Future Spectroscopy Studies at Jefferson Lab

E. Chudakov$^1$

$^1$JLab, Hall D

Presented at Workshop
COMPASS beyond 2020
CERN, 21-22 Mar 2016
Outline

1. JLab at 12 GeV
2. Physics motivation for JLab spectroscopy program
3. Experiments at JLab: GlueX in Hall D and CLAS12 in Hall B
   - Apparatus
   - Performance of GlueX during commissioning
4. Experimental schedule
Continuous Electron Beam Accelerator (CEBAF)

- Up to 5 passes through 2 superconducting linacs ($\sim 1500$ MHz at $2^\circ$K)
- Injector: 3 independent 500 MHz beams
- Parallel delivery of 1-5 passes beams to 3 Halls
- Electron beam polarization

History:

- 1995 4 GeV CEBAF and Hall C started
- 1997 4 GeV 3 hall operations started
- 1999-2012 6 GeV operations
- 2007-2017 12 GeV Upgrade (includes a new Hall D)
- 2016 12 GeV operations started for Hall D and Hall A
CEBAF Upgrade to 12 GeV

- Accelerator: 2.2 GeV/pass
- Halls A,B,C: $e^-$ 1-5 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
JLab Experimental Halls

<table>
<thead>
<tr>
<th>Hall D</th>
<th>Hall B</th>
<th>Hall C</th>
<th>Hall A</th>
</tr>
</thead>
<tbody>
<tr>
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<td>spectroscopy program</td>
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**Spectroscopy at JLab**

E.Chudakov

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JLab Experimental Halls

### Hall D
- photoproduction by tagged real photons

### Hall B
- photoproduction by tagged virtual photons at low $Q^2$

### Table

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- spectroscopy program
Spectroscopy of Hadrons - Highlights

**Important Historic Role**
- Structure - the Quark Model was motivated by hadron spectroscopy
- Forces - QCD forces were derived from the spectra of charmonium

**Present Highlights**
- Observation of the predicted states and identification of the observed non-exotic states
- Are there multi-quark states? Interpretation of the observed X,Y,Z stated: are they multi-quark states, or threshold effects, or something else?
- Is there a glueball?
- Are there hybrid states made of quarks and “constituent” gluons?
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The focus of the spectroscopy program at JLab for 2016-2022 Complimentary to the current COMPASS research - a different beam will be used
Gluons in QCD

Asymptotic Freedom
High Energy $\iff$ Small Distance
Gluons self-interaction is weak

- Perturbative QCD - calculable
- Gluon Jets observed

3-jet event, JADE 1980

Confinement
Low Energy $\iff$ Large Distance
Gluons self-interaction is strong

- Lattice QCD calculations
- ChP theory
- The field makes most of the hadron’s mass
- No explicit manifestation of gluons has been observed so far
Gluonic field in a $\bar{q}q$ pair

$\bar{c}c$ spectra suggested a QCD potential:

$$V(r) \propto -\frac{a}{r} + \kappa r$$

Linear term $\Rightarrow$ confinement

LQCD calculation

Quenched LQCD, heavy quarks

- Flux tube model (Nambu 1970)
- Lattice QCD Calculations

The models and the LQCD predict gluonic excitations which may be observable in the mass spectra

“Constituent gluon”:

LQCD: $1^{+-}$, mass 1.3 GeV/c$^2$
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: $J^{PC}$:
  $P = (-1)^{L+1}$, $C = (-1)^{L+S}$

<table>
<thead>
<tr>
<th>J</th>
<th>--</th>
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$q\bar{q}$ QN  “exotic” QN

Gluonic excitations $\Rightarrow$ hybrid mesons

- Exotic QN: an excellent signature of a new degree of freedom
  no mixing with the regular $\bar{q}q$ states
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C. SU(3)F point, m/C25 = 702 MeV, (16;20)3/C2 128
In this case we take all three quark flavors to be mass degenerate, ... will be discussed later.

TOWARD THE EXCITED ISOSCALAR MESON SPECTRUM ...

Lattice QCD - the Meson Spectra

Hybrids identified: States with non-trivial gluonic fields

Calculations for $m_\pi \sim 400 \text{MeV}$
Orange frames - lightest hybrids
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Lattice QCD - the Meson Spectra


Hybrids identified: States with non-trivial gluonic fields

Lowest-lying hybrid supermultiplet

\[ 1^{--}, 0^{--}, 1^{++}, 2^{--} \]

exotic

Nonets: 2 1 2

J^- regular QN

J^+ regular QN

Exotic QN

\( m_\pi = 391 \text{MeV} \)

24^3 \times 128

isoscalar

isovector

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Spectroscopy at JLab
In this case we take all three quark flavors to be mass degenerate, \( m/C_2^5 = 702 \text{ MeV} \), \((16;20) \overline{3}/C_2^1 128\).

