The Phenomenology of Glueball and Hybrid Mesons

Workshop on Future Physics with COMPASS

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1. Why?
2. Glueballs
3. Hybrids
4. Summary

*For a recent review see Godfrey and Napolitano, Rev Mod Phys 71, 1411 (1999)
Why is this important?
10 Physics Questions to Ponder for a Millennium or Two

One of those questions:

How can we understand quark and gluon confinement in Quantum Chromodynamics?

Meson Spectroscopy is the ideal laboratory to accomplish this
A fundamental question to this is end is

“How does glue manifest itself in the soft QCD regime?”

Models of hadron structure

- Lattice QCD (C. McNeille)
- Bag Model
- Flux tube model
- Sum rules approach

predict new forms of hadronic matter with the glue degree of freedom manifest explicitly:

- Glueballs
- Hybrids

and in addition: Multiquark States
Much theoretical progress:

- Lattice QCD is a first principles calculation starting from the QCD lagrangian (C. McNeille)
- Gives a good description of the observed spectrum or heavy quarkonium
- Potential description works well

Bali, Schilling and Wachter
hep-ph/9611226
Glueballs:

- Need to unambiguously observe glueballs and measure their properties
- This will test QCD
- But deeper than this it builds up confidence that we really can do nonperturbative field theory calculations
Hybrids:

Lattice calculations supports the flux tube picture:

From G. Bali
• Excited states have non-trivial representation of the flux tube symmetry
• Similar to electron wavefunctions in diatomic molecules
• Need to map out the higher adiabatic surfaces to test our understanding of “Soft QCD”

• Not enough to discover one meson with exotic quantum numbers

• Need to find enough excited states to map out the excited surfaces

Lattice calculations not yet enough.

Also need phenomenological models to help to find these states:

• Disentangle their properties
• Build up a physical picture
**Conventional Mesons:**

Mesons are composed of a quark-antiquark pair

*Combine u, d, s, c, b quark and antiquark to form various mesons:*

**Meson quantum numbers characterized by given \( J^{PC} \)**

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

**Allowed:**

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

**Not allowed: exotic combinations:**

\[
J^{PC} = 0^{--} \quad 0^{+-} \quad 1^{++} \quad 2^{++} \ldots
\]
• Although goal is to discover exotics can’t ignore conventional states
• Need to understand them to disentangle exotics from $q\bar{q}$

• Couplings of states are sensitive to the internal structure

• An important tool in disentangling the observed spectrum
  • Strong decays modeled by
    • $^3P_0$ Model
    • Flux tube breaking model
  • em couplings:
    • $2\gamma$ couplings
      \[ \Gamma_{\gamma\gamma}(f_2) \cdot B(f_2 \rightarrow \pi^0\pi^0) \]
    • single photon transitions
      \[ \Gamma[(q\bar{q})_i \rightarrow \gamma(q\bar{q})_f] \] (via Primakoff?)

2. Glueballs

Mass predictions by Lattice QCD are fairly robust.

Lowest mass glueballs have conventional quantum numbers:
- $M_{0^{++}} \sim 1.6$ GeV
- $M_{2^{++}} \sim 2.3$ GeV
- $M_{0^{-+}} \sim 2.5$ GeV

Lowest lying glueballs with exotic quantum numbers $0^{+-}, 2^{+-}, 1^{-+}$ are much higher in mass.

- Difficult to produce exotic glueballs
- Difficult to disentangle glueballs with conventional Q#’s from dense background of conventional states
Expect glueball decays to have flavour symmetric couplings to final state hadrons:

\[
\frac{\Gamma(G \to \pi\pi:K\bar{K}:\eta\eta:\eta':\eta':\eta')}{\text{Phase Space}} = 3:4:1:0:1
\]

But situation complicated by mixing with \( q\bar{q} \) and \( q\bar{q}q\bar{q} \)

Physical states are linear combinations:

\[
|f_0\rangle = \alpha |nn\rangle + \beta |ss\rangle + \gamma |G\rangle + \delta |q\bar{q}q\bar{q}\rangle
\]

