Physics with the GlueX DIRC

Justin Stevens

William & Mary
CHARTERED 1693
Physics with the GlueX DIRC

**DIRC:** Detection of Internally Reflected Cherenkov Light
to identify charged kaon final states

Justin Stevens
Confined states of quarks and gluons

Observed mesons and baryons well described by 1st principles QCD

But these aren’t the only states permitted by QCD

... Baryons can now be constructed from quarks by using the combinations (q q q), (q q q q q), etc., while mesons are made out of (q q̄), (q q̄ q̄ q̄), etc. ...

Phys. Lett. 8 (1964) 214
Confined states of quarks and gluons

Observed mesons and baryons well described by 1\textsuperscript{st} principles QCD

But these aren’t the only states permitted by QCD

Do gluonic degrees of freedom manifest themselves in the bound states we observe in nature?
Lattice QCD

Dudek et al. PRD 88 (2013) 094505

Lightest hybrid mesons

Negative parity:
- $2^-$
- $3^-$
- $4^-$

Positive parity:
- $1^+$
- $2^+$
- $3^+$
- $4^+$

Exotics:
- $0^+$
- $1^{++}$
- $2^{++}$

Meson Mass (MeV)

$J^{PC}$

$m_\pi = 391$ MeV

$24^3 \times 128$

Iso scalar: black

Iso vector: blue

Justin Stevens, William & Mary
Lattice QCD

Lightest hybrid mesons

Most experimental searches for hybrids limited to the $\pi_1$ state
\[ \eta\pi/\eta'\pi \text{ spectroscopy at COMPASS with JPAC} \]

Coupled channel fit to \( \eta\pi \) and \( \eta'\pi \) determine pole positions for \( a_2, a_2', \) and exotic \( \pi_1 \).

COMPASS: PLB 740 (2015) 303  
JPAC: PRL 122 (2019) 042002
Large acceptance detector for charged and neutral particles (many final states)

Orders of magnitude higher statistics than previous photoproduction experiments
ηπ/η’π spectroscopy at GlueX

- Analysis of ηπ and η’π final states well underway
- Several well-known mesons identified with only 20% of GlueX Phase-I
- Expect twice COMPASS statistics with full GlueX Phase-I dataset

See talks by Sean Dobbs and Stuart Fegan yesterday
Strangeness program

* Lattice predicts **strange** and **light** quark content for mesons
* Search for a **pattern** of hybrid states in many final states
* Requires clean identification of charged pions and kaons

<table>
<thead>
<tr>
<th>Final States</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi_1$</td>
</tr>
<tr>
<td>$\eta_1$</td>
</tr>
<tr>
<td>$\eta'_1$</td>
</tr>
</tbody>
</table>

**PRD 88 (2013) 094505**
Strangeness program: decay patterns

- Experimentally infer quark flavor composition through branching ratios to strange and non-strange decays

\[
\frac{\mathcal{B}(f'_2(1525) \to \pi\pi)}{\mathcal{B}(f'_2(1525) \to KK)} \approx 0.009
\]

\[
\frac{\mathcal{B}(f_2(1270) \to \pi\pi)}{\mathcal{B}(f_2(1270) \to KK)} \approx 20
\]

- Consistent with lattice QCD mixing angle for \(2^{++}\), and predictions for hybrids

- Need capability to detect strange and non-strange to infer hybrid flavor content

PRD 88 (2013) 094505
Strangeness program: Y(2175)

- Y(2175) \(^{J^P}C^C=1^{--}\) state observed by 3 experiments
- Decay pattern similar to Y(4260) in charmonium
  \[ Y(2175) \rightarrow \phi \pi^+ \pi^- \quad Y(4260) \rightarrow J/\psi \pi^+ \pi^- \]
- Is there evidence for such strangeonium states in photoproduction?
Hyperon Spectroscopy at \( \Lambda^* \):

\[ \gamma p \rightarrow K^+ K^- p \]

