The XYZ’s of cc: Hints of Exotic New Mesons?

Steve Godfrey
Carleton University
FPCP 2006, Vancouver, April 10 2006
• Spectroscopy: Conventional and Hybrids

• New Charm States
  • $D_{sJ}^*(2317)$, $D_{sJ}(2460)$, $D_{sJ}(2630)$
  • $D_0^*(2308)$, $D_1'(2440)$,

• New Charmonium states
  • $X(3872)$, $X(3943)$, $Y(3943)$, $Z(3931)$ and $Y(4260)$

• Summary
General Remarks about Spectroscopy

Meson quantum numbers characterized by given $J^{PC}$:

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

For given spin and orbital angular momentum configurations & radial excitations generate the meson spectrum

$$V(r) = -\frac{4}{3} \alpha_s(r) \frac{1}{r} + br$$

The XYZ’s of cc
Spin-dependent potentials:

- Lorentz vector 1-gluon exchange + scalar confinement
- Spin-dependent interactions are \((v/c)^2\) corrections

Spin-spin interactions:

\[
H_{ij}^{bap} = \frac{4\alpha_s(r)}{3m_i m_j} \left\{ \frac{8\pi}{3} \vec{S}_i \cdot \vec{S}_j \delta^3(\vec{r}_{ij}) + \frac{1}{r_{ij}^3} \left[ \frac{3\vec{S}_i \cdot \vec{r}_{ij} \vec{S}_j \cdot \vec{r}_{ij} - \vec{S}_i \cdot \vec{S}_j}{r_{ij}^2} \right] \right\}
\]

\[1S \quad 1^3S_1 J/\psi \]

\[1^1S_0 \eta_c \]

Spin-orbit interactions:

\[
H_{ij}^{s.o.(cm)} = \frac{4\alpha_s(r)}{3r_{ij}^3} \left( \frac{1}{m_i} + \frac{1}{m_j} \right) \left( \frac{\vec{S}_i}{m_i} + \frac{\vec{S}_j}{m_j} \right) \cdot \vec{L}
\]

\[
H_{ij}^{s.o.(tp)} = -\frac{1}{2r_{ij}} \frac{\partial V(r)}{\partial \vec{r}_{ij}} \left( \frac{\vec{S}_i}{m_i^2} + \frac{\vec{S}_j}{m_j^2} \right) \cdot \vec{L}
\]

\[1P \]

\[\chi_2(1^3P_2) \]

\[\chi_1(1^3P_1) \]

\[\chi_0(1^3P_0) \]
**Strong Decays**

The $^3P_0$ decay model describes hadron decays reasonably well.

Important to understand charmonium states to identify states that don't fit and might represent new spectroscopies.
Quarks move in adiabatic potentials.
Lowest excited adiabatic surface corresponds to transverse excitations.
Doubly degenerate lowest mass hybrids:
\[ J^{PC} = 0^{-+} 0^{-} 1^{-+} 1^{-} 2^{-+} 2^{-} 1^{++} 1^{--} \]

T. Barnes, F. E. Close, and E. S. Swanson

<table>
<thead>
<tr>
<th>State</th>
<th>mass (GeV)</th>
<th>Model</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H_c )</td>
<td>( \approx 3.9 )</td>
<td>Adiabatic bag model</td>
<td>[20]</td>
</tr>
<tr>
<td></td>
<td>4.2–4.5</td>
<td>Flux tube model</td>
<td>[12–14]</td>
</tr>
<tr>
<td></td>
<td>4.1–5.3</td>
<td>QCD sum rules (most after 1984)</td>
<td>[26–28]</td>
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<tr>
<td></td>
<td>4.19(3) ± syst.</td>
<td>HQLGT</td>
<td>[23]</td>
</tr>
</tbody>
</table>
**Hybrids Decays**

Important decay modes:

1. \( \psi_g \rightarrow D(\ast,\ast) \bar{D}(\ast,\ast) \)
   - Hybrid decays to P-wave + S-wave mesons:
     - \( D(L=0) + D^{**}(L=1) \) should dominate
     - \( DD \) should not occur and \( DD^* \) have small widths

