Status and Future of Hall D/Gluex

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Presented at Workshop
Nuclear Photoproduction with GlueX
JLab, 28-29 Apr 2016
1 JLab at 12 GeV
2 Physics motivation for Hall D: meson spectroscopy
3 Experiment GlueX in Hall D
   - Apparatus
   - Performance of GlueX during commissioning
4 Experimental program and future plans
CEBAF Upgrade to 12 GeV

- Accelerator: 2.2 GeV/pass
- Halls A,B,C: $e^- 1\text{--}5$ passes $\leq 11$ GeV
- Hall D: $e^- 5.5$ passes 12 GeV $\Rightarrow$ $\gamma$-beam
- Beam separation to 4 Halls at 250 MHz

**Upgrade Status**

- 12 GeV started in Feb 2016
- Halls A,D: running; B,C: start in 2017
Hall D at Jefferson Lab

- Hall D - a new hall at Jefferson Lab
  - Commissioning is complete

- Physics with high intensity polarized photon beams
  - *Experiment GlueX*: search for exotic hybrid mesons
  - Radiative widths of pseudoscalars, pion polarizability
  - Other topics in preparation: rare decays, nuclear effects

- A new beamline and a new large acceptance detector
  - Coherent Bremsstrahlung $\Rightarrow$ linearly polarized photons
  - Large solenoidal spectrometer $\Rightarrow$ a uniform acceptance
  - Fully pipelined electronics $\Rightarrow$ very high trigger/DAQ rate
Meson spectroscopy

**Naive quark model:**

- Mesons are $\bar{q}q$, constituent quarks are $S = 1/2$ fermions
- No gluonic degrees of freedom
- Restrictions on the quantum numbers: $J^{PC}$:
  $$P = (-1)^{L+1}, \ C = (-1)^{L+S}$$

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<td>“exotic” QN</td>
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Gluonic excitations $\Rightarrow$ hybrid mesons

- Predicted by models, Lattice QCD
- “Constituent gluon”:
  - LQCD: $1^{+-}$, mass of 1-1.5 GeV
- Exotic QN: an excellent signature of a new degree of freedom
  - no mixing with the regular $\bar{q}q$ states
**Meson spectroscopy**

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Glue and spectroscopy

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$q\bar{q}$ QN: “exotic” QN

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C. SU(3)F point, $m/C_{25} = 702$ MeV, $(16;20)3/C_2 128$

In this case we take all three quark flavors to be mass degenerate, with the mass we have tuned to correspond to the physical strange quark. Here, because there is an exact SU(3) flavor symmetry, we characterize mesons in terms of their SU(3)F representation, octet ($^8$) or singlet ($^1$), and compute correlation matrices using the basis in Eq. (5).

The octet correlators feature only connected diagrams while the singlets receive an additional contribution from a disconnected diagram. Since the strange quarks are now no heavier than the ''light'' quarks, any splitting between states in the octet and singlet spectra is purely due to the disconnected diagrams and thus to ''annihilation dynamics.'' In Fig. 13 we present the spectra extracted on two lattice volumes.

D. Quark mass and volume dependence

Figures 14–16 show the quark mass and volume dependence of the extracted isoscalar and isovector spectra. In general, the extracted spectrum is fairly consistent across quark masses. There are some cases, such as the second level in $^3_1/C_0$, that are not cleanly extracted at the lowest pion mass.

We refrain from performing extrapolations of the masses to the limit of the physical quark masses, since, as we have already pointed out, we expect most excited states to be unstable resonances. A suitable quantity for extrapolation might be the complex resonance pole position, but we do not obtain this in our simple calculations using only single-hadron operators.

We discuss the specific case of the $^1_0/C_0$ and $^1_1/C_0/C_0$ systems in the next subsections.

E. The low-lying pseudoscalars:

In lattice calculations of the type performed in this paper, where isospin is exact and electromagnetism does not feature, the $^{1}_{25}$ and $^{1}_{17}$ mesons are exactly stable and $^{1}_{17}0$ is rendered stable since its isospin conserving $^{1}_{25}/^{1}_{25}$ decay mode is kinematically closed. Because of this, many of the caveats presented in Sec.III B do not apply.