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Lower-lying exotic hybrids: masses, widths, decays

**LQCD: masses**

1−+ \(\sim 2.0 - 2.4 \text{ GeV/c}^2\)

0+- \(\sim 2.3 - 2.5 \text{ GeV/c}^2\)

2−− \(\sim 2.4 - 2.6 \text{ GeV/c}^2\)

**Models: widths and decays**

\(\Gamma \sim 0.1-0.5 \text{ GeV/c}^2\),

\(\Gamma(1^{--}) \sim \Gamma(2^{+-}) < \Gamma(0^{+-})\)

---

\(\begin{array}{c}
\text{easy} \Rightarrow \text{statistics} \Rightarrow \text{hard} \\
\text{reach} \quad \text{needed}
\end{array}\)

\(\pi_1 \to \rho\pi, b_1\pi, f_1\pi, \eta'\pi, a_1\eta\)

1−+ \(\eta_1 \to f_2\eta, a_2\pi, f_1\eta, \eta'\eta, \pi(1300)\pi, a_1\pi\)

\(\eta'_1 \to K^*\bar{K}, K(1270)\bar{K}, K(1410)\bar{K}, \eta'\eta,\)

\(b_2 \to \omega\pi, a_2\pi, \rho\eta, f_1\rho, a_1\pi, h_1\pi, b_1\eta\)

2−− \(h_2 \to \rho\pi, b_1\pi, \omega\eta, f_1\omega\)

\(h'_2 \to K_1(1270)\bar{K}, K(1410)\bar{K}, K^0\bar{K}, \phi\eta, f_1\phi\)

Final states:

\((p, n) + 3\pi, 4\pi, 3\pi\eta, 4\pi\eta...\)

\(70\% \geq 1\pi^0\)

\(50\% \geq 2\pi^0\)

\(b_0 \to \pi(1300)\pi, h_1\pi, f_1\rho, b_1\eta\)

0+- \(h_0 \to b_1\pi, h_1\eta\)

\(h'_0 \to K_1(1270)\bar{K}, K(1410)\bar{K}, h_1\eta\)
**Photoproduction Mechanisms**

**Allowed Processes**

\[
\begin{align*}
\mathcal{P}, \pi, \eta, \rho, \omega, \ldots & \rightarrow X \\
\text{N: } J^P &= 0^+, 1^-, 2^+, \ldots \\
\text{U: } J^P &= 0^-, 1^+, 2^-, \ldots
\end{align*}
\]

**Exchange particle**

<table>
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<td>$\mathcal{P}$</td>
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<tr>
<td>$\pi^0$</td>
<td>$0^{--}$</td>
</tr>
<tr>
<td>$\pi^\pm$</td>
<td>$0^{--}$</td>
</tr>
<tr>
<td>$\omega$</td>
<td>$1^{--}$</td>
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Can couple to all the lightest exotic hybrid nonets through photoproduction and VMD

**Photon Polarization at JLab**

- Coherent Bremsstrahlung at $E_e = 12$ GeV provides $\mathcal{P} \sim 40\%$ at $E_\gamma \sim 9$ GeV
Photoproduction Mechanisms

\[ \rho^0, \omega, \phi \to X \]

\[ P, \pi, \eta, \rho, \omega, ... e \]

Effect of Beam Linear Polarization

Filter on the naturality
MC simulation $\gamma p \to 3 \pi p$:

\[ 2^{++}, 2^- \]

Allowed Processes

Vector meson + exchange particle

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<td>BKEI, 6 GeV 1993</td>
<td>1320$\pm$5</td>
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<td>MPS, 18 GeV 1997</td>
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<td>$\pi^- p \rightarrow \eta \pi^0 n$</td>
<td>E-852, 18 GeV 2007</td>
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<td>$\bar{p}p \rightarrow \eta \pi^0 \pi^0$</td>
<td>CBAR, 0 GeV 1999</td>
<td>1360$\pm$25</td>
<td>360$\pm$80</td>
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<td>E-852, 18 GeV 2005</td>
<td>2010$\pm$25</td>
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## Experimental Evidence for Exotic Hybrids $1^{--}$