2. \( \psi_g \rightarrow (c\bar{c})(gg) \rightarrow (c\bar{c}) + (\pi\pi, \eta, \ldots) \)
   - Offers cleanest signature
   - IF total width small significant BR
     - \( \psi_g(0^{+-}, 2^{+-}) \rightarrow J/\psi + (\pi\pi, \eta) \)
     - and \( \psi_g(1^{++}) \rightarrow \eta_c + (\pi\pi, \eta) \)
     - LGT (UKQCD) finds these decays to be large
       \(~\sigma(10's \text{ MeV})\)
   (shown for \( \chi_bS \) where \( S \) is light scalar)  
   [hep-lat/0201006]
Some other new states:

\[ \Upsilon(1D) \]

\[ M = 10161.1 \pm 0.6 \text{(stat)} \pm 1.6 \text{(syst)} \text{ MeV} \]
In agreement with potential models and Lattice QCD

\[ B_c \]
CDF: hep-ex/0505076

\[ M = 6287.0 \pm 4.8 \text{(stat)} \pm 1.1 \text{(syst)} \text{ MeV}/c^2 \]
vs 6304 \pm 12 (stat+syst) Lattice
6271 quark potential model

\[ \eta_c' \]

\[ M = 3637.4 \pm 4.4 \text{ vs 3623 in quark potential model} \]

\[ h_c \]

\[ M = 3524.4 \pm 0.6 \text{(stat)} \pm 0.4 \text{(syst)} \text{ MeV}/c^2 \]
\[ M(3P_J) - M(1P_1) = 1.0 \pm 0.6 \text{(stat)} \pm 0.4 \text{(syst)} \]
D_{sJ} (2317) & D_{sJ} (2460)

BABAR:

\( M = 2316.8 \pm 0.4 \text{ MeV} \)
\( \Gamma \leq 3.8 \text{ MeV} \)

Also seen and studied by BELLE
Properties consistent with \( J^P = 0^+ \) and \( 1^+ \)

CLEO:

\( M = 2463 \pm 0.4 \text{ MeV} \)
\( \Gamma \leq 3.5 \text{ MeV} \)

(Widths from Gowdy, Moriond talk)
$j_q=1/2$ predicted to be broad and decay to $DK$ and $D^*K$ not previously observed

But $D_{sJ}^*(2317)$ below $DK$ threshold and very narrow!
$D_{sJ}(2460)$ below $D^*K$ threshold and very narrow!
Created major industry: (almost 300 citations!)

- Multiquark state
- Molecular state
- $D_\pi$ atom
- Conventional $cs$ state but model needs improvement

The problem is the mass predictions

Once the masses are fixed the narrow widths follow
Radiative transitions are expected to have large BR's so their measurement is an important probe.

\[ B(D_{sJ}(2460)^- \rightarrow D_s^*\pi^0) = 0.51 \pm 0.11 \pm 0.09 \]

\[ B(D_{sJ}(2460)^- \rightarrow D_s^-\gamma) = 0.15 \pm 0.03 \pm 0.02 \]  

Preliminary

Gowdy (Babar)  
Moriond talk

\[ B(D_{sJ}(2460)^+ \rightarrow D_s^+\pi^+\pi^-) = 0.04 \pm 0.01 \text{ (stat. only)} \]

Where does the other (30 \pm 15)\% go?