Figure 17 shows the quality of the principal correlators from which we extract the meson masses, in the form of an effective mass, $m_{\text{eff}} = \frac{1}{14t} \log \left( \frac{t}{t + \frac{1}{4}t} \right)$; (16)

for the lightest quark mass and largest volume considered. The effective masses clearly plateau and can be described at later times by a constant fit which gives a mass in agreement with the two exponential fits to the principal correlator that we typically use.

Figure 18 indicates the detailed quark mass and volume dependence of the $^{1}_{17}$ and $^{1}_{17}0$ mesons. We have already commented on the unexplained sensitivity of the $^{1}_{17}0$ mass to the spatial volume at $m/C_{25} = 391$ MeV, and we note that
Hybrids identified: States with non-trivial gluonic fields

C. SU(3)_F point, m/C_{25} = 702 MeV, (16;20)_3/C_{21} 128

In this case we take all three quark flavors to be mass degenerate, with the mass we have tuned to correspond to the physical strange quark. Here, because there is an exact SU(3)_F flavor symmetry, we characterize mesons in terms of their SU(3)_F representation, octet (8) or singlet (1), and compute correlation matrices using the basis in Eq. (5).

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D. Quark mass and volume dependence

Figures 14–16 show the quark mass and volume dependence of the extracted isoscalar and isovector spectra. In general, the extracted spectrum is fairly consistent across quark masses. There are some cases, such as the second level in 3^+}/C_0, that are not cleanly extracted at the lowest pion mass.

We refrain from performing extrapolations of the masses to the limit of the physical quark masses, since, as we have already pointed out, we expect most excited states to be unstable resonances. A suitable quantity for extrapolation might be the complex resonance pole position, but we do not obtain this in our simple calculations using only single-hadron operators.

We discuss the specific case of the 0^+}/C_0 and 1^+}/C_0/C_0 systems in the next subsections.

E. The low-lying pseudoscalars: C_{25}, C_{17}, C_{17}^0

In lattice calculations of the type performed in this paper, where isospin is exact and electromagnetism does not feature, the C_{25} and C_{17} mesons are exactly stable and C_{17}^0 is rendered stable since its isospin conserving C_{17}/C_{25}/C_{25} decay mode is kinematically closed. Because of this, many of the caveats presented in Sec.III B do not apply.

Figure 17 shows the quality of the principal correlators from which we extract the meson masses, in the form of an effective mass,

\[ m_{\text{eff}}(t) = \frac{1}{2} \ln \left( \frac{m(t)}{m(t+2t)} \right) \]

for the lightest quark mass and largest volume considered. The effective masses clearly plateau and can be described at later times by a constant fit which gives a mass in agreement with the two exponential fits to the principal correlator that we typically use.

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Hybrids identified: States with non-trivial gluonic fields

In this case we take all three quark flavors to be mass degenerate, with the mass we have tuned to correspond to the physical strange quark. Here, because there is an exact SU(3) flavor symmetry, we characterize mesons in terms of their SU(3)F representation, octet (8) or singlet (1), and compute correlation matrices using the basis in Eq. (5). The octet correlators feature only connected diagrams while the singlets receive an additional contribution from a disconnected diagram. Since the strange quarks are now no heavier than the ''light'' quarks, any splitting between states in the octet and singlet spectra is purely due to the disconnected diagrams and thus to ''annihilation dynamics.''

In Fig.13 we present the spectra extracted on two lattice volumes.

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Figures 14–16 show the quark mass and volume dependence of the extracted isoscalar and isovector spectra. In general, the extracted spectrum is fairly consistent across quark masses. There are some cases, such as the second level in 3+0, that are not cleanly extracted at the lowest pion mass.