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<td></td>
</tr>
<tr>
<td></td>
<td>$\pi^- p \to \pi^- \pi^0 \pi^0 p$</td>
<td>E-852, 18 GeV 2006</td>
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<td>COMPASS, 190 GeV 2009</td>
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<td>COMPASS, 190 GeV 2005</td>
<td>1600±50</td>
<td>340±50</td>
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<tr>
<td></td>
<td>$\pi^- p \to \eta \pi^+ \pi^- \pi^- p$</td>
<td>E-852, 18 GeV 2004</td>
<td>1710±60</td>
<td>400±90</td>
</tr>
<tr>
<td></td>
<td>$\pi^- p \to \omega \pi^- \pi^0 p$</td>
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<td>VES, 18 GeV 2005</td>
<td>1600</td>
<td>300</td>
</tr>
<tr>
<td>2000</td>
<td>$\pi^- p \to b_1 \pi, f_1 \pi$</td>
<td>E-852, 18 GeV 2005</td>
<td>2010±25</td>
<td>230±80</td>
</tr>
</tbody>
</table>

**Signal:** solid, seen by several experiments

**Interpretation:** unclear, but not a hybrid:
- 1400 - dynamic origin; 4-quark state

---

E.Chudakov

COMPASS > 2020, Mar 2016

Spectroscopy at JLab

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### Experimental Evidence for Exotic Hybrids $1^{--}$

<table>
<thead>
<tr>
<th>mass</th>
<th>reaction</th>
<th>experiment</th>
<th>mass</th>
<th>width</th>
</tr>
</thead>
<tbody>
<tr>
<td>1400</td>
<td>$\pi^- p \rightarrow \eta \pi^0 n$</td>
<td>GAMS, 100 GeV 1988</td>
<td>1406±20</td>
<td>180±20</td>
</tr>
<tr>
<td></td>
<td>$\pi^- p \rightarrow \eta \pi^- p$</td>
<td>BKEI, 6 GeV 1993</td>
<td>1320±5</td>
<td>140±10</td>
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<tr>
<td></td>
<td>$\pi^- p \rightarrow \eta \pi^- p$</td>
<td>MPS, 10 GeV 1997</td>
<td>1270±60</td>
<td>260±100</td>
</tr>
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<td></td>
<td>$\bar{p}p \rightarrow \eta \pi^0 \pi^0$</td>
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<tr>
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</tr>
<tr>
<td>1600</td>
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</tr>
<tr>
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<td>E-852, 18 GeV 2002</td>
<td>1500±40</td>
<td>170±60</td>
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**Signal:** solid, seen by several experiments

**Interpretation:** unclear, but not a hybrid: dynamic origin; 4-quark state

### Signal: $3\pi$ - controversial - leakage from $2^{--}$

**COMPASS:** confirmation in $\pi^- A$

**COMPASS:** in progress $\pi^- p$

### Interpretation: $\eta'/\pi^-$ - promising

**Interpretation:** may be a hybrid

needs more analysis and data

---

E.Chudakov COMPASS > 2020, Mar 2016  Spectroscopy at JLab
Experimental Evidence for Exotic Hybrids \(1^{--}\)

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<tr>
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<td>CBAR, 0 GeV 1998</td>
<td>1400±30</td>
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**Signal:** solid, seen by several experiments

**Interpretation:** unclear, but not a hybrid:

1400  
dynamic origin; 4-quark state

---

**Signal:** \(3\pi\) - controversial - leakage from \(2^{--}\)

**Interpretation:** may be a hybrid

1600  
needs more analysis and data

---

**Signal:** weak - one experiment only

**Interpretation:** may be a hybrid

2000  
expected decay modes

2000  
needs more data
### JLab approved program for spectroscopy

<table>
<thead>
<tr>
<th>Program</th>
<th>CLAS12 Hall B</th>
<th>GlueX Hall D</th>
</tr>
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<tbody>
<tr>
<td>1 Search for hybrid mesons</td>
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<td>2 Search for hybrid baryons: regular QN, identification through electrocouplings</td>
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**Features:**

- Beam: linearly polarized photons
- Acceptance: uniform and hermetic
- High statistics
- Partial Wave Analysis (PWA): a strong organized support from the JLab theory group and a broader community
## JLab approved program for spectroscopy

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**Features:**

- Beam: linearly polarized photons
- Acceptance: uniform and hermetic
- High statistics
- Partial Wave Analysis (PWA): a strong organized support from the JLab theory group and a broader community

\[
\Lambda(1405): \frac{1}{2}^-
\]

