Gluonic charmonium resonances at BaBar and Belle?

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Abstract

We confront predictions for hybrid charmonium and other gluonic excitations in the charm region with recently observed structures in the mass range above 3 GeV. The Y(4260), if resonant, is found to agree with expectations for hybrid charmonium. The possibility that other gluonic excitations may be influencing the data in this region is discussed.

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1 Introduction

In a series of papers since 1995 we have defined the properties of gluonic hybrid charmonium and developed a strategy for producing and identifying such states [1, 2, 3, 4, 5, 6, 7, 8]. In this paper we compare these predictions with recently observed structures in the mass region above 3 GeV. We shall argue that the $Y(4260)$, if resonant, has properties consistently in line with our historical predictions.

Our starting point is that four recent experiments have reported the discovery of broad states consistent with charmonia: $Y(3940)$ seen in $J/\psi\omega$ [9], $X(3940)$ seen in $D^*\bar{D}$ [10], $\chi_{c2}(3930)$ [11] and $Y(4260)$ [12]. (The inclusion of charge-conjugated reactions is implied throughout this paper.) Furthermore there are also three prominent enhancements $X$ in $e^+e^- \rightarrow J/\psi + X$ [10], which are consistent with being the $\eta_c$, $\eta'_c$, and $\chi_0$.

In this paper we address the question of whether any of these states may signal the excitation of gluonic degrees of freedom in the charmonium regime.

(i) The $Y(3940)$ has been supposed to be hybrid charmonium [9]: we critically assess this claim.

(ii) By contrast, the $Y(4260)$ [12] has mass, width, production and decay properties, all in accord with those that we predicted historically for hybrid charmonium.

(iii) The prominent enhancements $X$ seen in $e^+e^- \rightarrow J/\psi + X$ [10]: We suggest that these states be studied further as their production may be strongly affected by $C^+=+$ glueballs predicted to occur in this range, and there are prima facie inconsistencies with simply associating them with known $c\bar{c}$ states.

We open with some brief remarks about points (iii) and then (i); the main thrust of this paper will be to discuss in detail the evidence related to the hybrid charmonium hypothesis, point (ii).

In pQCD the amplitude for $e^+e^- \rightarrow J/\psi + c\bar{c}$ is the same order as $e^+e^- \rightarrow J/\psi + gg$ and has led to the suggestion [13] that $C^+=+$ glueballs could be produced at a significant level. Although the coupling of such states to light flavours may give them large widths, and make a simple glueball description naive, it is nonetheless possible that their presence may enhance the production of $c\bar{c}$ states with the same $J^{PC}$. We note that in lattice QCD gluonic activity in the $0^{-+}$ channel is predicted $\sim 3.6$ GeV [14], which is potentially degenerate with the mass for the $\eta_c(2S)$ [15]. Note there are potentially different masses obtained for the state in electromagnetic ($\gamma\gamma$) and $B \rightarrow K\eta_c$ decays [15]; thus it is possible that different production mechanisms expose the presence of non-trivial mixing between the $c\bar{c}$ and gluonic sectors here. Lattice QCD also predicts activity in the gluonic waves $1^{++}$, $1^{-+}$, $2^{-+}$
and $3^{++}$ in this mass region [14]. We advocate that until careful spin-parity analysis is done, one should be cautious about identifying these enhancements naively with $c\bar{c}$ states.

Indeed, there are already some potential problems with the specific fits to $e^+e^- \rightarrow J/\psi + X$ in Ref. [10], which assigns the resonance bumps on the basis of the masses of states in the PDG [16]. As a result they identify $\chi_0$ but no prominent $\chi_{1,2}$, though there may be room for these states in the small fluctuations around $3.5 - 3.6$ GeV in Fig. 1 of Ref. [10]. The Born cross-sections containing more than two charged tracks are approximately for $X = \eta_c$ : $25.6$ fb; $\chi_0$ : $6.4$ fb; $\eta_c'$ : $16.5$ fb [17] and $X(3940)$ : $10.6$ fb [10].

