLab Energies — Vincent Mathieu
• Photoproduction of the $\rho^0(770)$ meson at GlueX — Alexander Austregesilo
• Beam asymmetry $\Sigma$ for $\pi^0$ and $\eta$ photoproduction on the proton at GlueX — Zhenyu Zhang
• Photoproduction of $\pi\pi$ Resonances at GlueX — Jonathan Zarling
• Analysis of the $\eta(548) \rightarrow \pi^+ \pi^- \pi^0$ and $\eta'(958) \rightarrow \pi^+ \pi^- \eta$ channels using a 8–9 GeV tagged photon beam for the GlueX Experiment — Tegan Beattie
• Photoproduction of J/Psi at GlueX — Kam Seth
• K-Long Facility for JLab and its Scientific Potential — Igor Strakovsky
• Antikaon-nucleon scattering and the hyperon spectrum — Cesar Fernandez-Ramirez
• Performance of the GlueX Polarized Photon Source — Richard Jones
• A survey of multi-photon final states using the GlueX detector — Simon Taylor
• Exclusive $\omega(782)$ photoproduction at GlueX — Michael Staib
• $\eta'\pi$ production and search for exotic mesons at COMPASS and JLab12 — Vladyslav Pauk
• Study of the $\eta'(f) \rightarrow \pi^+ \pi^- \gamma$ decay at GlueX and Transition Form Factors — Cristiano Fanelli
• Partial wave analysis of $3\pi$ with pion and photon beams — Andrew Jackura
• Leptophobic Boson Searches — John Hardin
• $3\pi$ resonance poles from COMPASS data — Mikhail Mikhasenko
The GlueX Experiment: Photon Beamline

- Photon beam generated via coherent bremsstrahlung off thin diamond radiator
- Photon energies tagged by scattered electrons
- Photon linear polarization $P_{\gamma} \approx 40\%$ in peak
- Design intensity of $10^8 \gamma/s$ in peak

![Diamonds diagram](image)
GlueX Detector, August 2014
The GlueX Experiment: Calorimetry

BCAL — lead/scin. fiber
3840 SiPM readout

FCAL
2800 lead glass blocks
The GlueX Experiment: Tracking

CDC — 28 layers, 3500 straws, $r = 8 \text{ mm}$

FDC — 4 x 6 planes
2300 wires, 10400 cathodes
The GlueX Experiment: Particle ID

Start Counter
30 scin. paddles

TOF — 2 planes
48 scin. paddles ea.
GlueX Calorimetry Performance

Measured using $\gamma p \rightarrow p \gamma \gamma \gamma \gamma \gamma$ events
GlueX Tracking Performance

Central Drift Chamber (CDC)

Position Resolution [µm]

Track to Wire Distance (d) [mm]

Design Resolution: 150 µm

Forward Drift Chamber (FDC)

Wire Position Resolution [µm]

Track to Wire Distance [mm]

Achieved Cathode Resolution: 150 µm

Design Resolution for Cathodes and Wires: 200 µm

Straw Efficiency

3D Reconstruction Efficiency

Colors Index Chambers in the Third Package

S. Dobbs — JLab — Feb. 16, 2017 — From Light Hadrons to Charm: Early Results from GlueX
GlueX Particle ID Performance

Positively Charged Particles

Negatively Charged Particles

Incorrect RF Bunch

Positively Charged Particles

CDC dE/dx [keV/cm]
Beam Asymmetries

Lab Floor

π^+

|| Polarization

π^−

p Decay Plane

Photon Beam Polarization Plane

φ

S. Dobbs — JLab — Feb. 16, 2017 — From Light Hadrons to Charm: Early Results from GlueX
Electron Identification

- Electrons identified by energy deposition in calorimeter
- FCAL: 2800 lead-glass blocks
  - Electrons have $E(\text{cal})/p(\text{track}) \sim 1$
- BCAL: lead/scintillating fiber matrix
  - 192 $\phi$-segments
    4 radial layers
  - Electrons have $E(\text{cal})/p(\text{track}) \sim 1$
  - Can also use shower shape information [under study]
J/ψ Production: Event Selections

- We fully reconstruct $\gamma + p \rightarrow p + J/\psi$, $J/\psi \rightarrow e^+e^-$ events using the $\sim 5$ pb$^{-1}$ of data taken in Spring 2016 with the following criteria:

  - At least 3 tracks in the event; event matched to tagged beam photon, $E_\gamma > 8$ GeV
  - Standard loose timing cuts on electrons and proton
  - Electron ID: $E_{\text{cal}} / p_{\text{track}} > 0.8$
    - Identifying $e^+$ and $e^-$ reduces background by $\sim 10^4$
  - $|\text{Missing mass of } p\, e^+e^-|^2 < 0.05$ GeV$^2$
  - Energy/momentum conservation kinematic fit is performed

S. Dobbs, L. Robison, T. Xiao, K. Seth (NU), L. Pentchev (JLab)
Using tighter electron identification reveals $\phi \rightarrow e^+e^-$ peak

Electron ID is being optimized for this lower mass region

Opens possibility of doing dilepton physics at lower masses (vector meson production, TCS, etc.)
Event Topology of $\gamma p \rightarrow p \eta$ ($\eta \rightarrow e^+e^-\gamma$)
J/ψ Photoproduction Near Threshold

- Threshold production is experimentally clean, ideal for studying J/ψ+N interaction
- Can also study coupling of resonant J/ψ+p states to photon
- $P_c(4450)$ produced at $E(\gamma) \sim 10.3$ GeV
- Several existing studies:
  Example: KR finds $\sigma_{\text{peak}} \sim 12$ nb assuming $\text{Br}(P_c \rightarrow p \ J/\psi) = 10\%$.
  Large theoretical uncertainties exist.

Theory papers:
Wang, Liu, and Zhao, PRD 92, 034022 (2015).
Karliner and Rosner, PLB 752, 329 (2016).
Transition Radiation Detector

- $e/\pi$ separation: for $p > 1.5$ GeV, $\pi$ suppression factor $100-1000$ depending on # of chambers
- Prototype tests done with Ar and Xe gas mixtures, using electrons with/without radiator
- Chamber design similar to ALICE TRD: