GlueX: Photoproduction of Hybrid Mesons

Hybrid mesons – masses and decay modes
Expectations from LQCD and models
Photoproduction and GlueX

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for the GlueX Collaboration
12th International Workshop on Meson Production, Properties and Interaction
Quarks are confined inside colorless hadrons

Quarks combine to “neutralize” color force

Allowed by QCD, but do they exist in nature?
Normal Mesons – q\bar{q} color singlet bound states

Spin/angular momentum configurations & radial excitations generate the known spectrum of light quark mesons.

Starting with $u - d - s$ we expect to find mesons grouped in nonets - each characterized by a given $J$, $P$ and $C$.

$S = S_1 + S_2$
$J = L + S$
$P = -(-1)^L$
$C = (-1)^{L+S}$

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

Allowed combinations

Not-allowed: exotic
Families of Exotics

$K_1 \ I^G(J^{PC}) = \frac{1}{2} \ (1^-)$

$\pi_1 \ I^G(J^{PC}) = 1^- (1^-)$

$\eta_1 \ I^G(J^{PC}) = 0^+ (1^-)$

$\eta'_1 \ I^G(J^{PC}) = 0^+ (1^-)$

Couple to vector meson + exchanged particle

$\pi_1 \ \leftrightarrow \ \rho \pi$

$\eta_1 \ \leftrightarrow \ \rho b_1, \ \omega \phi$

$\eta'_1 \ \leftrightarrow \ \phi \omega$

$\gamma \ \leftrightarrow \ \rho, \omega, \phi$
Meson Spectroscopy from LQCD

Isovector mesons, $m_\pi \sim 700$ MeV

Dudek PRD 83 (2011) 111502
Dudek PRD 84 (2011) 074023

Friday Plenary 3
Meson Spectroscopy from LQCD

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Friday Plenary 3

Elton S. Smith  MESON2012  May 31 – June 5, 2012
At $m_\pi = 400$ MeV, mass ($1^{-+}$) $\sim 1.9$ GeV, mass ($0^{+-}$) $\sim 2.5$ GeV
Models for hybrid mesons

Lattice QCD

Flux Tube
$J_g^{PC}=1^{+-}$ and $1^{--}$

Isgur Phys Rev Lett 54 (1985) 869
Models for hybrid mesons

Mass (GeV)

Lattice QCD

Effective QCD Hamiltonian
Models for hybrid mesons

Mass (GeV)

Lattice QCD

Constituent Gluon $J_g^{PC=1-}$

Similar features as LQCD spectrum

Guo PRD 78 (2011) 056003
How do exotics decay?

Possible daughters:

L=1: a, b, h, f, ...
L=0: π, ρ, η, ω, ...

The angular momentum in the flux tube stays in one of the daughter mesons (L=1) and (L=0) meson, e.g:

Example: \( π_1 \rightarrow b_1π \)

\( \omega π \rightarrow (3π)π \)

or \( \omega π \rightarrow (πγ)π \)

simple decay modes such as \( ηπ, ρπ, \) ... are suppressed.
Partial width dependence on hybrid mass

FIG. 1. Dominant partial widths of a $1^{-+}$ isovector hybrid at various hybrid masses. The partial widths to $K_1(1400)K$, $\eta(1295)\pi$, $b_1\pi$ and $\rho\pi$ correspond to the highest to the lowest intersections with the vertical axis.
### Experimental status of exotic $1^{-+} \pi(1600)$

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Reaction</th>
<th>Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>VES</td>
<td>$\pi^- A \rightarrow \pi^- b_1 A$</td>
<td>$\pi^- f_1 A$, $\pi^- \eta' A$</td>
</tr>
<tr>
<td>E852</td>
<td>$\pi^- p \rightarrow \rho \pi^- p$</td>
<td>$b_1 \pi^- p$, $f_1 \pi^- p$, $\eta' \pi^- p$</td>
</tr>
<tr>
<td>Crystal Barrel</td>
<td>$\bar{p}n \rightarrow b_1 \pi^-$</td>
<td></td>
</tr>
<tr>
<td>E852-IU</td>
<td>$\pi^- p \not\rightarrow (\rho \pi^-)_{\pi_1} p$</td>
<td>$(\rho \pi^0)_{\pi_1} n$</td>
</tr>
<tr>
<td>CLAS</td>
<td>$\gamma p \not\rightarrow (\rho \pi^+)_{\pi_1} n$</td>
<td></td>
</tr>
<tr>
<td>COMPASS</td>
<td>$\pi^- A \rightarrow \rho \pi^- A$</td>
<td></td>
</tr>
<tr>
<td>CLEO-c</td>
<td>$\psi(2S') \rightarrow \gamma \chi_{c1}$, $\chi_{c1} \rightarrow \eta' \pi^+ \pi^-$</td>
<td></td>
</tr>
</tbody>
</table>