There is no sign of the $X(3872)$; this state now appears to have $C = +$ and be consistent with $1^{++}$ [18]. This $J^{PC}$ was first suggested in Ref. [19] and a dynamical picture of it as a quasi-molecular $D^{*0}\bar{D}^0$ state discussed in Refs. [19, 20]. The suppression of this state among prominent $C = +$ charmonium states [10] may thus be consistent with its molecular versus simple $c\bar{c}$ nature.

A natural first guess is to associate the $X/Y(3940)$ with radially excited $2P$ charmonium. In $\gamma\gamma$ production the radial charmonium $\chi_2(3930)$ has now been reported [11], which gives a benchmark for comparing the other novel states. The nearness of $X(3940)$ and $Y(3940)$ to the $\chi_{c2}(3930)$ suggests that these state(s) are consistent with radially excited P-wave charmonia which are predicted in that mass region. In particular, decays to $J/\psi \omega$ and $D^{*}\bar{D}$ with absence of $D\bar{D}$ are consistent with these two states being the same and identified as being $2P(3P_1)$. This assignment has the advantage that the phase-space limited $J/\psi \omega$ mode is in S-wave, while another possibility, $0^{-+}$, does not share this feature.

It is possible that the effect of nodes in the wavefunctions of radially excited states could cause an accidental suppression of $D\bar{D}$, for example in $2P(3P_0)$ and confuse the identification of excited charmonium states; this seems unlikely if the results of Ref. [21] are a guide. However, the absence of a prominent $\chi_1$ state in the data advises caution in identifying the prominent $X/Y(3940)$ as solely the radially excited $2P(3P_1)$ state. If one interprets $e^+e^- \rightarrow J/\psi + X$ as a measure of the cross section for $X (C = +)$, then the meson pair production thresholds with $C = +$ are opening in relative S-waves in this mass region and some of the structure may reflect the opening of such channels rather than being simply resonant. Angular distributions of, for example, $D\bar{D}$, $D^{*}\bar{D}$ and $D^{*}\bar{D}$ should be investigated to establish if there are specific resonances or alternatively threshold effects driving the enhancement.

Such information already exists qualitatively and can help to constrain interpretations. If the 3940 MeV enhancement consists of a single state, then
the observation of significant $D^*\bar{D}$ in the decay of $X(3940)$ suggests that this state is not simply a gluonic hybrid charmonium [1]. However, the branching ratios into $D^*\bar{D}: J/\psi \omega$ need to be established; if the $D^*\bar{D}$ is small, then hybrid charmonium may be relevant. The mass also is low compared to that predicted for hybrid charmonia which are more generally expected to be at $\sim 4.2$ GeV [3, 22] unless, as we discuss later, there are significant $J^P_C$ dependent mass shifts.

While the interpretation of these states may depend rather critically on first establishing their $J^P_C$, the appearance of a further state, $Y(4260)$ with $J^P_C = 1^{--}$ has properties that appear uniformly to be consistent with those predicted earlier for hybrid charmonium. We now assess the experimental information about this state.

2 Experimental information

The BaBar collaboration recently observed a new structure at $4259 \pm 8^{+2}_{-6}$ MeV with a width of $88 \pm 23^{+6}_{-4}$ MeV and a significance greater than $8\sigma$ [12]. The structure is known to be produced in initial state radiation from $e^+e^-$ collisions and hence to have $J^P_C = 1^{--}$. It is seen decaying to $J/\psi \pi^+\pi^-$ and

$$\Gamma(Y(4260) \rightarrow e^+e^-) B(Y(4260) \rightarrow J/\psi \pi^+\pi^-) = 5.5 \pm 1.0^{+0.8}_{-0.7} eV. \quad (1)$$

There are several consequences of the experimental work that are worth noting, and which align themselves most naturally with a hybrid charmonium interpretation.