We refrain from performing extrapolations of the masses to the limit of the physical quark masses, since, as we have already pointed out, we expect most excited states to be unstable resonances. A suitable quantity for extrapolation might be the complex resonance pole position, but we do not obtain this in our simple calculations using only single-hadron operators.

We discuss the specific case of the 0− and 1− mesons systems in the next subsections.

E. The low-lying pseudoscalars: 25, 17, 0

In lattice calculations of the type performed in this paper, where isospin is exact and electromagnetism does not feature, the 25 and 17 mesons are exactly stable and 17 is rendered stable since its isospin conserving 17/25 decay mode is kinematically closed. Because of this, many of the caveats presented in Sec.III Bdo not apply.

Figure 17 shows the quality of the principal correlators from which we extract the meson masses, in the form of an effective mass,

\[ m_{\text{eff}} = \frac{1}{t} \log \left( \frac{t}{t + \frac{1}{4}t} \right) \]

for the lightest quark mass and largest volume considered. The effective masses clearly plateau and can be described at later times by a constant fit which gives a mass in agreement with the two exponential fits to the principal correlator that we typically use.

Figure 18 indicates the detailed quark mass and volume dependence of the 17 and 20 mesons. We have already commented on the unexplained sensitivity of the 20 mass to the spatial volume at \( m/C_{25} = 391 \text{ MeV} \), and we note that...
Hybrids: expected features and ways to detect

**Masses**
- LQCD: $1^{-+} \sim 2.0 - 2.4 \text{ GeV/c}^2$
- $0^{+-} \sim 2.3 - 2.5 \text{ GeV/c}^2$
- $2^{+-} \sim 2.4 - 2.6 \text{ GeV/c}^2$

**Full Widths**
- **Models**: $0.1 - 0.5 \text{ GeV/c}^2$

**Decays**
- Final states: multiple $\pi^\pm$ and $\gamma$

No calculations for the decay widths or cross sections so far.

*How to detect the hybrids?*

- Detect the final states
- Identify the QN using the Partial Wave Analysis (PWA)
GlueX Experiment: Design Goals and Features

- General requirements:
  - Hermeticity and uniform acceptance for charged particles and photons
  - Good enough resolution to identify exclusive reactions
  - High statistics

- Specific feature: tagged photon beam
  - *Linear polarization helps the QN identification*
  - Beam $\gamma$ and $\pi^-$ have different couplings to the hybrid states
    $\Rightarrow$ complementary to the $\pi^-$-beam experiments
  - Few photoproduction data exist so far

- Considerable theoretical support for the PWA

Over 100 collaborators from 23 institutions. Others are planning to join and more are welcome.
Hall D Complex

Connection to existing tunnel

Civil
Photo July 2011
Ready Dec 2011

Beam/detector
Ready Oct 2014

Hall D Beam Transport Line (Phase III)

Service Building

Cryogenics Plant

Hall D

Counting House

Electron Beam Dump

Photon Beam Pipe

Collimator Enclosure

Tagger Area

Photon Beam Line, buried concrete, enclosed in pipe, see structural

Electron Beam Dump

See Sheet A105-2

Hall D

Service Building

VACN, Retaining Wall

Electron Beam Dump

See Sheet A105-2

Civil

Ready Dec 2011

Beam/detector
Ready Oct 2014

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Status of Hall D

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Hall D/GlueX Beamline

- 12 GeV $e^-$ beam 0.05 – 2.2 $\mu$A
- 20 $\mu$m diamond: coherent <25 $\mu$rad
- Collimation $r < 1.8$ mm at $\sim 80$ m
- Coherent peak 8.4 – 9.0 GeV $P \sim 40\%$
- 2.2 $\mu$A $\Rightarrow$ 100 MHz $\gamma$
- Energy/polarization measured:
  - Tagger spectrometer $\sigma_E/E \sim 0.1\%$
  - Pair spectrometer: spectrum $\Rightarrow \sigma_P/P \sim 5\%$

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Hall D/GlueX Spectrometer and DAQ