*from CLAS PRL 112 (2014)*
JLab approved program for spectroscopy

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**Features:**

- Beam: linearly polarized photons
- Acceptance: uniform and hermetic
- High statistics
- Partial Wave Analysis (PWA): a strong organized support from the JLab theory group and a broader community
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

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

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
Hall B/CLAS12 Forward Tagger

- CLAS12 acceptance $5^\circ < \theta$
- CLAS12 max $e^- p$ –luminosity $10^{35}$ cm$^{-2}$s$^{-1}$
- Tagged photon rate 50 MHz
- Advantage for very thin targets
- Linear polarization $\sim (1 + \nu^2/2EE')^{-1}$

$E_{e'}: 0.5-6.0$ GeV
$\theta_{e'}: 2.5^\circ-4.5^\circ$
$E_{\gamma}: 5.0-10.5$ GeV
$P_{\gamma}: 10-85%$
$Q^2: 0.01-0.3$ GeV$^2$

CLAS12 acceptance $5^\circ < \theta$

CLAS12 max $e^- p$ –luminosity $10^{35}$ cm$^{-2}$s$^{-1}$

Tagged photon rate 50 MHz

Advantage for very thin targets

Linear polarization $\sim (1 + \nu^2/2EE')^{-1}$

E.Chudakov COMPASS > 2020, Mar 2016 Spectroscopy at JLab
Spectrometer, Detectors and Dimensions

- **Solenoid**: 390 cm long, inner radius: 65 cm, outer radius: 90 cm
- **Barrel Calorimeter**: 342 cm
- **Central Drift Chamber (CDC)**: 48 cm
- **Forward Drift Chambers (FDC)**: 560 cm
- **Forward Calorimeter (FCAL)**: 240 cm diameter, 45 cm thick
- **BCAL**: 185 cm
- **GlueX Detector**: 30-cm target

**Future Particle ID**
- Photon beam angles:
  - 10.8°
  - 14.7°
  - 118.1°
  - 126.4°
Spectrometer, Detectors and Dimensions

Central Drift Chamber

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

- **GlueX Detector**
  - 30-cm target

Forward Drift Chambers (FDC)

Barrel Calorimeter (BCAL)

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

Future

- Particle ID
- Photon beam
- 10.8°, 14.7°, 118.1°, 126.4°
Spectrometer, Detectors and Dimensions

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

**Barrel Calorimeter (BCAL)**
- 48 cm
- 342 cm
- 560 cm

**GlueX Detector**
- 30-cm target
- Readout: strips ⇒ FADC
- Readout: wires ⇒ TDC

**Future**
- 4 × 6 planes, Ar/CO₂ 50/50
- 2300 wires, 10 mm pitch
- 10400 cathode strips
- 5 mm pitch

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

**Photon beam**
- 10.8°
- 14.7°
- 118.1°
- 126.4°

**Future Particle ID**
- Photon beam

E. Chudakov
COMPASS > 2020, Mar 2016
Spectroscopy at JLab

Jefferson Lab
Spectrometer, Detectors and Dimensions

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

**Forward Calorimeter**

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

**BCAL**
- Readout: $\Rightarrow$ 1536 FADC
- $\Rightarrow$ 1152 TDC

**GlueX Detector**
- Photon beam
- 30-cm target

**Dimensions**
- 560 cm
- 342 cm
- 48 cm
- 185 cm
- 390 cm long
- Inner radius: 65 cm
- Outer radius: 90 cm
- 560 cm
- 342 cm
- 48 cm

**Future**

E. Chudakov<br>COMPASS $>$ 2020, Mar 2016 <br>*Spectroscopy at JLab*
Spectrometer, Detectors and Dimensions

Forward Calorimeter

**Lead glass**

4 × 4 × 45 cm³

**Central Drift Chamber**

FDC

Forward Drift Chambers

Solenoid

**Forward Calorimeter**

240 cm diameter
45 cm thick

**Future Particle ID**

10.8°

14.7°

**Future**

**Particle ID**

Photon beam

10.8°

14.7°

118.1°

126.4°

**Lead glass**

4 × 4 × 45 cm³

**Readout:** → 2800 FADC

**GlueX Detector**

390 cm long
55 cm outer radius: 90 cm
342 cm
560 cm

**FCAL**

**Barrel Calorimeter**

30-cm target

CL

**Future**

**Particle ID**

photon beam

10.8°

14.7°

118.1°

126.4°
Spectrometer, Detectors and Dimensions

Start Counter, TOF

Solenoid

Forward Drift Chambers (FDC)