Will shift unquenched glueball mass and distort naïve couplings

Meson properties can be used to extract the mixings and understand the underlying dynamics.

\[ \text{pp} \rightarrow p_s \ [KK, \pi\pi] p_f \ @ \ 450 \text{ GeV} \]

\[
\begin{align*}
  f_0(1370) & \sim KK \lessapprox 1 \ (0.5 \pm 0.2) \\
  f_0(1500) & \sim \pi\pi \ll 1 \ (0.3 \pm 0.1) \\
  f_0(1710) & \sim \pi\pi \gg 1 \ (5.5 \pm 0.8)
\end{align*}
\]

Using decay information Close and Kirk get:

\[
\begin{align*}
  |f_0(1370)\rangle &= -0.79|n\bar{n}\rangle - 0.13|s\bar{s}\rangle + 0.60|G\rangle \\
  |f_0(1500)\rangle &= -0.62|n\bar{n}\rangle + 0.37|s\bar{s}\rangle - 0.69|G\rangle \\
  |f_0(1710)\rangle &= +0.14|n\bar{n}\rangle + 0.91|s\bar{s}\rangle + 0.39|G\rangle
\end{align*}
\]

The point is not the details of the mixing but that mixing is an important consideration in the phenomenology.
\[ | f > = \cos \alpha | \quad \bar{n}n > -\sin \alpha | \quad \bar{s}s > \]

\[
R_1 = \frac{\gamma^2(\eta\eta)}{\gamma^2(\pi\pi)} \\
R_2 = \frac{\gamma^2(K\bar{K})}{\gamma^2(\pi\pi)}
\]

as a function of \( \alpha \)

works perfectly for 2\(^{++} \) mesons: \( \alpha = 82^\circ \), as from mass formula

Assuming \( qq^- \): \[
\begin{cases} 
    f_0(1500) \text{ is dominantly } \bar{n}n > & -10^\circ < \alpha < 5^\circ \\
    f_0(1700) \text{ is dominantly } \bar{s}s > & 
\end{cases}
\]
An important test of glue content is comparing the gluon rich channel $J/\Psi \rightarrow \gamma X$ to $\gamma \gamma$ couplings.

$$S = \frac{\Gamma(J/\Psi \rightarrow \gamma X)}{PS(J/\Psi \rightarrow \gamma X)} \times \frac{PS(\gamma \gamma \rightarrow X)}{PS(\gamma \gamma \rightarrow X)}$$

large Stickiness reflects enhanced glue content
Production of Glueballs:

1. $J/\psi \rightarrow \gamma X$

2. $p\bar{p}$ annihilation

3. $pp \rightarrow p_f (G) p_s$ central production (Donskov)

• In central production diffractive process via "gluonic pomeron exchange"

• Expect competition with $q\bar{q}$ production

• But kinematic filter discovered which appears to suppress established $q\bar{q}$ states when in P-wave or higher wave
**Central Production:**

\[ pp \rightarrow p_f (G) p_s \]

- \( p_s \) and \( p_f \) represent the slowest and fastest particles
- Believe to be dominated by double Pomeron exchange
- Pomeron believed to have large gluonic content
- Folklore assumed that Pomeron is \( 0^{++} \) with flat distribution
- But distributions not flat
- Modelled with \( J=1 \) exchange particle:
  - Pomeron transforms as a non-conserved vector current
- Data from WA102 appears to support this hypothesis
Kinematic filter seems to suppress established $q\bar{q}$ when they are in P and higher waves

The pattern of resonances depends on the vector difference of the transverse momentum recoil of the final state protons

$$dP_T = \left| \vec{k}_{T_1} - \vec{k}_{T_2} \right|$$

for

- $dP_T$ large well established $q\bar{q}$ states are prominent
- $dP_T$ small, established $q\bar{q}$ states are suppressed while $f_0(1500), f_0(1710), f_0(980)$ survive
\( \phi \), the angle between \( k_T \) vectors

Close Kirk & Schuler give a good account of the data modeling Pomeron as Vector exchange particle:

0\(^{-+} \) - parity requires the vector pomeron to be transversely polarized; peaks at 90\(^o\).