GlueX

Resolutions
\[ h^\pm: \sigma_p/p \sim 1 - 3\% \]
\[ \gamma: \sigma_E/E \sim 6%/\sqrt{E} \pm 2\% \]
Acceptance \(1^\circ < \theta < 120^\circ\)

Detectors
► CDC, FDC
► BCAL, FCAL
► TOF, ST

Plans to add
► 2017 L3
► 2018 Cherenkov

Photoproduction \(\gamma p\) 15 kHz for a 100 MHz beam
Beam 10 MHz/GeV: inclusive trigger 20 kHz \(\Rightarrow\) DAQ \(\Rightarrow\) tape
Beam 100 MHz/GeV: inclusive trigger 200 kHz \(\Rightarrow\) DAQ \(\Rightarrow\) L3 farm \(\Rightarrow\) tape
**Spectrometer, Detectors and Dimensions**

- **Barrel Calorimeter**
  - 390 cm long
  - Inner radius: 65 cm
  - Outer radius: 90 cm

- **Forward Drift Chambers (FDC)**

- **Central Drift Chamber (CDC)**

- **Solenoid**
  - 390 cm long
  - Inner radius: 65 cm
  - Outer radius: 90 cm

- **Forward Calorimeter (FCAL)**
  - 240 cm diameter
  - 45 cm thick

- **30-cm target**

- **GlueX Detector**

- **Future Particle ID**
  - Photon beam
  - $\theta = 10.8^\circ$
  - $\theta = 14.7^\circ$
  - $\theta = 118.1^\circ$
  - $\theta = 126.4^\circ$
Spectrometer, Detectors and Dimensions

Central Drift Chamber (CDC)
- Inner radius: 65 cm
- Inner radius: 90 cm
- 390 cm long

Forward Drift Chambers (FDC)

Barrel Calorimeter (BCAL)
- 560 cm
- 342 cm
- Inner radius: 65 cm
- Outer radius: 90 cm
- 48 cm
- 342 cm
- 560 cm

Photon beam

30-cm target

GlueX Detector

Future

3500 straws 28 layers
Aluminized Mylar, r=8 mm
Wire 20 µm; Ar/CO₂ 50/50

Readout ➔ FADC

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Status of Hall D
Spectrometer, Detectors and Dimensions

**Forward Drift Chambers**

- **Solenoid**
  - 390 cm long
  - Inner radius: 65 cm
  - Outer radius: 90 cm

- **Barrel Calorimeter**
  - 48 cm
  - 342 cm
  - 560 cm

- **Central Drift Chamber (CDC)**
  - 118.1°
  - 126.4°

- **Forward Drift Chambers (FDC)**
  - 4 × 6 planes, Ar/CO₂ 50/50
  - 2300 wires, 10 mm pitch
  - 10400 cathode strips, 5 mm pitch

**GlueX Detector**

- **In front of the solenoid**

**Readout**

- Strips ⇒ FADC
- Wires ⇒ TDC

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Status of *Hall D*
Spectrometer, Detectors and Dimensions

**Barrel Calorimeter**
- Central Drift Chamber (CDC)
- Forward Drift Chambers (FDC)
- Solenoid

**GlueX Detector**
- 30-cm target
- 390 cm long
  - inner radius: 65 cm
  - outer radius: 90 cm

**Lead-scintill.fibers**
- 3840 light guides $\Rightarrow$ SiPMs

**Future**
- BCAL
  - 240 cm diameter
  - 45 cm thick

**Photonic Beam**
- 10.8°
- 14.7°
- 118.1°
- 126.4°

**Readout**
- 1536 FADC
- 1152 TDC

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Status of Hall D
Spectrometer, Detectors and Dimensions

**Forward Calorimeter**

- **Solenoid**
  - 390 cm long
  - Inner radius: 65 cm
  - Outer radius: 90 cm
- **Central Drift Chamber (CDC)**
- **Forward Drift Chambers (FDC)**
- **Barrel Calorimeter (BCAL)**
  - 342 cm
  - 30-cm target
- **Lead glass**
  - 4×4×45 cm³
- **Forward Calorimeter (FCAL)**
  - 240 cm diameter
  - 45 cm thick

