GlueX a search for gluonic degrees of freedom in mesons.

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TJNAF

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QCD and Hadron Spectroscopy

- Visible universe: Mostly Hadrons
- Quark model: mesons, baryons $q\bar{q}$, $qqq$

Mesons

Baryons
QCD and Hadron Spectroscopy

- Visible universe: Mostly Hadrons
- Quark model: mesons, baryons $q\bar{q}$, $qqq$
- Hadron mass is mostly dynamic
- QCD, underlying theory of quark interactions
QCD and Hadron Spectroscopy

- Visible universe: Mostly Hadrons
- Quark model: mesons, baryons $q\bar{q}$, $qqq$
- Hadron mass is mostly dynamic
- QCD, underlying theory of quark interactions
- QCD allows other configurations:

- Tetraquark
- Hadronic molecule
- Pentaquark
- "Hybrid" meson
Light Meson Spectroscopy

2-fermion system: $q\bar{q}$

Spectroscopy: $(2S+1)L_J$

$S=\text{Spin, } 0 \text{ or } 1$
$L=\text{Orbital Momentum, } 0,1,2,...$
$J=\text{Total Orbital Momentum, } 0,1,2,...$

$J^{--} \text{ and } J^{++} \ C = P \Rightarrow S = 1$

$J^{PC}$ Quantum Numbers

- Parity = $(-1)^{L+1}$
- Charge Conjugation = $(-1)^{L+S}$
- Spin = $J = |L - S|, L, L + S$
- Vacuum = $^3P_0 \cong 0^{++}$

Quark Degrees of Freedom ONLY

Experimental observation!!
Light Meson Spectroscopy

2-fermion system: $q\bar{q}$

Spectroscopy: $(2S+1)L_J$

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Quark Degrees of Freedom ONLY

<table>
<thead>
<tr>
<th>$J^{PC}$</th>
<th>0--</th>
<th>0++</th>
<th>0--</th>
<th>0++</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1--</td>
<td>1++</td>
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<td>5--</td>
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<td>5++</td>
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</tbody>
</table>

$J^{PC}$ Exotic quantum numbers
Mesons with exotic quantum numbers?

HYBRID-Meson $q\bar{q}$ with constituent gluon ($J^{PC} = 1^{+-}, 1^{--}$):

<table>
<thead>
<tr>
<th>$S = 0$, $L = 0$, $m = 1$</th>
<th>$S = 1$, $L = 0$, $m = 1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J^{PC} = 1^{--}$, $1^{+-}$</td>
<td>$J^{PC} = 0^{--}$, $0^{++}$</td>
</tr>
<tr>
<td>non exotic states</td>
<td>$1^{--}$, $1^{++}$</td>
</tr>
<tr>
<td>exotic states require $S$ or $L \neq 0$</td>
<td>$2^{--}$, $2^{++}$</td>
</tr>
</tbody>
</table>

$J^{PC}$ Exotic quantum numbers are a signature for exotic mesons such as Glueball, $q\bar{q}-q\bar{q}$ Molecule or Hybrid Mesons

GlueX: Search for hybrid mesons with exotic quantum numbers
Lattice calculations predict exotic $J^{PC}$ states

*Dudek, Edwards, Guo, and Thomas, PRD 88, 094505 (2013)*
Hybrid Masses and Decays

Masses (lattice QCD)
- $1^{-+} \sim 2.0 - 2.4 \text{ GeV}$
- $0^{+-} \sim 2.3 - 2.5 \text{ GeV}$
- $2^{+-} \sim 2.4 - 2.6 \text{ GeV}$

Decay widths (from Models)
- $\Gamma \sim 0.1 - 0.5 \text{ GeV}$

1$^{-+}$
- $\pi_1 \rightarrow \rho \pi, b_1 \pi, f_1 \pi, \eta' \pi, a_1 \eta$
- $\eta_1 \rightarrow f_2 \pi, a_2 \pi, f_1 \eta, \eta' \eta, \pi(1300)\pi, a_1 \pi$
- $\eta'_1 \rightarrow K^*\bar{K}, K_1(1270)\bar{K}, K^*(1410)\bar{K}, \eta' \eta$