1\(^{++} \) - one transverse the other longitudinal; peaks at 180\(^o\).

2\(^{-+} \) - similar to 0\(^{-+} \) case; peaks at 0\(^o\) (helicity 2 suppressed by Bose statistics).

2\(^{++} \) - established states peak at 180\(^o\) while \( f_2(1950) \) at 0\(^o\).

0\(^{++} \) - peaks at 0\(^o\) for some states while others are spread out:

- \( f_0(1500) \), \( f_0(1710) \), \( f_0(980) \) peak at small \( \phi \).
- \( f_0(1370) \) peaks at large \( \phi \).

Fact that \( f_0(1370) \) and \( f_0(1500) \) have different \( \phi \) dependence indicates not just J dependent phenomena.
$0^{++}, 2^{++}$ expect both TT & LL contributions

\[
\frac{d\sigma}{d\phi} \sim \left[ 1 + \frac{\sqrt{t_1 t_2}}{\mu^2 \frac{a_T}{a_L}} \cos \phi \right]^2
\]

described by varying $\mu^2 a_L / a_T$

= -0.5 GeV$^2$ for $f_0(1370)$
= +0.7 GeV$^2$ for $f_0(1500)$
= -0.4 GeV$^2$ for $f_2(1270)$
= +0.7 GeV$^2$ for $f_0(1950)$

$\phi$ distributions fitted with only 1 parameter

Hybrid Mesons:

Hybrid mesons are defined as those in which the gluonic component is non-trivial.

Two types of hybrids:
- Vibrational hybrids
- Topological hybrids

- Quarks move in effective potentials of adiabatically varying state of flux tubes
- A given adiabatic surface corresponds to various string topologies and excitations
- In Flux-Tube model the lowest excited adiabatic surface corresponds to transverse excitations
Lattice results generally consistent with these predictions

\[ M(1^{-+}) \approx 1.9 \text{ GeV} \]
\[ M(0^{+-}) \approx 2.1 \text{ GeV} \]
\[ M(2^{+-}) \approx 2.1 \text{ GeV} \]

Lowest mass hybrids at 1.9 GeV
Doubly degenerate:

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

Expect degeneracies to be broken by different excitation energies of flux tube modes, spin dependence, mixings with \( q\bar{q} \)

S. Godfrey, Carleton University / DESY

UKQCD; Lacock et al, PR D54, 6997 (1996); PL B401, 308 (1997)
Decay Properties:
Decays need to preserve symmetries

A General Selection Rule:
To preserve symmetries of quark and colour fields about the quarks the $\Pi_u$ hybrid must decay to a meson in a P-wave

- e.g. cannot transfer angular momentum as relative angular momentum but appears as internal angular momentum

This appears to be a universal selection rule

For $1^{-+}$ exotic expect $\hat{\rho} \rightarrow b_1 \pi, f_1 \pi$ modes to dominate
Need model to calculate hybrid properties:

**Flux tube model** is based on the strong coupling Hamiltonian lattice QCD

- Based on quark and flux-tube degrees of freedom
- Provides a unified framework of:
  - conventional hadrons,
  - multiquark states,
  - hybrids
  - glueballs

Expect strong mixing between non-spin exotic hybrids and conventional mesons
For exotic hybrids:

<table>
<thead>
<tr>
<th>$A$</th>
<th>$B, C$</th>
<th>$L$</th>
<th>$\Gamma_1$</th>
<th>$\Gamma_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^1^{--}$</td>
<td>$b_1(1235)\pi$</td>
<td>S</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>$f_1(1285)\pi$</td>
<td>S</td>
<td>30</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>D</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>$\omega^1^{--}$</td>
<td>$a_1(1260)\pi$</td>
<td>S</td>
<td>90</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D</td>
<td>60</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>$K_1(1400)K$</td>
<td>S</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>$\pi^2^{++}$</td>
<td>$a_2(1320)\pi$</td>
<td>P</td>
<td>350</td>
<td>450</td>
</tr>
<tr>
<td></td>
<td>$a_1(1260)\pi$</td>
<td>P</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>$h_1(1170)\pi$</td>
<td>P</td>
<td>125</td>
<td>150</td>
</tr>
</tbody>
</table>