**Future Particle ID**

**GlueX Detector**

**Readout:** → 2800 FADC
Spectrometer, Detectors and Dimensions

### GlueX Detector

- **Start Counter, TOF**
- **Central Drift Chamber (CDC)**
- **Forward Drift Chambers (FDC)**
- **Barrel Calorimeter (BCAL)**
- **Forward Calorimeter (FCAL)**

### Dimensions
- **Solenoid**: 390 cm long, inner radius: 65 cm, outer radius: 90 cm
- **Forward Calorimeter**: 240 cm diameter, 45 cm thick
- **30-cm target**

### Future Particle ID
- Photon beam: 10.8°, 14.7°, 118.1°, 126.4°

### Other
- Scintillator (Scintil.): 30 counters, 160 counters
- Start Counter, TOF (ST)
- E.Chudakov NPG2016, Apr 2016 Status of Hall D
Hall D/GlueX Commissioning Status

Runs with beam:

- **Fall 2014** 10.0 GeV beam: beam commissioning and detector checkout
  - Unpolarized beam and nuclear target
- **Spring 2015** 5.5 GeV beam: 1 week of beam - commissioning
  - Commissioning of the linearly polarized beam
  - Commissioning of the Liquid Hydrogen target
- **Spring 2016** 12 GeV beam (Feb 10 - Apr 25)
  - Engineering run: commissioning is complete
  - Data for early physics results
  - \( \sim 24 \) G events recorded
Hall D/GlueX Beam: Coherent Bremsstrahlung

- 20-50 $\mu$m thick diamond radiators
- Precision alignment using a goniometer

Polarization measurements
- Derived from the spectrum
- Triple polarimeter
  \[ \gamma e^- \rightarrow e^+ e^- e^- \]
- Processes like $\gamma p \rightarrow \rho^0 p$

Run 10492: 50 $\mu$m diamond

Run 10782: 20 $\mu$m diamond

Rate crystal/amorphous

$P \approx 40\%$
Physics With Linearly Polarized Beam

from 2016 data

- 38k $\gamma p \rightarrow \rho^0 p$
in $8.4 < E_\gamma < 9.0$ GeV
- 2 crystal orientations at 90°
- $\frac{N_0 - N_{90}}{N_0 + N_{90}} = P\Sigma \cos 2\psi$

$P\Sigma = 0.341 \pm 0.007\%$

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

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

$d\sigma / d\psi \propto (1 + P \cos 2\psi)$

$\rho$ asymmetry: 50 μm diamond (J1A50)

Integrated over $8.4 < E_\gamma < 9$ GeV:

$P\Sigma = 0.341 \pm 0.007\%$

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Status of Hall D

Jefferson Lab
**2015 data**

\[ \gamma p \rightarrow \gamma \gamma p \]

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

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

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

\[ \omega \rightarrow \pi^+ \pi^- \pi^0 \]

\[ \eta \rightarrow \pi^+ \pi^- \pi^0 \]

**Event Reconstruction and Signals Observed**

**from 2016 data**

\[ \gamma p \rightarrow 2\pi^0 \gamma p \rightarrow 5\gamma p \]

\[ M(2\pi^0 \gamma), \text{GeV}/c^2 \]

\[ b_1(1235) \]

\[ \omega \]

\[ M(\pi^0 \gamma), \text{GeV}/c^2 \]
Event Reconstruction and Signals Observed

\[ M(4\gamma) \ [\text{GeV/c}^2] \]

\[ 0.0 \ 0.5 \ 1.0 \ 1.5 \ 2.0 \]

\[ M(\gamma\gamma) \ [\text{MeV/c}^2] \]

\[ 0.0 \ 0.2 \ 0.4 \ 0.6 \ 0.8 \ 1.0 \]

\[ \pi^0\pi^0 \text{ Region} \]

\[ f_2(1270) \]

\[ \alpha/f_0(980) \]

\[ \eta\pi^0 \text{ Region} \]

\[ a_0(980) \]

\[ a_2(1320) \]

\[ \gamma p \rightarrow 4\gamma p \]

\[ \text{Candidates / 10 MeV/c}^2 \]

\[ \text{M(\gamma\gamma) for Pair 1 [GeV/c}^2\text{]} \]

\[ \text{M(\gamma\gamma) for Pair 2 [GeV/c}^2\text{]} \]