**The mass coincides with the $D_1(2420)\bar{D}$ threshold:** The state can couple to $D_1(2420)\bar{D}$, and related thresholds to be discussed later, in S-wave. The $D_1(2420)\bar{D}$ thresholds are at 4287 MeV ($D_1(2420)^o\bar{D}^o$) and 4296 MeV ($D_1(2420)^\pm\bar{D}^\mp$) [15]. At an S-wave threshold, re-scattering effects may drive the $J/\psi \pi^+\pi^-$ signal. A resonance above 4.26 GeV, which couples strongly to $D_1\bar{D}$, can through re-scattering give an enhancement in $J/\psi \pi\pi$ at the $D_1\bar{D}$ threshold (for example see Ref. [23]), in which case the true mass of $Y(4260)$ could be $O(100)$ MeV above 4.26 GeV. It is even possible for such a phenomenon to occur without any resonance. Therefore it is important to establish that $Y(4260)$ is resonant and not a threshold effect. With these caveats, we shall now analyze for the case where $Y(4260)$ is resonant.

**The decay modes $J/\psi \sigma$, $J/\psi f/a_0(980)$ appear to dominate:** An S-wave phase space model of the three-body decay $J/\psi \pi^+\pi^-$ [12] does not appear consistent with the data (Fig. 3, Ref. [12]). On the other hand, two-body
decay, which usually dominates three-body decay, would easily explain the data, which are consistent with \( \pi^+ \pi^- \) peaks at the \( \sigma \) and \( f_0(980)/a_0(980) \) masses. These mesons are the only ones in the mass region 0.3 – 1.0 GeV displayed [12] with \( C = + \), as required by C-parity conservation. The mode \( J/\psi K\bar{K} \) should be searched for as the strong coupling of \( f/a_0(980) \) to \( K\bar{K} \) should manifest itself at the \( K\bar{K} \) threshold if these states are important in the decay.

\( \Gamma(Y(4260) \to e^+e^-) \) is much smaller than all other \( 1^- \) charmonia: Noting that the cross-section \( \sigma(e^+e^- \to Y \to X) \) into final state \( X \) is proportional to \( \Gamma(Y \to e^+e^-)B(Y \to X) \),

\[
\frac{\Gamma(Y \to e^+e^-)B(Y \to \text{hadrons})}{\Gamma(Y \to e^+e^-)B(Y \to J/\psi \pi^+\pi^-)} = \frac{\sigma(e^+e^- \to Y \to \text{hadrons})}{\sigma(e^+e^- \to Y \to J/\psi \pi^+\pi^-)},
\]

and using Eq. 1, \( \sigma(e^+e^- \to Y \to \text{hadrons}) \approx 4\% \times 14.2 \text{ nb} \) [12] [10], and \( \sigma(e^+e^- \to Y \to J/\psi \pi^+\pi^-) \approx 50 \text{ pb} \) [12], it follows that

\[
5.5 \pm 1.3 \text{ eV} \leq \Gamma(Y(4260) \to e^+e^-) \leq 62 \pm 15 \text{ eV},
\]

using that \( B(Y \to \text{hadrons}) \) is very near to unity. (The lower bound on the width is obtained from Eq. 1.) This \( e^+e^- \) width is at least a factor of 4 smaller than that of the established \( 1^- \) charmonium with the smallest width, the \( \psi(3770) \) [16]. However, unmixed radially excited D-wave \((2D) c\bar{c} \) states can have widths consistent with Eq. 3 as their widths in potential models are typically 64 times lower than \( 3S \) states [24]. The experimental width only just overlaps with that in a four-quark interpretation of \( Y(4260) \), which predicted that it should be \( 50 – 500 \text{ eV} \) [25].