For review see Meyer PRC 82 (2010) 025208 [Saturday Plenary 4]
CLEO-c exotic $\pi_1$

$\psi(2S) \rightarrow \gamma \chi_{c1}, \; \chi_{c1} \rightarrow \eta' \pi^+ \pi^-$

Exotic $1^+ \pi_1 \rightarrow \eta' \pi$
Mass = $1670 \pm 36$ MeV, $\Gamma = 240 \pm 78$ MeV
4 sigma significance

Adams PRD 84 (2011) 112009
Other suspected hybrid signals

New state $\gamma(4260) 1^{-+}$ state found by Babar/CLEO
Does not fit into the quark model spectrum
Properties consistent with hybrid charmonium state.

A second new state $\gamma(2175)$ is proposed as its light quark analog $s\bar{s}g$


[Friday C1] Belle PRD 80 (2009) 031101
Decomposition of total cross section $E_\gamma = 9.3$ GeV

<table>
<thead>
<tr>
<th>Topology</th>
<th>$\sigma$ ((\mu b))</th>
<th>% of $\sigma$ with neutrals</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-prong</td>
<td>8.5 ± 1.1</td>
<td>100</td>
</tr>
<tr>
<td>3-prong</td>
<td>64.1 ± 1.5</td>
<td>76 ± 3</td>
</tr>
<tr>
<td>5-prong</td>
<td>34.2 ± 0.9</td>
<td>86 ± 4</td>
</tr>
<tr>
<td>7-prong</td>
<td>6.8 ± 0.3</td>
<td>86 ± 6</td>
</tr>
<tr>
<td>9-prong</td>
<td>0.61 ± 0.08</td>
<td>87 ± 21</td>
</tr>
<tr>
<td>With visible strange decay</td>
<td>9.8 ± 0.4</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>124.0 ± 2.5</td>
<td>82 ± 4</td>
</tr>
</tbody>
</table>

Approximately the 70% of total cross section in the energy region $E_\gamma \sim 7$-12 GeV has multiple neutrals and is completely unexplored.
\( \gamma \) and \( \pi \) beams

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

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


Note: much more photon data from Jlab at lower energy
Photoproduction and linear polarization

### Production
- The expectation from the flux tube model is that hybrids will be produced at a rate comparable to normal mesons.
- This expectation is corroborated by recent lattice calculations that show that the strength of charmonium hybrid radiative decays are similar to normal mesons:
  \[
  \Gamma (\eta_{c1} \rightarrow J/\psi \gamma) \sim 100 \text{keV} 
  \]

### Polarization
- For a given produced resonance, linear polarization enables one distinguish between naturalities of exchanged particles.
- If the production mechanism is known, linear polarization enables one to filter resonances of different naturalities.

\[ \text{Dudek} \quad \text{PRD 79 (2009) 094504} \]
Minimum photon energy for search

Resonant shapes generated with the same widths and production cross sections. Yield and line shape determined by production kinematics.

\[ N(m_X) = A \cdot BW(m_X) \cdot e^{-8|t|} \]

Mass = 2.5 GeV

\[ E_\gamma = 9 \text{ GeV} \]

\[ E_\gamma = 10 \text{ GeV} \]
GlueX strategy for hybrid meson search

- Use 8 – 9 GeV polarized photons (12 GeV electron beam)
  - Expect production of hybrids to be comparable to normal mesons
  - Dearth of experimental data

- Use hermetic detector with large acceptance
  - Decay modes expected to have multiple particles
  - hermetic coverage for charged and neutral particles
  - high data acquisition rate to enable amplitude analysis

- Perform amplitude analysis
  - identify quantum numbers as a function of mass
  - check consistency of results in different decay modes
Areal view of accelerator

North-Linac

Injector

South-Linac

A

B

C
Hall D civil construction complete

Service Bldg.  Cryo plant  Counting house  Hall-D

Beam line  Tagger Hall

Summer 2011
Linearily Polarized Photon Beam

Rates are based on
- 12 GeV electron beam
- 20 µm diamond crystal
- 300 nA electron beam
- Rad-collimator: 76 m
- Collimator diameter: 3.5mm