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Forward Kaon Identification

Present PID: TOF, $dE/dx$, Kinematics

**Upgrade**

- 4 of the BaBar DIRC bar boxes
- New readout system
- Allows to study:
  - Strangeonium and hybrids
  - Hyperons
- Installation planned for 2018

The synthetic fused Silica bars ($n = 1.473$) used in BARBAR DIRC detector can potentially be used in GlueX spectrometer of Hall-D to provide additional charged particle identification in the forward region with a momentum coverage between 1.5 to 4 GeV where either the existing Time-of-Flight detector or a threshold gas Cherenkov detector will have difficulties to cover.

The geometry of existing BARBAR DIRC bars is 17.25 mm × 35.00 mm × 4.9 mm. Each of them consists of four 1.225 m long bars glued end-to-end. BARBAR DIRC used 14 bars in total to cover the whole azimuthal acceptance.

At normal incidence, the DIRC will introduce a total of about 17% radiation length thickness including supports.

In GlueX spectrometer, the DIRC bars will be placed right in front of the TOF wall to reduce the impact on photon reconstruction due to its thickness. 68 DIRC bars will be reconfigured into two flat panels to provide an angular coverage up to 11 degrees with a 10 cm gap in between for beam exit as Figure 1. One side of bars will be covered by mirrors and Cherenkov lights will be collected on the other side.

The Focusing DIRC readout currently being developed by SLAC will provide better performance than the original one used in BARBAR. The new design uses focusing mirrors to remove the smearing due to finite thickness of the bars. In addition, the use of Multi-anode PMTs will allow a much more compact design of the readout assembly (25 times smaller) and the faster timing resolution (~150 ps) can be used to correct chromatic dispersion. As a result, the new design will improve the angular resolution of single Cherenkov photon from 9.6 mrad to less than 7 mrad, thus boost the upper limit of π/K separation with 3 standard deviations from 3.8 GeV to 4.3 GeV.

For GlueX, 276 2" MaPMTs will be needed to readout all 68 bars and the cost for them alone will be about $1.4 M. Furthermore, the recent development carried out by the large-area picoseconds photo-detector (LAPPD) collaboration since 2009 may provide a very attractive alternative readout solution than MaPMT. The approach is to apply micro-channel plate (MCP) technology to produce large-area photo-detectors with excellent space and time resolution. The MCP-PMTs can provide much better timing resolution (<10 ps), similar spatial resolution compared to MaPMT at a much lower cost: $140 k for GlueX DIRC (photo-detector alone, another $110 k for DAQ). As the development of individual components is going very well, small size (5 cm × 5 cm) samples will be available by the end of 2013.
Hall D Preliminary Running Schedule

- 2016-2018 GlueX at “low” intensity of \(10\ \text{MHz}\) in the peak
- 2018 PRIMEX (Primakoff) experiment
- 2018 DIRC installation
- 2019-2022 GlueX at “high” intensity \(5 \times 10\ \text{MHz}\) in the peak
  focus on hidden strangeness and hyperon resonances
<table>
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<tr>
<th>Proposal/ experiment</th>
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<td>E12-06-102</td>
<td>A</td>
<td>Mapping the Spectrum of Light Quark Mesons and Gluonic Excitations with Linearly Polarized Photons</td>
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<td>E12-10-011</td>
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<td>A Precision Measurement of the $\eta$ Radiative Decay Width via the Primakoff Effect</td>
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<td>C12-14-004</td>
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