\( \Gamma(Y(4260) \to J/\psi \pi^+\pi^-) \) is much larger than all \( 1^- \) charmonia: Using Eqs. 1 and 3 it is immediate that

\[
B(Y(4260) \to J/\psi \pi^+\pi^-) \approx 88\%; \quad \Gamma(Y(4260) \to J/\psi \pi^+\pi^-) \approx 7.7 \pm 2.1 \text{ MeV}.
\]

This is much larger than \( \Gamma(\psi(3770) \to J/\psi \pi^+\pi^-) \) which is in the \( 80 – 90 \text{ keV} \) range [16] [26]. It is also much larger than \( \Gamma(\psi(4040); \psi(4160); \psi(4415) \to J/\psi \pi^+\pi^-) \), as is now shown. The \( Y(4260) \) is seen in the BaBar experiment and \( \psi(4040), \psi(4160) \) and \( \psi(4415) \) not [12]. Using a ball-park estimate that the error bars can mask the latter resonances if their cross-section is four times smaller than \( Y(4260) \) (Fig. 1, Ref. [12]), and noting that \( \sigma(e^+e^- \to X \to J/\psi \pi^+\pi^-) \) into intermediate state \( X \) is proportional to \( \Gamma(X \to e^+e^-)B(X \to J/\psi \pi^+\pi^-) \), we have
\[ \mathcal{B}(\psi' \to J/\psi \pi^+\pi^-) \lesssim \frac{\Gamma(Y \to e^+e^-) \mathcal{B}(Y \to J/\psi \pi^+\pi^-)}{4 \Gamma(\psi' \to e^+e^-)}, \]  

(5)

where \( \psi' \) denotes any of \( \psi(4040), \psi(4160) \) or \( \psi(4415) \). Together with Eq. 1 this can be used to calculate a bound on the branching ratio of each \( \psi' \). Translating into widths \[16\]

\[ \Gamma(\psi(4040); \psi(4160); \psi(4415) \to J/\psi \pi^+\pi^-) \lesssim 100 \pm 30, 140 \pm 60, 130 \pm 60 \text{ keV}. \]

(6)

The simplest interpretation of this is that the \( J/\psi \pi\pi \) is not due to disconnected \( J/\psi gg \) diagrams but instead involves some strong affinity. This could be due to a four-quark interpretation \[25\] or due to intrinsic gluonic excitation in the initial state, as will be discussed below.

## 3 \( Y(4260) \) as hybrid charmonium

Lattice QCD inspired the flux-tube model of mesons \[27\], which has been used to predict observables that, at the time, were beyond the bounds of lattice computation but which have subsequently been largely confirmed and extended by these more fundamental techniques. In particular and of relevance to the present discussion, we cite the early prediction of exotic \( J^{PC} \) states for both light and heavy flavours, whose masses and spin dependent mass splittings are now being confirmed by lattice computations. The detailed production and decay signatures for hybrid states are still largely beyond the bounds of lattice QCD, and for these we are still restricted to the model. In due course we anticipate that these results will be tested by the lattice. In the meantime they are arguably the nearest we have and it is on the basis of their implications that we proceed to examine the \( Y(4260) \).

The eight low-lying hybrid charmonium states \( (c\bar{c}g) \) were predicted in the flux-tube model to occur at \( 4.1 - 4.2 \) GeV \[3\], and in UKQCD’s quenched lattice QCD calculation with infinitely heavy quarks to be \( 4.04 \pm 0.03 \) GeV (with un-quenching estimated to raise the mass by \( 0.15 \) GeV) \[22\]. The splittings of \( c\bar{c}g \) from the above spin-average was predicted model-dependently for long distance (Thomas precession) interactions in the flux-tube model \[28\], and for short distance (vector-one-gluon-exchange) interactions in cavity QCD \[2, 7\]. For the \( 1^{--} \) state the long and short distance splittings are respectively 0 MeV and 60 MeV.