Leads to $10^7 \gamma/s$ on target

Design is expandable to $10^8 \gamma/s$
Hermetic detection of charged and neutral particles in solenoid magnet

Initial Flux $10^7 \gamma/s$
18,000 FADCs
4,000 pipeline TDCs
20 KHz L1 trigger
300 MB/s to tape

Tagger Spectrometer (Upstream)
Detector status

Solenoidal Magnet: tested at 1500 A

BCAL: All 48 modules built

CDC: all 3500 wires strung

FDC: 60% done

FCAL: all 2800 lead glass and PMTs

Electronics: 70% ordered
Sample amplitude analysis with GlueX

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

generated waves

\[ a_1(1260) \rightarrow \rho\pi \quad (S - \text{wave}) \]
\[ a_2(1320) \rightarrow \rho\pi \quad (D - \text{wave}) \]
\[ \pi_1(1600) \rightarrow \rho\pi \quad (P - \text{wave}) \]
\[ \pi_2(1670) \rightarrow f_2\pi \quad (S - \text{wave}) \]
\[ \pi_2(1670) \rightarrow \rho\pi \quad (P - \text{wave}) \]

1\(^{+}\) exotic wave

generated with 1.6\% relative strength

Corresponds to 3.5 hours
GlueX data, full detector simulation and reconstruction
12 GeV Project Schedule

- Hall A commissioning start Jan 2014
- Hall D commissioning start October 2014
- Halls B and C commissioning start April 2015
Summary

- **QCD on the Lattice**
  - Lattice calculations have made great strides in calculating the spectrum of normal and hybrid mesons.
  - Hybrid masses are expected in the range of 1.8 to 2.7 GeV
  - The spectrum is consistent with the constituent gluon model ($J_g=1^{+-}$)

- **Model expectations**
  - In photoproduction, gluonic excitations will be produced with roughly the same cross sections as normal mesons.
  - Gluonic excitations are expected to decay preferentially to multi-particle final states

- **The GlueX experiment will study the spectrum of mesons with a polarized photon beam up to $M \sim 2.8$ GeV with sensitivities of a few percent of the total cross section.**
Backup Slides
Meson Spectroscopy from LQCD

normal mesons

exotics

\( m_\pi \sim 400 \text{ MeV} \)

\( m_\pi = 396 \text{ MeV} \)

Dudek PRD 83 (2011) 111502
Dudek PRD 84 (2011) 074023
Can we learn anything qualitative about QCD?

- Determination of the spectrum of hybrids will provide insight into
  - The nature of strongly interacting gluon fields
  - The gluon configuration for light quark masses
## Naming Scheme for u,d Mesons

<table>
<thead>
<tr>
<th>Name (I=1, I=0)</th>
<th>L</th>
<th>S</th>
<th>$J^{PC}$</th>
<th>$2S+1L_J$</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi$, $\eta$</td>
<td>0</td>
<td>0</td>
<td>0-+</td>
<td>$^1S_0$</td>
<td>$\pi$, $\eta$</td>
</tr>
<tr>
<td>$\rho$, $\omega$</td>
<td>0</td>
<td>1</td>
<td>1--</td>
<td>$^3S_0$</td>
<td>$\rho(770)$, $\omega(782)$</td>
</tr>
<tr>
<td>$b$, $h$</td>
<td>1</td>
<td>0</td>
<td>1+-</td>
<td>$^1P_1$</td>
<td>$b_1(1235)$, $h_1(1170)$</td>
</tr>
<tr>
<td>$a$, $f$</td>
<td>1</td>
<td>1</td>
<td>0++</td>
<td>$^3P_0$</td>
<td>$a_0(980)$, $f_0(980)$</td>
</tr>
<tr>
<td>$a$, $f$</td>
<td>1</td>
<td>1</td>
<td>1++</td>
<td>$^3P_1$</td>
<td>$a_1(1260)$, $f_1(1285)$</td>
</tr>
<tr>
<td>$a$, $f$</td>
<td>1</td>
<td>1</td>
<td>2++</td>
<td>$^3P_2$</td>
<td>$a_2(1320)$, $f_2(1270)$</td>
</tr>
<tr>
<td>$\pi$, $\eta$</td>
<td>2</td>
<td>0</td>
<td>2-+</td>
<td>$^1D_2$</td>
<td>$\pi_2(1670)$</td>
</tr>
<tr>
<td>$\rho$, $\omega$</td>
<td>2</td>
<td>1</td>
<td>1--</td>
<td>$^3D_1$</td>
<td>$\rho_1(1700)$, $\omega_1(1600)$</td>
</tr>
<tr>
<td>$\rho$, $\omega$</td>
<td>2</td>
<td>1</td>
<td>2--</td>
<td>$^3D_2$</td>
<td></td>
</tr>
<tr>
<td>$\rho$, $\omega$</td>
<td>2</td>
<td>1</td>
<td>3--</td>
<td>$^3D_3$</td>
<td>$\rho_3(1670)$</td>
</tr>
<tr>
<td>$b$, $h$</td>
<td>3</td>
<td>0</td>
<td>3+-</td>
<td>$^1F_3$</td>
<td></td>
</tr>
<tr>
<td>$a$, $f$</td>
<td>3</td>
<td>1</td>
<td>2++</td>
<td>$^3F_2$</td>
<td></td>
</tr>
<tr>
<td>$a$, $f$</td>
<td>3</td>
<td>1</td>
<td>3++</td>
<td>$^3F_3$</td>
<td></td>
</tr>
<tr>
<td>$a$, $f$</td>
<td>3</td>
<td>1</td>
<td>4++</td>
<td>$^3F_4$</td>
<td></td>
</tr>
</tbody>
</table>