$\hat{a}_0$, $\hat{f}_0^{'}$ too broad
$\hat{\omega}_1$ decays to $[a_1\pi]_S$
with $\Gamma \approx 100$ MeV
similarly for $\hat{\Phi}_1$

Best bets:

$\hat{\rho}_1 \rightarrow [b_1\pi]_S$, $[f_1\pi]_S$

$\hat{f}_2 \rightarrow [b_1\pi]_P$ (\(\Gamma \approx 350\ MeV\))

$\hat{f}_2^{'} \rightarrow [K_2^*\overline{K}]_P$ (\(\Gamma \approx 300\ MeV\))

$\rightarrow [K_1\overline{K}]_P$ (\(\Gamma \approx 250\ MeV\))

But there is variation in model predictions

Isgur, Kokoski and Paton, PRL, 54, 907
For non exotic hybrids:

To distinguish non-exotic hybrids from conventional states need detailed predictions of properties:

$$\pi(1800)$$

**Table III. Decay of quark model and hybrid $$\pi(1800)$$**

<table>
<thead>
<tr>
<th>State</th>
<th>$$\pi\rho$$</th>
<th>$$\omega\rho$$</th>
<th>$$\rho(1465)\pi$$</th>
<th>$$f_0(1300)\pi$$</th>
<th>$$f_2\pi$$</th>
<th>$$K*K$$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$$\pi_{3S}(1800)$$</td>
<td>30</td>
<td>74</td>
<td>56</td>
<td>6</td>
<td>29</td>
<td>36</td>
</tr>
<tr>
<td>$$\pi_H(1800)$$</td>
<td>30</td>
<td>—</td>
<td>30</td>
<td>170</td>
<td>6</td>
<td>5</td>
</tr>
</tbody>
</table>

$$\rho\omega$$ can be used as discriminator between possibilities observed in $$\pi f_0(1300)$$

(but recent paper by Swanson and Szczepaniak [PR D56, 5692] predicts small $$\rho\omega$$ partial width)
$\rho'$ and $\omega'$$$
Expect mixing: \quad |V\rangle = \alpha |2^3S_1\rangle + \beta |1^3D_1\rangle + \gamma |V_H\rangle 

<table>
<thead>
<tr>
<th></th>
<th>$\pi\pi$</th>
<th>$\omega\pi$</th>
<th>$\rho\eta$</th>
<th>$\rho\rho$</th>
<th>KK</th>
<th>$K^*K$</th>
<th>$h_1\pi$</th>
<th>$a_1\pi$</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho_{2S}(1465)$</td>
<td>74</td>
<td>122</td>
<td>25</td>
<td>-</td>
<td>35</td>
<td>19</td>
<td>1</td>
<td>3</td>
<td>279</td>
</tr>
<tr>
<td>$\rho_{1D}(1700)$</td>
<td>48</td>
<td>35</td>
<td>16</td>
<td>14</td>
<td>36</td>
<td>26</td>
<td>124</td>
<td>134</td>
<td>435</td>
</tr>
<tr>
<td>$\rho_H(1500)$</td>
<td>0</td>
<td>5</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>140</td>
<td>$\approx 150$</td>
</tr>
</tbody>
</table>

the $\pi h_1$ and $\pi a_1$ can discriminate between $\rho_{2S}$, $\rho_{1D}$ and $\rho_H$ or to disentangle the mixings