\( K^- p \) Mass (GeV)
Hyperon Spectroscopy at $\Xi$: $\gamma p \rightarrow K^+ K^+ \Lambda \pi^-$

$\Xi^- (1320)$

See talk by Ashley Ernst on Friday @ 9:45 in Hadron Spectroscopy
Hyperon Spectroscopy at GlueX : Ξ

\[ \gamma p \rightarrow K^+ K^+ \Lambda \pi^- \]

<table>
<thead>
<tr>
<th>Λπ⁻ Invariant Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Events ( / \ (0.005) )</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>0.5</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>1.5</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>2.5</td>
</tr>
<tr>
<td>3</td>
</tr>
</tbody>
</table>

\( \Xi^- (1320) \)

\( \Xi^- \) Invariant Mass

mean = 1.32204 ± 0.00010
nbkgd = 4158 ± 63
nsig = 2614 ± 56
sigma = 0.004295 ± 0.000089

See talk by Ashley Ernst on Friday @ 9:45 in Hadron Spectroscopy

✿ Longer term: \( K_L \) beam facility (PAC proposal)
Particle ID provided by **time-of-flight** with $\pi/K$ separation up to 2 GeV
Particle ID provided by time-of-flight with $\pi/K$ separation up to 2 GeV
New **DIRC** detector installed to provide $\pi/K$ separation up to 4 GeV
Particle Identification: DIRC

- **DIRC**: Detection of Internally Reflected Cherenkov Light
- Pioneered for BaBar detector at SLAC PEP-II
- Image photons to measure Cherenkov angle

\[ \langle n \rangle = 1.473 \]
Particle Identification: DIRC

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- Image photons to measure Cherenkov angle

\[ \langle n \rangle = 1.473 \]
Particle Identification: DIRC

- **DIRC**: Detection of Internally Reflected Cherenkov Light
- Pioneered for BaBar detector at SLAC PEP-II
- Image photons to measure Cherenkov angle

BaBar: *NIMA 538* (2005) 281
Transported 1/3 of BaBar DIRC radiators to JLab
DIRC upgrade

48 fused silica radiator bars installed, covering $\theta < 11^\circ$
DIRC upgrade

Cherenkov Photon Trajectories

Expansion Volume

Particle Track

Sensors

48 fused silica radiator bars installed, covering θ < 11°
DIRC upgrade

~12k Multi-anode PMT pixels to detect the Cherenkov photon hit pattern
DIRC upgrade

~12k Multi-anode PMT pixels to detect the Cherenkov photon hit pattern
DIRC upgrade

~12k Multi-anode PMT pixels to detect the Cherenkov photon hit pattern

Simulation

~12k Multi-anode PMT pixels to detect the Cherenkov photon hit pattern
February 2019: 10 days of GlueX beamtime with 1/2 of DIRC installed for commissioning

Example π+ Cherenkov photon hit pattern
Each photon detected has multiple ambiguous paths with different Cherenkov angles $\theta_C$.
Each photon detected has multiple ambiguous paths with different Cherenkov angles $\theta_C$

Cumulative $\theta_C$ over many photons
DIRC reconstruction

- Each photon detected has multiple ambiguous paths with different Cherenkov angles $\theta_C$
- Cumulative $\theta_C$ over many photons

![Graphs showing distribution of Cherenkov angles for different numbers of photons]
DIRC reconstruction

- Each photon detected has multiple ambiguous paths with different Cherenkov angles $\theta_C$
- Cumulative $\theta_C$ over many photons
- Compute likelihood for $\pi$ and $K$ mass hypothesis over all detected photons
February 2019: 10 days of GlueX beamtime with 1/2 of DIRC installed for commissioning

Samples of exclusive $\rho$ and $\phi$ production provide pure samples of $\pi$ and $K$ tracks for PID studies
DIRC commissioning