These mass predictions are very much in accord with the \( Y(4260) \) and somewhat removed from those for \( X/Y(3940) \).
A lattice inspired flux-tube model showed that the decays of hybrid mesons, at least with exotic $J^{PC}$, are suppressed to pairs of ground state $1S$ conventional mesons \[27, 29\]. This was extended to all $J^{PC}$, for light or heavy flavours in Ref. \[1\]. A similar selection rule was found in constituent gluon models \[30\] and later in QCD sum rules \[31\], and their common quark model origin is now understood \[32\]. It was further shown that these selection rules for light flavoured hybrids are only approximate, but that they become very strong for $c\bar{c} \[1, 2\]$. This implied that decays into $D\bar{D}$, $D_s\bar{D}_s$, $D^*\bar{D}$ and $D_s^*\bar{D}_s^*$ are suppressed whereas $D^*D$ and $D_s^*\bar{D}_s$ are small, and $D^{**}\bar{D}$, if above threshold, would dominate. (P-wave charmonia are denoted by $D^{**}$).

As $c\bar{c}g$ is predicted around the vicinity of $D^{**}\bar{D}$ threshold, the opportunity for anomalous branching ratios in these different classes was proposed as a sharp signature \[1, 3\]. (To the best of our knowledge Ref. \[1\] was the first paper to propose such a distinctive signature for hybrid charmonium.)

It has become increasingly clear recently that there is an affinity for states that couple in S-wave to hadrons, to be attracted to the threshold for such channels \[33\]. The hybrid candidate $1^{--}$ appearing at the S-wave $D_1(2420)\bar{D}$ is thus interesting.

More recently the signatures for hybrid charmonia were expanded to note the critical region around $D^{**}\bar{D}$ threshold as a divide between narrow states with sizable branching ratio into $c\bar{c}$ + light hadrons and those above where the anomalous branching ratios would be the characteristic feature \[5, 7, 8\]. Here widths of order 10 MeV were anticipated around the threshold. It was suggested to look in $e^+e^-$ annihilation in the region immediately above charm threshold for state(s) showing such anomalous branching ratios \[8\]. The leptonic couplings to $e^+e^-$, $\mu^+\mu^-$ and $\tau^+\tau^-$ were expected to be suppressed \[34\] (smaller than radial S-wave $c\bar{c}$ but larger than D-wave $c\bar{c}$, but with some inhibition due to the fact that in hybrid vector mesons spins are coupled to the $S = 0$, whose coupling to the photon is disfavoured \[8\]). Even stronger suppression obtains for $\gamma\gamma$ couplings \[35\].

Small conventional charmonium mixing with $c\bar{c}g$ or a glueball is expected. The latter is due to the penalty incurred by the creation of a $c\bar{c}$ pair, and the former is due to the heaviness of the charm quark which enable a Born-Oppenheimer approximation, separating conventional and hybrid charmonia by virtue of their orthogonal gluonic wave functions \[7\]. However, for $1^{--}$ hybrids, there is the possibility of substantial mixing with the radially and orbitally excited $c\bar{c}$ if mass degenerate: It was noted that hybrid charmonia with $1^{--}$ can in principle mix \[4, 36\] with radially excited $c\bar{c}$ states and a specific example was discussed of what would occur if the hybrid mass is $\sim 4.1$ GeV \[4\].

The discovery of $Y(4260)$ signals degrees of freedom beyond conven-
tional \( c\bar{c} \). This is because the only such \( 1^- \) expected up to 4.4 GeV are \( 1S, 2S, 1D, 3S, 2D \) and \( 4S \) \[^{22}\], and there are already established candidates for these states. Thus even in the case of mixing, the existence of \( Y(4260) \) hints that more than conventional \( c\bar{c} \) is needed.

We now consider tests and implications of the idea that \( Y(4260) \) signals the onset of hybrid charmonium. We describe these below, compare with the unmixed hybrid charmonium hypothesis and propose further tests.

