Meson spectroscopy and the ‘missing’ valence glue of QCD

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Meson spectrum

established meson states have \( J^{PC} \) quantum numbers of fermion-antifermion Fock-state, \( 0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 1^{++,} 2^{--} \ldots \), and no states with isospin > 1 or |strangeness| > 1

a reasonable interpretation is quasi-particle quarks and the gluonic ground state

QCD is non-abelian and non-perturbative at this scale, so where are the excitations of the gluonic field?

e.g. glueball spectrum in pure SU(3) Yang-Mills

potentially cleaner sector - hybrid mesons: valence quarks + excited glue

extra gluonic-field quantum numbers introduces new \( J^{PC} \) combinations

“exotic” \( 0^{--}, 0^{+-}, 1^{-+}, 2^{+-} \ldots \)
**$J^{PC}$ exotic mesons**

- alternative mechanism for $J^{PC}$ exotic is higher quark Fock state, e.g. $qqar{q}ar{q}$
- generically lead to flavour exotics - so easy to tell apart from hybrids
- lattice QCD at heavy quark masses has valence glue states with exotic $J^{PC}$

- lattice QCD at ‘lower’ quark masses has addressed the mass of the lightest $1^{-+}$ state

- extrapolation from this ‘bound-state’ region to the ‘resonance’ region not trivial, but indications are for a state in the 1.5-2.5 GeV region
- in accord with phenomenological flux-tube model
Flux-tube model

- quantum mechanical model, based on the idea that the gluonic field in a meson forms a tube between the quarks
- hybrids correspond to oscillatory excitation of tube
- prevailing model of hybrids, due somewhat to near ‘complete’ phenomenology

**spectrump**

\[ \delta m = \frac{\pi}{r} \]

\[ m_\mathcal{H} \sim 2 \text{ GeV} \]

1−+, 0++, 2++ + non-exotics

**hadronic decays**

\[ \pi_1 \rightarrow \pi \ b_1 \]

\[ \pi_1 \not\rightarrow \pi \rho \]

**photocouplings**

\[ \frac{A_\mathcal{H}}{A_C} \sim \frac{\sqrt{b}}{m_q} \sim O(1) \]
Next talk will inform you of the status of pion beam experiments.

Results have been tantalising, but inconclusive.

Photoproduction as a meson factory not previously considered.

Photocouplings (vs pion couplings) likely to lead to different weighting of meson states - new spectroscopic lever-arm.

Several arguments suggest photoproduction may be favourable for exotic hybrid mesons.
Photoproduction of exotic $J^{PC}$

- at the hadron-level, using a beam with $J^{PC} = 1^{--}$ we’d expect diffractive production of exotic $2^{+-}$
- at the quark-level, we note that the flux-tube model (and many others) have exotic hybrids with $S_{q\bar{q}} = 1$
- to the extent that spin-flip is suppressed, using a photon (virtual vector meson) beam with $S_{q\bar{q}} = 1$, is preferred to a pion beam with $S_{q\bar{q}} = 0$

- explicit calculations in the flux-tube model, coupling photons to quarks indicates hybrid photocouplings unsuppressed relative to conventional photocouplings
- conventional radiative decay rate (measured) $\Gamma(b_1^+ \to \pi^+ \gamma) = 230(80) \text{ keV}$
- exotic hybrid radiative decay rates (flux-tube model)
  - $\Gamma(\pi_1^+ \to a_2^+ \gamma) \sim 90 \text{ keV}$
  - $\Gamma(b_{0,2}^+ \to \rho^+ \gamma) \sim 2000(800) \text{ keV}$
- lattice QCD calculations of photocouplings underway at Jefferson Lab
Exotic hybrid decay widths

Several flux-tube model variants make predictions for hadronic widths

<table>
<thead>
<tr>
<th>$\Gamma_{\text{tot}}$/MeV</th>
<th>PSS (alt)</th>
<th>PSS (std)</th>
<th>PSS (2.0)</th>
<th>IKP</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi_1/\eta_1$</td>
<td>121/73</td>
<td>81/59</td>
<td>168/158</td>
<td>117/107</td>
</tr>
<tr>
<td>$b_0/h_0$</td>
<td>108/115</td>
<td>247/59</td>
<td>429/262</td>
<td>665/94</td>
</tr>
<tr>
<td>$b_2/h_2$</td>
<td>7/5</td>
<td>5/12</td>
<td>11/74</td>
<td>248/166</td>
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</tbody>
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Note that mainly these numbers are reasonably small.

Recent relevant lattice QCD result from C. Michael & C. McNeile

Compute a hadronic three-point function ‘on-shell’, e.g. $b_1 \rightarrow \omega \pi$

With $m(b_1) \approx m(\omega) + m(\pi)$

Extract an ‘on-shell’ coupling - difficulty is in extrapolation to the physical decay kinematics

Close & Burns applied flux-tube model style form-factors and found

$$\Gamma = |\vec{k}| \bar{g}^2 \left(1 - \frac{2|\vec{k}|^2}{9\beta^2}\right)^2 e^{-\frac{|\vec{k}|^2}{6\beta^2}} = 150(80) \text{ MeV}$$

Similarly for exotic decays:

$$\Gamma(\pi_1 \rightarrow b_1 \pi) \approx 70(40) \text{ MeV}$$

$$\Gamma(\pi_1 \rightarrow "f_1" \pi) \approx 20(15) \text{ MeV}$$

General large $N_c$ result from Cohen - exotic hybrid widths are same order as conventionals.
Summary

- photoproduction as a meson factory has not hitherto been explored
- it is likely to offer a different weighting to meson states to the traditional pion beam production, and may well help disentangle some confused regions of spectroscopy
- one of the most exciting possibilities is the production of exotic hybrid mesons
- flux-tube model predictions have been made, suggest healthy production rates and manageable total width
- lattice QCD now reaching the stage where phenomenologically relevant statements can be made

- a custom designed experiment coupled with a strong analysis program will realise the possibilities in photoproduction

GlueX