Recall:  
\[ D_{s1}^{1/2} = -P_1 \sin \theta + 3P_1 \cos \theta \]

So \[ D_{s1}(2463) \rightarrow D_s^*\gamma \] is where it goes

Can be used to determine mixing angle

\[ \frac{\Gamma(3P_1 \rightarrow 3S_1 + \gamma)}{\Gamma(1P_1 \rightarrow 1S_0 + \gamma)} = \frac{\omega_t^3}{\omega_s^3} \left| \langle r \rangle_t \right|^2 \frac{\cos^2 \theta}{\sin^2 \theta} \]

Appears to be conventional cs L=1 states with masses shifted due to strong S-wave coupling to DK(*)
Charmed mesons:

• Almost all the theoretical effort has concentrated on the $D_{sJ}$ states
• But important to test the models on the D states which also contain important information

<table>
<thead>
<tr>
<th>Decay</th>
<th>Expt*</th>
<th>Theory</th>
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<tbody>
<tr>
<td>$D_2^* \rightarrow D^*\pi$</td>
<td>$43.8 \pm 2$</td>
<td>55</td>
</tr>
<tr>
<td>$D_2^* \rightarrow D^*\pi$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$D_1 \rightarrow D^*\pi$</td>
<td>20.3</td>
<td>25</td>
</tr>
<tr>
<td>$D_1 \rightarrow D^*\pi$</td>
<td>339 $\pm$ 76</td>
<td>244</td>
</tr>
<tr>
<td>$D_0^* \rightarrow D\pi$</td>
<td>276 $\pm$ 66</td>
<td>277</td>
</tr>
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</table>

* Average of PDG Belle PR D69 112002 (2004)
CLEO NPA 663, 647 (2000)
CDF JP Conf Ser 9, 67 (2005)
First Observation of a Narrow Charm-Strange Meson $D_{sJ}(2632) \rightarrow D_s^+ \eta$ and $D^0 K^+$
(The SELEX Collaboration)


Seen in hadro-production in $M=2632.6\pm1.6$ MeV/c$^2$ $\Gamma<17$ MeV/c$^2$ at 90% C.L.

$\Gamma(D^0 K^+) / \Gamma(D_s^+ \eta) = 0.16 \pm 0.06$

(Not seen by CLEO, Belle, Babar)
Possibilities:

• $2^3S_1(cs)$ State
• cs Hybrid
• 2-meson molecule

cs hybrid expected to be $\sim 3170$ MeV

Most plausible cs state is $2^3S_1$ with $M(2^3S_1)=2730$ MeV
& $M(1^3D_1)=2900$ MeV

masses could be shifted by mixing with 2-meson continuum
Assuming the $D_{sJ}(2632)$ is $2^3 S_1(c\bar{s})$ with $M=2632$

The allowed open-flavour decay modes are: $DK$, $D_s \eta$, $D^* K$

SELEX finds:

$$BR(DK / D_s \eta) = 0.32 \pm 0.12$$ \hspace{1cm} (assuming $BR(D^0 K^+) = BR(D^{+} K^0)$)

In $^3P_0$ model for preferred expect:

$$\Gamma(D^* K) > \Gamma(DK) >> \Gamma(D_s \eta)$$

$$\Gamma(D_{sJ}(2632)) = 36 \text{ MeV}$$

$$\Gamma(DK) / \Gamma(D_s \eta) \approx 9$$

Not consistent with experiment
It is possible to tune model to achieve agreement with experiment

But this tuning seems unlikely

\textbf{SELEX D}_{sj}(2632) state:}

1. Needs confirmation

2. If $2^{3}S_{1}$ state expect to see D$^{*}\text{K}$ decay mode

3. Should see the $2^{3}S_{1}$ in B decays

4. The $1^{3}D_{1}$ state should be $\sim 200$ MeV higher in mass
Possible new C=(+) cc states at these masses!

2P or not 2P that is the question!
X(3940)

Seen by Belle recoiling against $J/\psi$ in $e^+e^-$ collisions

$M=3943 \pm 6 \pm 6$ MeV

$\Gamma < 52$ MeV

$BR(X \rightarrow DD^*) = 96^{+45}_{-32} \pm 22\%$

$BR(X \rightarrow DD) < 41\%$ (90% CL)

Suggests unnatural parity state

$BR(X \rightarrow \omega J/\psi) < 26\%$ (90% CL)

• Decay to DD* but not DD suggests unnatural parity state
• Belle speculates that X is $3^1S_0$ given the $3^3S_1 \psi(4040)$
  • Mass is roughly correct
  • $\eta_c$ and $\eta'_c$ are also produced in double charm production