<table>
<thead>
<tr>
<th></th>
<th>$\rho\pi$</th>
<th>$\omega\eta$</th>
<th>KK</th>
<th>$K^*K$</th>
<th>$b_1\pi$</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega_{2S}(1419)$</td>
<td>328</td>
<td>12</td>
<td>31</td>
<td>5</td>
<td>1</td>
<td>378</td>
</tr>
<tr>
<td>$\omega_{1D}(1649)$</td>
<td>101</td>
<td>13</td>
<td>35</td>
<td>21</td>
<td>371</td>
<td>542</td>
</tr>
<tr>
<td>$\omega_H(1500)$</td>
<td>20</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>$\approx 20$</td>
</tr>
</tbody>
</table>

$\omega(1420) \rightarrow \pi b_1$ and $\omega(1600) \rightarrow \pi b_1$ are observed to be small so both unlikely to be pure $1^3D_1$ state implying $\omega_H$ admixture.
Production of Hybrids:

1. $J / \psi \rightarrow \gamma X$
2. $p \bar{p}$ annihilation
3. peripheral production \hspace{1cm} (Dorofeev)
4. photoproduction \hspace{1cm} (Moinester)
Peripheral production:

- LASS, E852, BENKEI, VES, GAMS

Evidence for $\hat{\rho}(1600)$ (Dunnweber, Dorofeev)

Serpukhov: $\pi^- N \to (\pi^+ \pi^- \pi^-) N$ at 40 GeV/c π beam in $\rho^0 \pi^-, \pi \eta$ and $\pi b_1$

BNL E852: $\pi^- p \to \pi^- \pi^+ \pi^- p$ at 18 GeV/c π beam signal in $\pi f_1(1285)$

Beam particle is excited and continuous to move forward exchanging momenta and quantum #’s with recoiling nucleus

eg: LASS, E852, BENKEI, VES, GAMS
• No reason a priori to expect that any type of hadron is preferred over any other in this mechanism

\( \pi \) exchange only provides access to natural parity states

• Advantage is high statistics

**E852 Results:** \( \pi^- p \rightarrow \pi^+ \pi^- \pi^- p \)

At 18 GeV/c to partial wave analysis
Results of Partial Wave Analysis

- Benchmark resonances
- Graphs showing mass versus intensity for different partial waves:
  - $0^{-+}$ (a)
  - $1^{++}$ (b)
  - $2^{-+}$ (c)
  - $2^{++}$ (d)

Resonances indicated:
- $a_1$
- $\pi_2$
- $a_2$
An Exotic Signal in E852

Leakage From Non-exotic Wave due to imperfectly understood acceptance

Correlation of Phase & Intensity

Exotic Signal

\[ M(\pi^+\pi^-\pi^-) \, \text{[GeV/c}^2\text{]} \]
Photoproduction:

Qualitative alternative to hadronic peripheral production
- series of preferred excitations is likely to be different
- strong source of ss states

Quark spins already aligned

- Production of exotic hybrids is favoured
- Almost no data is available
Compare $\pi p$ and $\gamma p$ Data

Compare statistics and shapes

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

ca. 1998 @ 18 GeV

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

ca. 1993 @ 19 GeV

SLAC

M(3$\pi$) [GeV / c$^2$]
Multiquark Mesons:

- No time to discuss but mention as another ingredient
  $f_0(980)$, $a_0(980)$ believed to be multiquark states
  $f_1(1430)$ long standing puzzle (E/1 puzzle)
  $f_J(1710)$ also open to interpretation
- Could also have multiquarks with exotic quantum #’s
- Best bets are fractional or doubly charged mesons
Summary

• The discovery and mapping out of the glueball and hybrid meson spectrum is a crucial test of QCD
• It will help validate Lattice QCD as an important computational tool for non-perturbative field theory
• It will take detailed studies to distinguish Glueball and Hybrid candidates from conventional $q\bar{q}$ states
• This will require extremely high statistics experiments
  • To measure meson properties
    • Partial widths
    • Production mechanisms
      • $t$-channel exchange
      • central production distributions
  • COMPASS is unique: It has numerous tools to do this: $\pi$, $K$, $p$, and $\mu$ beams
COMPASS can make important advances in this field

I strongly encourage you to do so