- February 2019: 10 days of GlueX beamtime with 1/2 of DIRC installed for commissioning
- Samples of exclusive $\rho$ and $\phi$ production provide pure samples of $\pi$ and $K$ tracks for PID studies
- Calibration and alignment in progress, but initial reconstruction studies show clear $\pi/K$ separation

$\pi/K$ separation power @ 3 GeV

[Graph showing $\ln L(\pi) - \ln L(K)$ with two distributions for pions and kaons]
Expected DIRC performance

Significantly extends reach in search for exotic hadrons (hybrid, multi-quark, etc.) containing strange quarks

BES III: $J/\psi \rightarrow \eta \phi \pi^+ \pi^-$

PRD 91, 052017 (2015)
Summary

* The GlueX experiment meson program is well underway with the initial “Low Intensity” Phase-I completed in 2018

* The DIRC upgrade and commissioning is in progress to improve the identification of charged kaons

* The “High Intensity” phase of the experiment begins in November to collect 10x higher statistics with the DIRC, enabling a robust strangeness program
Backup
commented on the unexplained sensitivity of the volume dependence of the mass in agreement with the two exponential fits to the described at later times by a constant fit which gives aective masses clearly plateau and can be for the lightest quark mass and largest volume considered.

Figure 17 shows the quality of the principal correlators from the paper, where isospin is exact and electromagnetism does not feature, the systems in the next subsections.

FIG. 11: Isoscalar (green/black) and isovector (blue) meson spectrum on the sites, the low-lying pseudoscalars: $\eta$, $\rho$, $\omega$, $\phi$, $\eta'$, $\pi$, $\pi^0$.

In lattice calculations of the type performed in this $1000 \rightarrow 1500 \rightarrow 2000 \rightarrow 500 \rightarrow 1000 \rightarrow 1500 \rightarrow 2000
\begin{align*}
u \bar{u} + d \bar{d} & \text{ black} \\
\bar{s} \bar{s} & \text{ green} \\
\phi &= \vert \bar{s} \bar{s} \rangle \\
\omega &= \vert u \bar{u} + d \bar{d} \rangle \\
\pi^0 &= \vert u \bar{u} - d \bar{d} \rangle \\
\text{Note: } m_\pi &= 392 \text{ MeV}
\end{align*}
Lattice QCD

Dudek et al. PRD 88 (2013) 094505

Meson Mass (MeV)

negative parity

positive parity

exotics

$m_\pi = 391$ MeV

$24^3 \times 128$

isoscalar

isovector

$J^{PC}$
Hybrid mesons and gluonic excitations

- Excited gluonic field coupled to $q\bar{q}$ pair
- Rich spectrum of hybrid mesons predicted by Lattice QCD
- Gluonic field with $J^{PC} = 1^{+-}$ and mass scale $\approx 1\text{--}1.5$ GeV
- “Exotic” $J^{PC}$: not simple $q\bar{q}$ from the non-rel. quark model

\[ J^{PC} = 0^{+-}, 1^{--}, 2^{+-} \ldots \]

hybrid meson

\[ \mathcal{J} = \mathcal{L} + \mathcal{S} \]
\[ P = (-1)^{L+1} \]
\[ C = (-1)^{L+S} \]
Ideally look for a pattern of hybrid states in multiple decay modes.

Primary goal of the GlueX experiment is to search for and ultimately map out the spectrum of light quark hybrid mesons.
Photon Beam and Tagger

Measured Flux

(a) Photon Flux (Arb. Units)

- Diamond: PARA
- Diamond: PERP
- Aluminum

Photon Beam Energy (GeV)

7.5 8 8.5 9 9.5 10 10.5 11 11.5

Measured Polarization

(b) Polarization

- PARA
- PERP

Photon Beam Energy (GeV)

7.5 8 8.5 9 9.5 10 10.5 11 11.5

3% Syst. Uncert.