2$^{+-}$
- $b_2 \rightarrow \omega \pi, a_2 \pi, \rho \eta, f_1 \rho, a_1 \pi$
- $h_2 \rightarrow \rho \pi, b_1 \pi, \omega \eta, f_1 \omega$
- $h'_2 \rightarrow K_1(1270)\bar{K}, K^*(1410)\bar{K}, K_2\bar{K}, \phi \eta$

0$^{+-}$
- $b_0 \rightarrow \pi(1300)\pi, h_1 \pi, f_1 \rho, b_1 \eta$
- $h_0 \rightarrow b_1 \pi, h_1 \eta$
- $h'_0 \rightarrow K_1(1270)\bar{K}, K^*(1410)\bar{K}, h_1 \eta$

- Complex Final States!
- Neutrals and Charged!
Hybrid Meson Production

Pion Beam on Hydrogen

- $\pi$ with $S=0$, $L=0$ and $\Delta m=1$
  - $1^{++}$, $1^{--}$
- Require spin flip

- E852, GAMS, KEK, VES, COMPASS
Hybrid Meson Production

Pion Beam on Hydrogen

- $\pi$ with $S=0$, $L=0$ and $\Delta m=1$
  - $1^{++}$, $1^{--}$
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Compass result on $\eta' \pi^{-}$ final state:

- Exotic $1^{-+}$ amplitude (P wave)
Hybrid Meson Production

Pion Beam on Hydrogen

- $\pi$ with $S=0$, $L=0$ and $\Delta m=1$
  $1^{++}, 1^{--}$
- Require spin flip
- E852, GAMS, KEK, VES, COMPASS

Photon Beam on Hydrogen

- $\gamma$ with $S=1$, $L=0$ and $\Delta m=1$
  $0^{--}, 0^{+-}, 1^{--}, 1^{+-}, 2^{--}, 2^{+-}$
- No spin flip required
- Photon linearly polarized
- CLAS, Omega-Photon Coll.
- GlueX
Where is Thomas Jefferson Lab and CEBAF?
CEBAF Accelerator site:
GlueX Hall D
The Hall-D Beam Line

- $e^-$ (12 GeV/c) beam
- 20 $\mu m$ thick diamond radiator
- Coherent Bremsstrahlung
- 76m Photon beam line for collimation.
- 40% polarization at 9 GeV
- Hall-D beam dump for photons only!
Photon Beam Tagger

- 20\(\mu\)m thick diamond radiator
- 76 m flight path to collimator
- 40% polarization at peak (9GeV)
- \(10^8\)\(\gamma\)/s at 8.4-9.0 GeV
- Fixed Array Hodoscope 3-11.7 GeV
- Microscope 800 MeV coverage
The GlueX Detector

Magnet, Target
- Solenoid (hermiticity)
- Super-conducting
- 2 Tesla
- LH$_2$ target
The GlueX Detector

Tracking Chambers

**CDC**
- Straw tube chamber
- $dE/dx$ for PID

**FDC**
- Cathode strips
  \[ \frac{\delta p}{p} \sim 1\text{-}2\% \]
The GlueX Detector

Calorimetry

Barrel Calorimeter
- Scin. fiber/lead
- $\delta E/E = 5.4/\sqrt{E} \oplus 2.3\%$

Forward Calorimeter
- Lead glass
- $\delta E/E = 5.7/\sqrt{E} \oplus 2.0\%$
The GlueX Detector

Timing

Start Counter
- Scintillators
- $\delta t/t = 280\text{ps}$

Time of Flight
- Scintillators
- $\delta t/t = 100\text{ps}$
The GlueX Detector

- Solenoid, Target
- Tracking
- Calorimetry
- Timing
- Future PID → DIRC
Running periods