Central Drift Chamber (CDC)

Barrel Calorimeter (BCAL)

Forward Calorimeter (FCAL)

30 counters

30-cm target

160 counters

Spectroscopy at JLab

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Hall D/GlueX Commissioning Status

Runs with beam:

- **Fall 2014** 10.0 GeV beam: beam commissioning and detector checkout
  - Unpolarized beam and nuclear target
  - 120 TB of data collected, 0.9 G events

- **Spring 2015** 5.5 GeV beam: 1 week of beam - commissioning
  - Commissioning of the linearly polarized beam
  - Commissioning of the Liquid Hydrogen target
  - 70 TB of data collected, 1.3 G events

- **Spring 2016** 12 GeV beam (started Feb 10, ongoing)
  - Finish the commissioning of all the systems
  - Data for early physics results
  - ∼ 8 G events recorded up to now
- 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**

**Rate crystal/amorphous**

**Enhancement: Diamond/Amorph**

**Degree of Polarization**

$P \approx 40\%$
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°
- $\frac{N_0 - N_{90}}{N_0 + N_{90}} = P\Sigma \cos 2\psi$

$P\Sigma = 0.341 \pm 0.007%$

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

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

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

$\gamma$ is preserved in $p$ production.
Event Reconstruction and Signals Observed

**2015 data**

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

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

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

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

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

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

**from 2016 data**

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

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

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

\[ b_1(1235) \]

\[ \omega \]

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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
Hall D Preliminary Running Schedule

- 2016-2018 GlueX at “low” intensity of 10 MHz in the peak
- 2018 PRIMEX (Primakoff) experiment
- 2018 DIRC installation
- 2019-2022 GlueX at “high” intensity $5 \times 10$ MHz in the peak
  focus on hidden strangeness and hyperon resonances
Spectroscopy is a big part of the JLab program for 2016-2022; the main focus is on the search for hybrid mesons.

GlueX (Hall D) and CLAS12 (Hall B) are of comparable capabilities, but have different acceptances, tagging methods etc.

GlueX is finishing the commissioning phase.

By the Fall 2016, GlueX is planning to be ready to start the main program - the search for exotic mesons.
## Hall D Physics Program

<table>
<thead>
<tr>
<th>Proposal/ experiment</th>
<th>Status</th>
<th>Title</th>
<th>Beam days</th>
<th>PAC #</th>
</tr>
</thead>
<tbody>
<tr>
<td>E12-06-102</td>
<td>A</td>
<td>Mapping the Spectrum of Light Quark Mesons and Gluonic Excitations with Linearly Polarized Photons</td>
<td>120</td>
<td>30</td>
</tr>
<tr>
<td>E12-10-011</td>
<td>A-</td>
<td>A Precision Measurement of the $\eta$ Radiative Decay Width via the Primakoff Effect</td>
<td>79</td>
<td>35</td>
</tr>
<tr>
<td>E12-13-003</td>
<td>A</td>
<td>An initial study of hadron decays to strange final states with GlueX in Hall D</td>
<td>200</td>
<td>40</td>
</tr>
<tr>
<td>E12-13-008</td>
<td>A-</td>
<td>Measuring the Charged Pion Polarizability in the $\gamma\gamma \rightarrow \pi^+\pi^-$ Reaction</td>
<td>25</td>
<td>40</td>
</tr>
<tr>
<td>E12-12-002</td>
<td>A</td>
<td>A study of meson and baryon decays to strange final states with GlueX in Hall D</td>
<td>220</td>
<td>42</td>
</tr>
<tr>
<td>C12-14-004</td>
<td>C2</td>
<td>Eta Decays with Emphasis on Rare Neutral Modes: The JLab Eta Factory Experiment (JEF) partly concurrent with GlueX ($\eta \rightarrow 3\pi$)</td>
<td>(130)</td>
<td>42</td>
</tr>
<tr>
<td>LOI12-15-001</td>
<td></td>
<td>Physics with secondary $K_L^0$ beam $\omega$-production on nuclei</td>
<td>43</td>
<td></td>
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<tr>
<td>LOI12-15-006</td>
<td></td>
<td></td>
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</table>
The GlueX Collaboration


Over 100 collaborators from 22 institutions. Others are planning to join and more are welcome.
Regular and hybrid multiplets

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

The lowest excitation \( L = 1: J^{PC} \): \( 1^{++} \) or \( 1^{--} \)

**Conventional mesons**

Regular quantum numbers:

- \( 0^{-+} \): \( S = 0, L = 0 \) \( \pi, \eta, K \)
- \( 1^{--} \): \( S = 1, L = 0 \) \( \rho, \omega, \phi, K^* \)
- \( 1^{+-} \): \( S = 0, L = 1 \) \( b_1, h_1, K_{1} \ldots \)
- \( 0^{++} \): \( S = 1, L = 1 \) \( a_0, f_0, K_0^* \)
- \( 1^{++} \): \( S = 1, L = 1 \) \( a_1, f_1, K_{1A}^* \)
- \( 2^{++} \): \( S = 1, L = 1 \) \( a_2, f_2, K_2^* \)

**Lower hybrid mesons**

Regular quantum numbers:

- \( 1^{--} \) ...  
- \( 1^{++} \) ...  

Exotic quantum numbers:

- \( 1^{-+} \): \( \pi_1, \eta_1 \ldots \)
- \( 2^{+-} \): \( b_2, h_2 \ldots \)
- \( 0^{+-} \): \( b_0, h_0 \ldots \)

etc.
Regular and hybrid multiplets

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

\[ J^{PC} \]

Conventional mesons

Regular quantum numbers:

- **0**\(^{-+} \quad S = 0, L = 0 \quad \pi, \eta, K\)
- **1**\(^{-+} \quad S = 1, L = 0 \quad \rho, \omega, \phi, K^*\)
- **1**\(^{++} \quad S = 0, L = 1 \quad b_1, h_1, K_{1A} \)
- **0**\(^{++} \quad S = 1, L = 1 \quad a_0, f_0, K_0^*\)
- **1**\(^{++} \quad S = 1, L = 1 \quad a_1, f_1, K_{1A}^*\)
- **2**\(^{++} \quad S = 1, L = 1 \quad a_2, f_2, K_2^*\)

etc.

Lower hybrid mesons

Regular quantum numbers:

- **1**\(^{-+} \quad ...\)
- **1**\(^{++} \quad ...\)

Exotic quantum numbers:

- **1**\(^{-+} \quad \pi_1, \eta_1 ...\)
- **2**\(^{-+} \quad b_2, h_2 ...
- **0**\(^{-+} \quad b_0, h_0 ...\)

etc.

The lowest excitation \( L = 1 \):

\[ J^{PC} : 1^{+-} \text{ or } 1^{--} \text{ Flux tube} \]
Regular and hybrid multiplets

Regular quantum numbers:

- **0**\(^{--}\) \(S = 0, L = 0\) \(\pi, \eta, K\)
- **1**\(--\) \(S = 1, L = 0\) \(\rho, \omega, \phi, K^*\)
- **1**\(+-\) \(S = 0, L = 1\) \(b_1, h_1, K_1\)
- **0**\(^{++}\) \(S = 1, L = 1\) \(a_0, f_0, K_0^*\)
- **1**\(^{++}\) \(S = 1, L = 1\) \(a_1, f_1, K_1^*\)
- **2**\(^{++}\) \(S = 1, L = 1\) \(a_2, f_2, K_2^*\)

Lower hybrid mesons

Exotic quantum numbers:

- **1**\(--\) \(\pi_1, \eta_1\)
- **2**\(^{--}\) \(b_2, h_2\)
- **0**\(^{+-}\) \(b_0, h_0\)

etc.
Event Display

- 2 positive tracks
- 1 negative track
- Hits in FDC, CDC, BCAL, FCAL, TOF
Track Reconstruction in Drift Chambers

Alignment, calibration: in progress

Field-off alignment

- FDC - tracks from the target
- CDC - cosmics

Empty LH$_2$ Target: thin windows

\[ \sigma_Z \sim 4 \text{ mm} \]

\begin{tabular}{|c|c|}
\hline
$\chi^2$/ndf & 360.1/302 \\
$p_0$ & 226.2 \pm 7.3 \\
p1 & 48.53 \pm 0.01 \\
p2 & 0.4007 \pm 0.0121 \\
p3 & 242 \pm 7.5 \\
p4 & 77.81 \pm 0.01 \\
p5 & 0.3604 \pm 0.0093 \\
p6 & 31.68 \pm 0.34 \\
\hline
\end{tabular}

H$_2$ gas

\[ \text{vacuum} \]

FDC: Resolution

- Wires: \( \sim 160 \mu m \)
- Cathode: \( \sim 200 \mu m \)

in progress

CDC efficiency

- Efficiency \( \sim 0.95\% \)
- Resolution \( \sim 200 \mu m \)