Filter on production mechanism
Exotic $J^{PC}$ in photoproduction

Meson X with particular $J^{PC}$

Production through t-channel
"quasi-particle" exchange

Meson Mass (MeV)

$J^{PC}$

$\gamma$, $\pi, \eta, \rho, \omega, P, ...$
Exotic $J^{PC}$ in photoproduction

Possible quantum numbers from Vector Meson Dominance and t-channel exchange: $(I^G)J^{PC}$

- Can couple to all states in the lightest hybrid multiplet through t-channel exchange and photoproduction (via Vector Meson Dominance)
- Photon beam polarization filters the “naturality” of the exchange particle

<table>
<thead>
<tr>
<th>Approximate $J^{PC}$</th>
<th>Mass (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi_1$</td>
<td>1900</td>
</tr>
<tr>
<td>$\eta_1$</td>
<td>2100</td>
</tr>
<tr>
<td>$\eta'_1$</td>
<td>2300</td>
</tr>
<tr>
<td>$b_0$</td>
<td>2400</td>
</tr>
<tr>
<td>$h_0$</td>
<td>2400</td>
</tr>
<tr>
<td>$h'_0$</td>
<td>2500</td>
</tr>
<tr>
<td>$b_2$</td>
<td>2500</td>
</tr>
<tr>
<td>$h_2$</td>
<td>2500</td>
</tr>
<tr>
<td>$h'_2$</td>
<td>2600</td>
</tr>
</tbody>
</table>

- $\rho \pi, \rho \omega \rightarrow \pi_1$
- $\omega \omega, \rho \rho \rightarrow \eta_1$
- $\omega \omega, \rho \rho, \phi \omega \rightarrow \eta'_1$
- $\rho P \rightarrow b_0$
- $\omega P \rightarrow h_0$
- $\omega P, \phi P \rightarrow h'_0$
- $\omega \pi, \rho \eta, \rho P \rightarrow b_2$
- $\rho \pi, \omega \eta, \omega P \rightarrow h_2$
- $\rho \pi, \omega \eta, \phi P \rightarrow h'_2$
Mapping the hybrid spectrum requires: large statistics samples of many particle final states in **strange** and **non-strange** decay modes

Experimentally access to strangeness content of the state by comparing strange vs non-strange decay modes
### Exotic $J^{PC}$ decays

C. A. Meyer and E. S. Swanson, Progress in Particle and Nuclear Physics B82, 21, (2015)

<table>
<thead>
<tr>
<th>Approximate Mass (MeV)</th>
<th>$J^{PC}$</th>
<th>Total Width MeV</th>
<th>Allowed Decay Modes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>PSS</td>
<td>IKP</td>
</tr>
<tr>
<td>$\pi_1$ 1900</td>
<td>$1^{-+}$</td>
<td>81 – 168</td>
<td>$\pi a_1, \pi a_2, \eta f_1, \eta f_2, \pi \eta (1300), \eta \eta', KK_A^1, KK_B^1$</td>
</tr>
<tr>
<td>$\eta_1$ 2100</td>
<td>$1^{-+}$</td>
<td>59 – 158</td>
<td>$\pi \pi (1300), \pi h_1, \rho f_1, \eta b_1$</td>
</tr>
<tr>
<td>$\eta'_1$ 2300</td>
<td>$1^{-+}$</td>
<td>95 – 216</td>
<td>$\pi b_1, \eta h_1, KK (1460)$</td>
</tr>
<tr>
<td>$b_0$ 2400</td>
<td>$0^{+-}$</td>
<td>247 – 429</td>
<td>$KK (1460), KK_A^1, \eta h_1$</td>
</tr>
<tr>
<td>$h_0$ 2400</td>
<td>$0^{+-}$</td>
<td>59 – 262</td>
<td>$KK_A^1, KK_B^1, KK^*_1$, $\eta h_1$</td>
</tr>
<tr>
<td>$h'_0$ 2500</td>
<td>$0^{+-}$</td>
<td>259 – 490</td>
<td>$KK_A^1, KK_B^1, KK^*_1$, $\eta h_1$</td>
</tr>
<tr>
<td>$b_2$ 2500</td>
<td>$2^{+-}$</td>
<td>5 – 11</td>
<td>$\pi a_1, \pi a_2, \pi h_1, \eta \rho, \eta b_1, \rho f_1$</td>
</tr>
<tr>
<td>$h_2$ 2500</td>
<td>$2^{+-}$</td>
<td>4 – 12</td>
<td>$\pi \rho, \pi b_1, \eta \omega, \omega b_1$</td>
</tr>
<tr>
<td>$h'_2$ 2600</td>
<td>$2^{+-}$</td>
<td>5 – 18</td>
<td>$KK_A^1, KK_B^1, KK^*_1, \eta h_1$</td>
</tr>
</tbody>
</table>