- **Spring 2016: 12 GeV Engineering run**
  - Electron Beam Energy: 12.05 GeV
  - Commissioning complete: Detector, Beamline, DAQ
  - Data taken for early physics results:
    $\sim 26$ billion events, $\sim 7$ billion with good quality

- **Spring 2017: GlueX Phase-I, first part**
  - Electron Beam Energy: 11.64 GeV
  - $58 \mu$m diamond radiator
  - DAQ trigger rate 30-50 kHz
  - Exceeded nominal luminosity
  - Accumulated $\sim 50$ billion events (20%)

- **October 2017: Continue GlueX Phase-I**
Calorimeter Resolutions

FCAL and BCAL Energy resolution with $\pi^0$:

**Forward Lead Glass Calorimeter**

\[
\frac{\sigma(M_{\gamma\gamma})}{M_{\gamma\gamma}} = 7.0% \\
1.0 \text{ GeV} < E_\gamma < 3.0 \text{ GeV}
\]

**Design Goal**

\[
\frac{\sigma(E)}{E} = \frac{5.6}{\sqrt{E[\text{GeV}]}} \oplus 3.5\%
\]

**Barrel Lead-Scintillating Fiber Calorimeter**

\[
\frac{\sigma(M_{\gamma\gamma})}{M_{\gamma\gamma}} = 8.7% \\
1.0 \text{ GeV} < E_\gamma < 3.0 \text{ GeV}
\]

**Design Goal**

\[
\frac{\sigma(E)}{E} = \frac{5.4}{\sqrt{E[\text{GeV}]}} \oplus 2.3\%
\]
Particle Identification

Positively Charged Particles

Negatively Charged Particles

Incorrect RF Bunch

Positively Charged Particles

Negatively Charged Particles

CDC dE/dx [keV/cm] vs Track Momentum [GeV/c]

FCAL Energy / Track Momentum vs Track Polar Angle [degrees]
Photon Beam Polarization

Triplet Polarimeter:
\[ \gamma e^- \rightarrow e^- e^+ e^- \]

\[ N_\parallel \propto A(\phi)(1 - P\Sigma \cos(2(\phi - \phi_0))) \]

Polarization: \( P(E_\gamma) \)
A road map to search for exotic mesons in GlueX.
Pseudo-scalar Mesons Beam Asymmetries

Pseudo-scalar mesons: $\pi^0$ and $\eta$

- $P_{||}$:
  $$\frac{d\sigma}{d\phi} \propto (1 - P\Sigma \cos(2\phi))$$

- $P_{\perp}$:
  $$\frac{d\sigma}{d\phi} \propto (1 - P\Sigma \cos(2\phi - \pi))$$

- Asymmetry: $A(\phi) = \frac{\frac{d\sigma}{d\phi \perp} - \frac{d\sigma}{d\phi \parallel}}{\frac{d\sigma}{d\phi \perp} + \frac{d\sigma}{d\phi \parallel}}$
  $$\approx P\Sigma \cos(2\phi)$$

Detector efficiency/acceptance CANCEL!
Photo-production of Pseudo-scalar Mesons

\[ \pi^0 \text{ and } \eta \text{ production:} \]

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

\[ 1^{--} : \omega, \rho \]

\[ 1^{+-} : b, h \]

- PRD 92 (2015) 074013
  \[ \Sigma = \frac{|\omega + \rho|^2 - |b + h|^2}{|\omega + \rho|^2 + |b + h|^2} \]

- Beam asymmetry sensitive to nature of exchange particles

- \( \Sigma \approx +1 \Rightarrow \text{vector meson dominance} \)
First GlueX Physics Result
Azimuthal Beam Asymmetries in $\pi^0$ and $\eta$ production:

- Both $\pi^0$ and $\eta$ asymmetries close to $+1$
- No dip observed at $t = -0.5$ (GeV/c)$^2$
- First measurement on $\eta$ asymmetries
- $\Sigma \approx +1 \Rightarrow$ vector meson exchange dominates
The $\rho$, Vector meson Beam Asymmetry