### 4 Implications of hybrid charmonium

There are several of the theoretical expectations already given for \( c\bar{c}g \) that are born out by \( Y(4260) \): (1) Its mass is tantalizingly close to the prediction for the lightest hybrid charmonia; (2) The expectation that the \( e^+e^- \) width should be smaller than for S-wave \( c\bar{c} \) is consistent with Eq. 3; (3) The predicted affinity of hybrids to \( D^{**}\bar{D} \) could be related to the appearance of the state near the \( D^{**}\bar{D} \) threshold. The formation of \( D^{**}\bar{D} \) at rest may lead to significant re-scattering into \( J/\psi \pi^+\pi^- \), which would feed the large signal (Eq. 4).

Quenched lattice QCD indicates that the \( c\bar{c}g \) \( 1^- \), \( (0,1,2)^+ \) are less massive than \( 1^{++} \), \( (0,1,2)^{+-} \) \[^{37}\]. The spin splitting for this lower set of hybrids in quenched lattice NRQCD is \( 0^- < 1^- < 1^- < 2^- \) \[^{38}\], at least for \( b\bar{b}g \). This agrees with the ordering found in the model-dependent calculations for \( q\bar{q}g \) \[^{39}\] in the specific case of \( c\bar{c}g \) \[^{2,7,28}\]. For \( b\bar{b}g \) lattice QCD predict substantial splittings \( \sim 100 \text{ MeV} \) or greater \[^{38}\], which become even larger in the model-dependent calculations for \( c\bar{c}g \) \[^{2,7,28}\]. Theory hence strongly indicates that if \( Y(4260) \) is \( c\bar{c}g \), and the splittings are not due to mixing or coupled channel effects, then the \( J^{PC} \) exotic \( 1^- \) and non-exotic \( 0^- \) \( c\bar{c}g \) are below \( D^{**}\bar{D} \) threshold, making them narrow by virtue of the selection rules. The \( 1^- \) decay modes \[^{5}\] and branching ratios \[^{8}\] have extensively been discussed.

The nearness of \( Y(4260) \) to the \( D_1(2420)\bar{D} \) threshold, and to the \( D'_1\bar{D} \) threshold, with the broad \( D'_1 \) found at a mass of \( \sim 2427 \text{ MeV} \) and width \( \sim 384 \text{ MeV} \) \[^{40}\], indicate that these states are formed at rest. Also, these are the lowest open charm thresholds that can couple to \( 1^- \) in S-wave (together with \( D_0\bar{D}^* \), where the \( D_0 \) mass \( \sim 2308 \text{ MeV} \) and width \( \sim 276 \text{ MeV} \) \[^{40}\]). Flux-tube model predictions are that the D-wave couplings of \( 1^- c\bar{c}g \) to the \( 1^+ \) and \( 2^+ D^{**} \) are small \[^{1,2,6}\], and there is disagreement between various versions of the model on whether the S-wave couplings to the two \( 1^+ \) states are large. If these couplings are in fact substantial, the nearness of \( Y(4260) \) to the thresholds may not be coincidental, because coupled channel effects could
shift the mass of the states nearer to a threshold that it strongly couples to; and it would experience a corresponding enhancement in its wave function. The broadness of $Y(4260)$ also implies that its decay to $D_1(2420)\bar{D}$, $D_s'\bar{D}$ and $D_0(2308)\bar{D}^*$ which feed down to $D^*\bar{D}\pi$ and $D\bar{D}\pi$ [11] would be allowed by phase space and should be searched for to ascertain a significant coupling to $D^{**}$.

Flux-tube model width predictions for other charm modes are $1 - 8$ MeV for $D^*\bar{D}$ [3], with $D\bar{D}$, $D_s\bar{D}_s$, $D^*\bar{D}^*$ and $D_s^*\bar{D}_s^*$ even more suppressed. Thus a small $D\bar{D}$ and $D_s\bar{D}_s$ mode could single out the hybrid interpretation. The hybrid decay pattern is very different from the $c\bar{s}s\bar{c}$ four-quark interpretation for $Y(4260)$ which decays predominantly in $D_s\bar{D}_s$ [25]. Thus a search for the latter channel, or limit on its coupling, could be a significant discriminator for the nature of the $Y(4260)$.