• Predicted width for $3^1S_0$ with $M=3943 \sim 50$ MeV close to $\Gamma(X(3943))$ upper bound

• Identification of $\psi(4040)$ as $3^3S_1$ state implies hyperfine splitting 88 MeV with X(3943)

• Larger than the 2S splitting and larger than predicted in potential models
• Discrepancy could be due to:
  • Difficulty in fitting true pole position of $3^3S_1$ state
  • Nearby thresholds with s-wave + p-wave charm mesons so possibly stronger threshold effects

See also Eichten Lane Quigg PRD73 014014(2006)
• Another possibility due to dominant DD* mode is the $2^3P_1 \chi_1'$

• Natural to try 2P cc assignment since
  \[ M(2^3P_J) = 3920-3980 \text{ MeV} \]
  \[ \Gamma(2^3P_J) = 30-165 \text{ MeV} \]

• If DD* mode is dominant suggests X(3940) is $2^3P_1$

• Problems: - No evidence for $1^3P_1$ in the same data
  - $\Gamma(2^3P_J) = 135 \text{ MeV}$ (for $M=3943 \text{ MeV}$)
  - Y(3943) also a candidate for $2^3P_1 \chi_1'$

Test of $3^1S_0 \eta_c$ assignment is search for this state in $\gamma\gamma \rightarrow DD^*$
\( \gamma(3940) \)

See in \( \omega \gamma / \psi \) subsystem of the decay \( B \rightarrow K \pi \pi \pi \gamma / \psi \)


\[ M=3943 \pm 11 \pm 13 \text{ MeV} \]
\[ \Gamma =87 \pm 22 \pm 26 \text{ MeV} \]

Not seen in \( Y \rightarrow DD \) or \( DD^* \)

Mass and width suggest radially excited P-wave charmonium

But \( \omega \gamma / \psi \) decay mode is peculiar:

\[ \text{BR}(B \rightarrow KY) \text{ BR}(Y \rightarrow \omega \gamma / \psi)=7.1 \pm 1.3 \pm 3.1 \times 10^{-5} \]

where one expects \( \text{BR}(B \rightarrow K \chi'_{cJ})< \text{BR}(B \rightarrow K \chi_{cJ})= 4 \times 10^{-4} \)

Implies \( \text{BR}(Y \rightarrow \omega \gamma / \psi) > 12\% \) which is unusual for state above open charm threshold
• Large width to $\omega J/\psi$ led Belle to suggest $Y(3943)$ might be hybrid

• But mass is 500 MeV below LGT estimates making hybrid assignment unlikely

• Possibility is $2^3P_1$ cc state: identifies $Y(3943)$ as $2P \chi'_{c1}$
  • $DD^*$ is the dominant decay mode
  • Width consistent with $Y(3943)$: $\Gamma = 135$ MeV
  • $\chi_{c1}$ is seen in B decays

• $1^{++} \rightarrow \omega J/\psi$ is unusual
  • but corresponding $\chi'_{b1,2} \rightarrow \omega Y(1S)$ also seen
  • Maybe rescattering: $1^{++} \rightarrow DD^* \rightarrow \omega J/\psi$
  • Maybe due to mixing with $1^{++}$ molecular state $X(3872)$?

• Important to - look for DD and $DD^*$
  - study angular distributions to DD and $DD^*$
Z(3930)

- Observed by Belle in $\gamma \gamma \rightarrow D D$
  - $M = 3929 \pm 5 \pm 2$ MeV
  - $\Gamma = 29 \pm 10 \pm 2$ MeV

- Two photon width:
  - $\Gamma_{\gamma \gamma} \cdot B_{DD} = 0.18 \pm 0.05 \pm 0.03$ keV

- DD angular distribution consistent with $J=2$

- Below $D^* D^*$ threshold

• Obvious candidate for $\chi'_c{}^2$ (the $\chi'_c{}^1$ cannot decay to DD)