* Predictions for the spectrum of hybrids from lattice, but decay predictions are model dependent

**1^{-+} channels observed**

- $\pi \rho \rightarrow \pi \pi \pi$
- $\pi \eta' \rightarrow \eta \pi \pi \pi$
- $\pi b_1 \rightarrow \omega \pi \pi$

**Some additional $1^{-+}$ channels**

- $\pi a_2 \rightarrow \eta \pi \pi$
- $\eta f_1 \rightarrow \eta \eta \pi \pi$
- $KK^* \rightarrow KK \pi$
- $KK_1 (1270) \rightarrow KK \pi \pi$
GlueX Physics Program

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
GlueX “Low intensity” Phase-I program completed in 2018

- ~25% of dataset currently under analysis, full statistics available this year

- Opportunistic measurements: J/ψ, hyperons, etc.

- “High intensity” DIRC program to begin in Fall 2019
**Amplitude Analysis**

- **Goal:** Identify $J^{PC}$ of $X \rightarrow \pi^+\pi^-\pi^+$
- **Model the intensity of events at the level of QM amplitudes (allow for interference)**

$\frac{dN}{d\vec{x}} = \left| \sum_{\alpha} V_{\alpha} A_{\alpha}(\vec{x}) \right|^2$

- **5-dimensional problem:** two new angles at each decay step ($X$ and $I$)

**Example Intensity:**

$X(1^{++}) \rightarrow \rho \pi^+$ (S wave)

$\rho \rightarrow \pi^+\pi^-$
Amplitude Analysis

\[ I(\vec{x}) = \frac{dN}{d\vec{x}} = \left| \sum_{\alpha} V_{\alpha} A_{\alpha}(\vec{x}) \right|^2 \]

- Expand set of possible amplitudes over many \( X \) and \( I \), and determine \( V_\alpha \) via maximum likelihood fit
- Good angular acceptance critical for disentangling \( J^{PC} \)

**Example Intensities:**

\[ X(1^{++}) \to \rho \pi^+ \quad (S \text{ wave}) \]

\[ X(2^{++}) \to \rho \pi^+ \quad (D \text{ wave}) \]
Hyperon Spectroscopy: $\Xi^-(dss)$

![Graph showing the spectrum and decay channels of hyperons](image)

- $\Xi^-(1320)$
- $\Xi^-(1530)$

**6 GeV**

**Graph Details**:
- **Counts/(5 MeV/c^2)**
- **MM(K^+K^+) (GeV/c^2)**
- **Counts/(MeV/c^2)**
- **M1: 1.3223 ± 0.0001**
- **σ1: 0.0067 ± 0.0001**
- **N1: 7678 ± 173**
- **M2: 1.5378 ± 0.0009**
- **σ2: 0.0105 ± 0.0011**
- **N2: 658 ± 91**

**Decay Channels**:
- a) $\gamma \rightarrow K / K^*$
- b) $\gamma \rightarrow K / K^*$