5 Experimental searches and production

It is possible that $Y(4260)$ is not a resonance, but reflects the opening of the $D_1(2420)\bar{D}$, $D_s'\bar{D}$ and $D_0(2308)\bar{D}^*$ thresholds. The reason is that this is the lowest energy at which open charm thresholds can couple to $e^+e^- (1^{--})$ in S-wave. Thus there is the possibility that BaBar [12] is observing the process $e^+e^- \rightarrow D^{**}\bar{D} \rightarrow J/\psi \pi^+\pi^-$, where $J/\psi \pi^+\pi^-$ is produced by re-scattering. This could occur without a resonance, or with a resonance, as follows. The essential ingredients are (i) the presence of a non-resonant background (in this case $J/\psi \pi\pi$); (ii) a resonance which strongly couples to a channel (in this case $D^{**}\bar{D}$); (iii) rescattering between the latter channel and the background. An example involving light quarks and an earlier claimed signal for a hybrid meson (in that case the $1^{--}$) was discussed in Ref. [23]; a specific model of rescattering involving charmonium was applied to the $X(3872)$ in Ref. [20]. Hence the resonant nature of $Y(4260)$ should be confirmed. If a similar rescattering effect occurs at the $D_{s1}\bar{D}_s$, $D_{s1}'\bar{D}_s$, $D_{s0}\bar{D}_s^*$ and $D_{s2}'\bar{D}_s^*$ thresholds then this could be investigated in $J/\psi K\bar{K}$. If Fig. 1 of Ref. [12] shows further structure beyond the $Y(4260)$ enhancement this may be due to the $D_{s^*}\bar{D}_s$ re-scattering in $J/\psi f_0(980)$ which yields a $J/\psi \pi^+\pi^-$ signal.

The nearness and S-wave coupling of $Y(4260)$ to specifically the $D_1(2420)^0D^0$ threshold, and also the $D_1(2420)^\pm D^{\mp}$ threshold, together with the sizable width of the state, lead to the expectation that mixing with both thresholds will be similar, and that the charmonium nature of $Y(4260)$ should imply that it is dominantly $I = 0$, as will be assumed in the remainder of this discussion. This can be established by searching for the isospin violating decays $J/\psi \pi^0$ and $\pi^+\pi^-$. 

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If either the model dependent spin splittings are a guide, or if the states are attracted towards S-wave thresholds, then we would expect that the $Y(4260)$ as vector hybrid $\psi_g$ states will imply that the $0^{-+}$ $\eta_c\bar{\eta}$ and exotic $1^{-+}$ will be at or below 4.3 GeV. The analyses of Refs. [6, 8] then imply the following:

(i) Any decays into the disfavoured $D^*\bar{D}$ channel will be in the ratios $1^{-+}:\psi_g:\eta_c\bar{\eta} = 1 : 2 : 4$ apart from phase space effects.

(ii) $\Gamma(1^{-+} \rightarrow D_1\bar{D}) > \Gamma(\psi_g \rightarrow D_1\bar{D})$.

(iii) $\eta_c \rightarrow D_0\bar{D}$ may be significant due to the broad width of the $D_0$. Even if this is kinematically suppressed, significant re-scattering may result into $J/\psi\omega$ [20, 42]. Hence the possibility that $X/Y(3940)$ contains $\eta_c\bar{\eta}$ may be realized; establishing the $J^{PC}$ of the 3940 MeV structure(s) is thus important.

(iv) $\eta_c \rightarrow \eta_c\pi\pi$ may be anticipated [8] and $\eta_c \rightarrow \eta_c f_0(980)$ may be a significant contributor. To this end, a search for $\eta_c(3940) \rightarrow \eta_c K\bar{K}$ is also merited. The $J/\psi \{\omega, \phi\}$ mode may be experimentally most tractable.