$P = (-1)^{L+1}$

$C = (-1)^{L+S}$

$PC = (-1)^{S+1}$

$G = C(-1)^{I}$
Experimental evidence for $1^{-+}$ exotic hybrids

<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></td>
<td>BKEI, 6 GeV 1993</td>
<td>1320±5</td>
<td>140±10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MPS, 18 GeV 1997</td>
<td>1370±60</td>
<td>380±100</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E-852, 18 GeV 2007</td>
<td>1260±40</td>
<td>350±60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CBAR, 0 GeV 1999</td>
<td>1360±25</td>
<td>360±80</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CBAR, 0 GeV 1998</td>
<td>1400±30</td>
<td>220±90</td>
</tr>
<tr>
<td>1600</td>
<td>$\pi^- A \rightarrow \pi^+ \pi^- \pi^- A$</td>
<td>VES, 37 GeV 2000</td>
<td>1610±20</td>
<td>290±30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>VES, 37 GeV 2005</td>
<td>1600</td>
<td>none</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E-852, 18 GeV 2002</td>
<td>1590±40</td>
<td>170±60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E-852, 18 GeV 2006</td>
<td>1600</td>
<td>none</td>
</tr>
<tr>
<td></td>
<td>$\pi^- p \rightarrow \pi^+ \pi^- \pi^- p$</td>
<td>E-852, 18 GeV 2004</td>
<td>1710±60</td>
<td>400±90</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E-852, 18 GeV 2005</td>
<td>1660±10</td>
<td>190±30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>VES, 18 GeV 2005</td>
<td>1600</td>
<td>300</td>
</tr>
</tbody>
</table>

Hybrid unlikely
Dynamical origin?

$\rho p \rightarrow \eta \pi n$
$\rho n \rightarrow \eta \pi^0 \pi^-$

May be hybrid
Challenge in $3\pi$ to separate exotic $\pi_1$ from $\pi_2$
Cleaner $\eta'\pi$ signal

$\pi^- A \rightarrow \eta\pi^- A$
$\pi^- p \rightarrow \eta \pi^+ \pi^- \pi^- p$
$\pi^- p \rightarrow \omega \pi^- \pi^0 p$
Flux Tube Expectations for $\pi_1(2000)$

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Final state</th>
<th>Partial Width PSS (MeV)</th>
<th>Partial Width IKP (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b_1(1235)\pi$</td>
<td>$\omega\pi\pi$</td>
<td>43</td>
<td>58</td>
</tr>
<tr>
<td>$K_1(1400)K$</td>
<td>$K\pi\pi K$</td>
<td>33</td>
<td>75</td>
</tr>
<tr>
<td>$\eta(1295)\pi$</td>
<td>$\eta\pi\pi\pi$</td>
<td>27</td>
<td>21</td>
</tr>
<tr>
<td>$\rho\pi$</td>
<td>$\pi\pi\pi$</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>$\rho(1450)\pi$</td>
<td>$\pi\pi\pi$</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>$f_1(1285)\pi$</td>
<td>$\pi\pi\pi\pi$</td>
<td>10</td>
<td>38</td>
</tr>
<tr>
<td>$a_1(1260)\eta$</td>
<td>$\rho\pi\eta$</td>
<td>7</td>
<td>13</td>
</tr>
<tr>
<td>$K_1(1270)K$</td>
<td>$K\rho K$</td>
<td>7</td>
<td>19</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>&gt; 155</strong></td>
<td><strong>&gt; 252</strong></td>
<td></td>
</tr>
</tbody>
</table>
Selection rules for decays

Strong interaction selection rules in the limit of non-relativistically moving quarks when the daughter states are identical except for isospin and spin.

