Suppressed decay into open charm for the $Y(4260)$ being a hybrid

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Outline

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1. Introduction: Is $Y(4260)$ hybrid?
2. Suppression mechanism of a hybrid decaying into $D\bar{D}$
3. Can the other $XY...$ be hybrid?
4. Conclusions

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What is $Y(4260)$?

- A resonance observed in initial-state radiation process $e^+e^- \rightarrow (\gamma_{\text{IR}})\pi^+\pi^-J/\psi$ Babar collab., PRL 95 (2005)

- Mass $4260$ MeV (just below $D_s\bar{D}_s^*$ and $D^*\bar{D}^{**}$) and width $88 \pm 23^{+2}_{-6}$ MeV

- $125 \pm 23$ events ($8\sigma$ signal) yielding $\Gamma(Y(4260) \rightarrow e^+e^-)Br(Y(4260) \rightarrow \pi^+\pi^-J/\psi) = (5.5 \pm 1.0^{+0.8}_{-0.7})$ eV

- Also found in $B^\pm \rightarrow K^\pm\pi^+\pi^-J/\psi$ decays ($3.1\sigma$ signal) Babar collab., hep-ex/0507090.

- Decays to $D^{(*)}\bar{D}^{(*)}$ are suppressed?
What is $1^{−−}$ hybrid meson?

$$(q\bar{q})+\text{constituent gluon}$$

$P = (-1)^{l_g+l_{cc}} \quad C = (-1)^{l_{cc}+s_{cc}}+1$

Unnatural parity is possible e.g. ($0^{+-}, 1^{--}, 2^{+-}$)

$\triangleright$ The $1^{−−}$ meson can be composed in two ways, $(l_g, l_{cc}, s_{cc}) = (0, 1, 1)$ or by $(1, 0, 0)$.

$\triangleright$ The state $(l_g, l_{cc}, s_{cc}) = (0, 1, 1)$ has been excluded due to its strong coupling to the continuum $D(\ast)\bar{D}(\ast)$ (the width exceeds 1 GeV). F. Iddir, S. Safir and O. Pene, PLB (1998)

$\triangleright$ Thumb rule for the mass $M_{cc} + M_g + M_{excited} \simeq (3.0 + (0.7 \sim 1) + 0.4$ GeV. (→ interesting challenge for lattice, see e.g. S. Perantonis and C. Michael, NPB (1990)).
Why $D\bar{D}$ is suppressed for $1^{--}$?

<table>
<thead>
<tr>
<th>$P$</th>
<th>S-wave</th>
<th>P-wave</th>
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<tbody>
<tr>
<td>$D\bar{D}$</td>
<td>$+$</td>
<td>$-$</td>
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<tr>
<td>$DD^*$</td>
<td>$+$</td>
<td>$-$</td>
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<tr>
<td>$D^<em>\bar{D}^</em>$</td>
<td>$+$</td>
<td>$-$</td>
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Similar results for charge conjugation and $D_s$ states.

- Decays to $D\bar{D}$ are suppressed by the total spin conservation.
- Decays to $D^{(*)}\bar{D}^*$ (in P-wave) are forbidden by the spacial sum-rule.
- Decays to $D^{**}\bar{D}^{(*)}$ are actually allowed (I will discuss about this later on...).
Selection rule for hybrid decays

Spacial symmetry forbids \((l_g, l_{\bar{c}c}, s_{\bar{c}c}) = (1, 0, 0)\) decaying into any two S-wave final states.

The proof of this selection rule using the chromo-harmonic model, see e.g.
(→ I will present a simple demonstration.)
1−− hybrid in chromo-harmonic Model

\[ H = \sum_{i=c,\bar{c},g} \frac{p_i^2}{2m_i} + b_0 \sum_a [T_{c}^a T_{\bar{c}}^a (r_c - r_{\bar{c}})^2 + T_{g}^a T_{c}^a (r_g - r_{c})^2 + T_{g}^a T_{c}^a (r_g - r_{c})^2] \]

The solution of the Schrödinger Equation yields:

\[ \Psi_{l_i}^{m_i}(p_i) = \sqrt{\frac{16\pi^3 R_i^{2l_i+3}}{\Gamma(\frac{3}{2} + l_i)}} p_i^{l_i} Y_{m_i}^{l_i}(\theta, \Omega) e^{-\frac{1}{2}R_i^2 p_i^2} \]

where the lower index \( i = c\bar{c}, g \) represents the \( c - \bar{c} \) system and gluon-\( c\bar{c} \) system, respectively. The radial part of the solutions are obtained as:

\[ R_{c\bar{c}}^2 = \frac{1}{\sqrt{2\mu_{c\bar{c}} \left( \frac{7b_0}{12} \right)}} \quad R_g^2 = \frac{1}{\sqrt{2\mu_g (-3b_0)}} \]