SLAC: PRD7(1973)3150

$\gamma p \rightarrow p \pi^+ \pi^-$
$E_\gamma = 9.3 \text{ GeV}$

$|t|/|t_0| > 0.02 \text{ GeV}^2$
3480 EVENTS

GlueX: large statistics

Invariant Mass (GeV/c^2)

Yield Asymmetry

$\psi (\degree)$

$-t (\text{GeV/c}^2)^2$

GlueX Spring 2016
$\gamma p \rightarrow \pi^+ \pi^- p$
The $\omega$, Beam Asymmetry

- Radiative/Hadronic $\omega$ decay
- $A^{\pi^0\gamma} = -\frac{1}{2} P \cos(2(\Phi - \phi))$
- $A^{3\pi} = P \cos(2(\Phi - \phi))$
- Beam Asymmetry Ratio
  \[ R = \frac{\sum 3\pi}{\sum \pi^0\gamma} \]
- Expect: $R = -2$

PRC 78 (2008) 038201
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  PRC 78 (2008) 038201
- Measured: $R = -1.88 \pm 0.13$
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Next:
- Determine Detector Acceptance
- Determine Detector Efficiencies
- Extract Cross Sections, $\frac{d\sigma}{dt}$
- Determine SDMEs for $\rho, \omega, \phi$
J/ψ Photo Production

- Study J/ψ-nucleon interaction
- Probe gluon in the nucleon
- Probe multi-quark correlations

leading-twist

higher-twist
J/ψ Photo Production

- Study J/ψ-nucleon interaction
- Probe gluon in the nucleon
- Probe multi-quark correlations
- N-gluon exchange
J/ψ Photo Production

- Study J/ψ-nucleon interaction
- Probe gluon in the nucleon
- Probe multi-quark correlations
- N-gluon exchange
- GlueX Range 12 GeV max

Graph showing cross-sections for 2, 3 gluon exchange as a function of photon energy (E_γ) in GeV.


**J/ψ Photo Production**

- Study $J/\psi$-nucleon interaction
- Probe gluon in the nucleon
- Probe multi-quark correlations
- N-gluon exchange
- GlueX Range 12 GeV max
- LHCb reports $J/\psi p$ pentaquark candidate
- PRL 115, 072001 (2015)
J/ψ Photo Production

s-channel production in GlueX:

- Study J/ψ-nucleon interaction
- Probe gluon in the nucleon
- Probe multi-quark correlations
- N-gluon exchange
- GlueX Range 12 GeV max
- LHCb reports J/ψp pentaquark candidate
- PRL 115, 072001 (2015)
- $P_c$ at $E_{γ\text{beam}} \sim 10$ GeV
**J/ψ at GlueX a first look**

Invariant $e^+e^-$ Mass distribution in GlueX:
- Lepton ID with $E/p$ in BCAL/FCAL
- Kinematic fit with $E_{\gamma_{beam}}$ and recoil proton

MC normalized to $\phi$ x-sec.  kin.fit $\chi^2 < 200$, $\theta_e > 2^0$

![Graph showing data and MC comparison for $e^+e^-$ invariant mass distribution]

$J/\psi \sim 100$ events

$\sigma = 9 \pm 1$ MeV

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**Introduction**

**Beam/Detector**

**Data Taking**

**First Physics**

**Conclusion**
J/ψ at GlueX a first look

J/ψ cross section as function of $E_{γbeam}$

Plan: Combine 2016/2017 data sets → upper limit to $P_c$ photo-production
Conclusions

• Successfully commissioned HallD beam line and GlueX detector
  beam asymmetries for $\pi^0$ and $\eta$
• GlueX physics program started: 20% complete (Phase-I)
• Data analysis underway to reach cross sections and SDMEs
• Next data taking period Fall 2017
• Other experiments in HallD:
  a) $\eta$ Radiative Decay Width via the Primakoff Effect
  b) Charged Pion Polarizability in the $\gamma\gamma \rightarrow \pi^+\pi^-$ Reaction
  c) Meson and baryon decays to strange final states
  d) Rare $\eta$ decay channels