It is singular that apart from the $\psi(2S)$, no other states are visible in the BaBar data [12] until the $Y(4260)$. Given that its $e^+e^-$ coupling is small, this observation suggests that it is the special affinity of this state for the $J/\psi\pi\pi$ channel that gives its visibility (Eqs. 3-4). The possible decays of $Y(4260)$ are listed in Table 1. A further test for the $\psi_g$ interpretation of $Y(4260)$ would be that $\psi_g \rightarrow \{\sigma, \eta\} h_c$ could be significant. This would arise if the decay was driven by flux-tube de-excitation, with quark spin conservation. Such a mechanism is expected in the model [11], though its strength is currently unquantifiable; there are suggestions from lattice QCD that such de-excitation modes may be significant for heavy flavours [13]. This particular mode could be detected by the isospin violating mode of the $h_c \rightarrow J/\psi\pi$.

A search for $\psi_g \rightarrow J/\psi\pi^+\pi^-$ at Belle and BaBar in $B \rightarrow K\psi_g$ should be fruitful [5], even though the small $e^+e^-$ coupling of $\psi_g$ suggests that its wave function at the origin is tiny. Production in $p\bar{p}$ annihilation in the formation process $p\bar{p} \rightarrow \psi_g$ is also feasible at future colliders.

If the $Y(4260)$ is $\psi_g$, then the radiative transition $\psi_g \rightarrow 1^{-+}\gamma$, though tiny, may reveal the exotic hybrid charmonium [4]. The decay $1^{-+} \rightarrow \chi_{0,1,2}\pi$ with $\sigma \rightarrow (\pi\pi)_g$ should be an excellent search mode [5] and is predicted to be large [43], although the $J/\psi \{\omega, \phi\}$ mode may be most tractable experimentally. However, given the small $e^+e^-$ width of the $Y(4260)$, this may require a dedicated search at BES or CLEO$_c$. An exciting possibility is that $e^+e^- \rightarrow J/\psi + X$ may reveal the $1^{-+}$ in the $X$ around or above 4 GeV [44].

While this work was in preparation, a discussion of the interpretations for $Y(4260)$ suggested that the hybrid charmonium assignment is favored [30].
Table 1: Possible two-body hadronic decay modes of $Y(4260)$, assuming that it has $I = 0$. Open charm modes may be suppressed by a selection rule discussed in the text. Hidden charm modes to low-lying charmonia are listed. For these modes, the charmonia tend to have the same $C$ as that of the parent $c\bar{c}g$, since, barring non-perturbative effects, two gluons $C = +$ are emitted in the lowest order process [5]. Electromagnetic modes like $\{\eta_c, \eta_c(2S), \chi_{c\{0,1,2\}}, h_c, X(3872)\}\gamma$ are expected to be small. Light hadron modes are restricted to hadrons up to the $\phi$ mass.

| Open charm | Hidden charm | Light hadrons |
|------------|--------------|---------------|
| $DD; D_sD_s$ | $\eta_c\{\omega, \phi, h_1\}$ | $\eta^{(1)}\{\omega, \phi\}; \rho\pi; a_0(980)\rho$ |
| $D^*\bar{D}, D_s^*\bar{D_s}$ | $J/\psi\{\sigma, f_0(980), \eta^{(1)}\}$ | $\{\sigma, f_0(980)\}\{\omega, \phi\}$ |
| $D^*\bar{D}^*; D_s^*\bar{D}_s^*$ | $\psi(2S)\{\sigma, \eta\}$ | $\{K, K^*\}\bar{K}; \{\kappa, K^*\}\bar{\kappa}$ |
| $D_1(2420)\bar{D}; D'_1\bar{D}$ | $\chi_{c\omega}; h_c\{\sigma, \eta\}$ | $K^*\bar{K}^*; p\bar{p}^*, p\bar{n}, n\bar{n}$ |

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*Note added:* After this work was completed, an enhancement consistent with $Y(4260)$ was observed in $B^- \to J/\psi \pi^+ \pi^- K^-$ [46]. Such a search was suggested earlier in this paper.

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