  • Predicted $\chi'_c{}^2$ mass is 3972
  $\Gamma(\chi'_c{}^2 \to DD) = 21.5$ MeV
  $\Gamma(\chi'_c{}^2 \to DD^*) = 7.1$ MeV
  $\Gamma = 47$ MeV assuming $M(\chi'_c{}^2) = 3931$

• In reasonable agreement with experiment

  • Predicted $BR(\chi'_c{}^2 \to DD) = 70\% \implies \Gamma_{\gamma\gamma} B_{DD} = 0.47$ keV
    ($\Gamma_{\gamma\gamma}$ from T. Barnes, IXth Intl. Conf. on $\gamma\gamma$ Collisions, La Jolla, 1992.)

• Observed two-photon width about 1/2 predicted value for $\chi'_c{}^2$
• No reason not to believe that $Z(3930)$ is not the $\chi'_{c2}$

• Another possibility is $\chi'_{c0}$ (unlikely due to angular distributions)

• Can confirm $\chi'_{c2}$ by searching for $DD^*$
  $\chi'_{c0}$ only decays to $DD$
  $\chi'_{c2}$ decays to $DD$ and $DD^*$ in ratio of $DD^*/DD \sim 1/3$

• Largest radiative transition is $\Gamma(\chi'_{c2} \to \gamma \psi') \sim 200$ keV vs $\Gamma(\chi'_{c0} \to \gamma \psi') \sim 130$ keV
  (ELQ find decays are suppressed due to coupled channel effects PRD73 014014(2006))
Could further study $2^3P_J$ states via radiative transitions:

Can find all three $^32P_J$ cc states using

$$\psi(4040) \text{ and } \psi(4160) \rightarrow \gamma DD, \gamma DD^*$$

All three E1 rad BF s of the $\psi(4040)$ are $\sim 0.5 \times 10^{-3}$.

These would further test whether the $Z, X, Y (3.9)$ are $2P$ cc
New state 1st observed by Belle: $X(3871)$


Confirmed by: CDF


$D^0\bar{D}^*$ molecule

$D^0D^*$ molecule

$A$ charmonium hybrid

$P_J$ $1^3D_2$ state?

Glueball?

$M=3872.0 \pm 0.6 \pm 0.5$ MeV

$\Gamma < 2.3$ MeV at 90% C.L.

Width consistent with detector resolution.
Consider the charmonium possibilities:

1D and 2P multiplets only states nearby in mass

\[ 1^3D_2 \quad 1^3D_3 \quad 2^1P_1 \] have \( C = - \)

\[ 1^1D_2 \quad 2^3P_0 \quad 2^3P_1 \quad 2^3P_2 \] have \( C = + \)

But \( X(3872) \rightarrow \gamma J/\psi \) implies \( C = + \)

Belle [hep-ex/0505037]
Babar Gowdy Moriond talk

Angular distributions favour \( J^{PC} = 1^{++} \)

The unique surviving charmonium candidate is \( 2^3P_1 \)

BUT identification of \( Z(3931) \) with \( 2^3P_2 \)

implies 2P mass \( \sim 3940 \text{ MeV} \)

\( D^0 D^{*0} \) molecule or "tetraquark"

is a popular/likely explanation: see Voloshin
\textbf{Y(4260)}

Discovered by Babar as enhancement in $\pi\pi J/\psi$ subsystem in $e^+e^- \rightarrow \gamma_{\text{ISR}} \psi \pi\pi$

PRL 95, 142001(2005) [hep-ex/0506081]

$M = 4259 \pm 8 \pm 4$ MeV

$\Gamma = 88 \pm 23 \pm 5$ MeV

$\Gamma_{ee} \times \text{BR}(Y \rightarrow \pi^+\pi^- J/\psi) = 5.5 \pm 1.0 \pm 0.8$ eV

ISR production tells us $J^{PC} = 1^{--}$

Further evidence in $B \rightarrow K(\pi^+\pi^- J/\psi)$ PR D73, 011101(2006)

Confirmed by CLEO

hep-ex/0602034
The first unaccounted $1^{-}$ state is the $\psi(3D)$.