Using \( m_c = m_{\bar{c}} = 1.7 \) GeV, \( m_g = 0.8 \) GeV, we obtain

\[ \frac{R_g^2}{R_{c\bar{c}}^2} \approx 0.51, \quad \frac{\omega_g}{\omega_{c\bar{c}}} \approx 2.6 \]

Large string tension between \( c\bar{c} \) and \( g \rightarrow \) two color-octet!
Suppression of two $S$-wave final states

The spatial overlap of $H_B \rightarrow D\bar{D}$ can be written in terms of three independent parameters $\pm p_f$ ($D(\bar{D})$ meson mom.), $p_{c\bar{c}}$ (reltv. mom. between $c - \bar{c}$), $k$ (reltv. mom. between $c\bar{c} - g$)

$$I = \int \frac{dp_{c\bar{c}}^- dp_{c}\bar{c}{k}}{\sqrt{2\omega(2\pi)^6}} d\Omega_f \begin{vmatrix} \psi_{l_H}^m(p_{c\bar{c}}, k) \\ \psi_{l_B}^{m_B}*(p_B) \psi_{l_C}^{m_C}*(p_C) \end{vmatrix} Y_{l}^m*(\Omega_f)$$

Let us consider the change of variable

$$\vec{k} \rightarrow -\vec{k} \quad \rightarrow (\vec{p}_B \leftrightarrow -\vec{p}_C).$$

- The hybrid wave function is odd in $k$ since $l_g = 1$.
- In the case of $S$-wave final mesons, the wave functions are even in $p_B$ and $p_C$. Thus, their product remains unchanged.
- The spherical harmonic function $Y_{l}^m*(\Omega_f)$ is a function of the unit vector $\hat{p}_f$ and is thus unchanged.

The decay $H_B \rightarrow D^*(\bar{D}^*)$ is forbidden in any potential model.
Allowed decays of $1^{--}$ hybrid

- Main decay channel

Hybrid, $0^{-+}$ colour-octet $c\bar{c}$ state with a magnetic gluon, decays into $1^{--}$ charmonium and $0^{++}$ two-gluon state which decays into $0^{++}$ two-pion.

- $D^{(*)}\bar{D}^{*}$ may occur from the mixing of hybrid to excited states of S-wave charmonium though this effect would be small.

- $D^{*}\bar{D}^{*}$ is not forbidden! We expect decay process such as $Y(4260) \rightarrow D^{(*)}\bar{D}^{(*)}\pi$'s.
Relevance to $X(3872)$ and $Y(3940)$

$X(3872)$: quantum number most likely $1^{++}$

$\rightarrow$ Can it be $1^{++}$, e.g. $(l_g, l_{c\bar{c}}, s_{c\bar{c}}) = (1, 1, 0)$ hybrid? Difficult, as long as the large isospin breaking effect remains.

$Y(3940)$

$\rightarrow$ Possible but we need to know the quantum number first. According to lattice computation, e.g. $0^{+-}, 1^{+-}, 1^{++}$ are heavier than $1^{--}$ in general.
Conclusions

- We have argued that the recently observed $Y(4260)$ shows peculiar characteristics possessed by a hybrid state; an octet $0^{-+} c\bar{c}$ state and gluon in a $P$-wave (a magnetic gluon).
- We presented that the symmetries of the wave functions forbid the decay of this hybrid meson into two $S$-wave open charm final mesons in any potential model.
- We showed that the observation channel $Y(4260) \rightarrow J/\psi \pi \pi$ can be naturally explained by hybrid and at the same time we expect decays such as $Y(4260) \rightarrow D^{**} \overline{D}^* \rightarrow D^*\overline{D}^*\pi'$s via a virtual $D^{**}$. 
The spacial overlap can be written as:

\[
I = \int \frac{dp_{\bar{c}c}^- d\vec{k}}{\sqrt{2\omega(2\pi)^6}} d\Omega_f \psi_{l_H}^{m_H}(\vec{p}_{\bar{c}c}, \vec{k}) \psi_{l_B}^{m_B}* (\vec{p}_B) \psi_{l_C}^{m_C}* (\vec{p}_C) Y_{l}^{m}*(\Omega_f)
\]

where

\[
Y_{l}^{m}*(\Omega_f)
\]

is the orbital momenta between the two final mesons.

In the c.m.s. of the hybrid meson, we have

\[
\begin{align*}
\vec{p}_{\bar{c}c} &= \vec{p}_{q\bar{q}} - \vec{p}_f, \\
\vec{p}_B(C) &= \pm \frac{mqp_f}{m_q + m_c} \pm \vec{p}_{q\bar{q}} - \frac{\vec{k}}{2}
\end{align*}
\]

where

- \(\pm p_f\); momentum of final mesons (with \(q\) and \(\bar{q}\))
- \(p_{q\bar{q}}\); relative momentum between final state light quarks
- \(k\); relative momentum between gluon and \(c\bar{c}\) state