- Decays of $J^{PC}=0^{-+}, 1^{-+}, 2^{-+}, \ldots$ exotic hybrids to pseudoscalar mesons vanish.
  - Hybrids do not decay to $\eta\pi$.
  - Hybrids decays to $\pi\pi$, $\rho\rho$, KK are forbidden.

- Decays of hybrids to s-wave mesons highly suppressed.
  - Hybrid decay to $\rho\pi$ is suppressed.

CLEO-c analysis of exotic
Experimental evidence for $1^{-+}$ exotic hybrids

$\pi_1(1400)$

$J^G(J^{PC}) = 1^-(1^{-+})$

See also the mini-review under non-$q\bar{q}$ candidates in PDG 06, Journal of Physics, G 33 1 (2006).

$\pi_1(1600)$

$J^G(J^{PC})$

$\pi_1(1600)$ MASS

<table>
<thead>
<tr>
<th>VALUE (MeV)</th>
<th>EVTS</th>
<th>DOCUMENT ID</th>
<th>TECN</th>
<th>CHG</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1662 $^{+8}_{-9}$</td>
<td>OUR AVERAGE</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$\pi_1(2015)$

$J^G(J^{PC}) = 1^-(1^{-+})$

<table>
<thead>
<tr>
<th>MASS (MeV)</th>
<th>WIDTH (MeV)</th>
<th>EVTS</th>
<th>DOCUMENT ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>2014 $^{+20}_{-16}$</td>
<td>230 $\pm$ 32 $\pm$ 73</td>
<td>145k</td>
<td>LU</td>
</tr>
<tr>
<td>2001 $^{+30}_{-92}$</td>
<td>333 $\pm$ 52 $\pm$ 49</td>
<td>69k</td>
<td>KUHN</td>
</tr>
</tbody>
</table>

Unlikely Hybrid Dynamical origin?

May be hybrid
Challenge in $3\pi$
to separate exotic $\pi_1$ from $\pi_2$
Cleaner $\eta'$ $\pi$ signal

Listed among “further states”
Needs confirmation
12 GeV CEBAF

- Add Hall D (and beam line)
- Upgrade magnets and power supplies
- Add 5 cryomodules
- 20 cryomodules
- Add arc
- Add 5 cryomodules
- CHL-2
- Enhance equipment in existing halls
Photon beam and experimental area

Top View

North linac
Tagger area
Hall D
Electron Beam dump
East arc

Electron beam
Coherent Bremsstrahlung photon beam
Collimator

Radiator
Tagger Area

75 m

Counting House
Phonon Beam dump
Solenoid-Based detector
Experimental Hall D
Particle kinematics

The GlueX Experiment

**Goal:** map the spectrum of exotic hybrid mesons

**Method:** Photo-produce hybrids off proton target and identify the quantum states using Partial Wave Analysis of decay product distributions

\[ \gamma + p \rightarrow p + X \]

- \( b_1 \pi \)
- \( \omega \pi \)
- \( \pi \pi \pi \)
- \( \eta \pi \)
- \( \pi \pi \pi \)

Detectable final state

- \( 5\pi + 1p \)
- (mixed charged and neutral)
- \( 5\pi + 1p \)
What to conclude from existing evidence?

Hybrids with exotic quantum numbers:

- Predicted by LQCD and models
- Masses evaluated by LQCD, production/decays by models
- Experimental evidence is tantalizing but not strong

Experimental requirements to move forward:

- Hermeticity and resolution
- All potentially important decay modes must be analyzed
- Amplitude analysis must be well understood and controlled
- Perhaps pions are not the optimal probe to produce exotic hybrids

*Photoproduction - few data so far*
Amplitude analysis $3\pi$ system in isobar model

The decay of the $3\pi$ system at point 1 to the di-pion resonance $R_{\pi\pi}$ and a bachelor pion is described in the Gottfried-Jackson frame.

The decay of $R_{\pi\pi} \rightarrow \pi_a \pi_b$ at point 2 is described in the helicity frame.