Quark models estimate $M(\psi(3D)) \sim 4500$ MeV much too heavy for the $Y(4260)$.

$Y(4260)$ represents an overpopulation of expected $1^{-}$ states.

Absence of open charm production also against conventional $cc$ state.

Other explanations are:

- $\psi(4S)$
  - Phys Rev D72, 031503 (2005)

- Tetraquark
  - Phys Rev D72, 031502 (2005)

- $cc$ hybrid
  - Phys Lett B625, 212 (2005);
Y(4260): Hybrid?

• Flux tube model predicts lowest cc hybrid at 4200 MeV

• LGT expects lowest cc hybrid at 4200 MeV [Phys Lett B401, 308 (1997)]

• Models of hybrids say Ψ(0)=0 so would have small e⁺e⁻ width

• LGT found bb hybrids have large couplings to closed flavour modes
  • Similar to BaBar observation of $Y \rightarrow \pi^+\pi^-J/\psi$:
    $\text{BR}(Y \rightarrow \pi^+\pi^-J/\psi) > 8.8\%$
    $\Gamma(Y \rightarrow \pi^+\pi^-J/\psi) > 7.7 \pm 2.1 \text{ MeV}$

• Much larger than typical charmonium transitions:
  $\Gamma(\psi(3770) \rightarrow \pi^+\pi^-J/\psi) \approx 80 \text{ keV}$

• Y is seen while $\psi(4040)$, $\psi(4160)$ $\psi(4415)$ are not
How to test Y(4260) hybrid assignment:

Decays:

• LGT study suggest searching for other closed charm modes with \( J^{PC}=1^- \)
  \( J/\psi \eta, J/\psi \eta', \chi_{J}\omega \ldots \)

• Models predict the dominant hybrid charmonium open-charm decay modes will be a meson pair with
  S-wave (D, D*, D_s, D_s*) + P-wave (D_J, D_{sJ})

• The dominant decay mode expected to be \( D+D_1(2430) \)
  \( D_1(2420) \) has width \( \sim 300 \) MeV and decays to \( D^*\pi \)
  • Suggests search for \( Y(4260) \) in \( DD^*\pi \)
  
• Evidence of large \( DD_1(2430) \) signal would be strong evidence for hybrid

• But models of hybrids are untested so to be cautious

• If seen in other modes like \( DD^*, D_sD_s^* \) comparable to \( \pi^+\pi^-J/\psi \)
  maybe still hybrid but decay model not accurate
Search for Partner States: (fill in the multiplet)

• Mass ca. 4.0 - 4.5 GeV, with LGT preferring the higher range.
  (e.g.: X.Liao and T.Manke, hep-lat/0210030)

• Confirm that no cc states with the same $J^{PC}$ are expected at this mass.

• Identify $J^{PC}$ partners of the hybrid candidate nearby in mass.

• The most convincing evidence:
  • partners, especially $J^{PC}$ exotics.

• The f-t model expects:
  $0^{++}, 1^{--}, 2^{--}, 0^{--}, 1^{++}, 2^{--}, 1^{++}, 1^{--}$
Summary

Many new results, considerable progress!

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<td>$X(3872)$</td>
<td>Molecule? - see Voloshin</td>
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<td>$X(3943)$</td>
<td>$\eta''_c(3^1S_0)$ - look for $\gamma\gamma \rightarrow DD^*$</td>
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<td>$Y(3943)$</td>
<td>$\chi'_{c1}(2^3P_1)$ - look for $DD$ &amp; $DD^*$</td>
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<tr>
<td>$Z(3930)$</td>
<td>$\chi'_{c2}(2^3P_2)$ - confirm by $DD^*$</td>
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<tr>
<td>$Y(4260)$</td>
<td>Hybrid?</td>
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• Much more to learn; ie search for $1^3D^2 1^3D 1^1D 1^3F^2 1^3F^4$

Thank experimentalists for all the wonderful results they’re providing