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$Y(4260)$: Hadronic molecule versus hadro-charmonium interpretation

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In this paper we confront both the hadronic molecule and the hadro-charmonium interpretations of the $Y(4260)$ with the experimental data currently available. We conclude that the data support the $Y(4260)$ being dominantly a $D_1\bar{D}$ + c.c. hadronic molecule while they challenge the hadro-charmonium interpretation. However, additional data are necessary to allow for stronger conclusions.

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In the past decade, a lot of new states, called X, Y, or Z, were observed in the heavy quarkonium mass region [1]. Quite a few of them are close to open-flavor meson-meson thresholds and can hardly be accommodated in the traditional quark model. Among these states, the charged charmonium-like (or bottomonium-like) states are intriguing as they are made of at least four quarks. After Belle's observations of the $Z_b(10610)$ and $Z_b(10650)$ close to $B\bar{B}^*$ + c.c. and $B^*\bar{B}^*$ thresholds, respectively [2], the BESIII Collaboration recently discovered their possible analogs in the charmonium mass region, the $Z_c(3900)$ [3], $Z_c(4025)$ [4], and $Z_c(4020)$ [5]. The $Z_c(3900)$ was soon confirmed by the Belle Collaboration [6] and an analysis based on the CLEO-c data [7].

In Ref. [8], it was argued that the strong signal of $Z_c(3900)$, being a $D\bar{D}^*$ + c.c. molecular state [8–10], in the $Y(4260)$ decays can be explained by a dominant D_1D molecular component in the $Y(4260)$ wave function [11,12].[1] Related discussions can also be found in Refs. [13,14], emphasizing different aspects.

Recently, the interpretation of the $Y(4260)$ as a D_1D molecular state was challenged in Ref. [15], where it is suggested that the $Y(4260)$ is a hadro-charmonium state (a compact quarkonium surrounded by light quarks) [16,17]. The argument is based on the fact that the production of a pair of $S_L^P = (1/2)^-$ and $S_L^P = (3/2)^+$ heavy mesons, where S_L is the sum of the spin of the light quark and the orbital angular momentum in the heavy meson, in electron-positron collisions is forbidden in the heavy quark limit—in the real world, this should translate to a suppressed production of both the D_1D continuum as well as D_1D molecular states.

In this paper, we confront both interpretations of the $Y(4260)$, the hadro-charmonium as well as the hadronic molecule, with the data currently available. Especially, we argue that the D_1D molecular interpretation of the $Y(4260)$ does not contradict the current experimental facts despite the suppression of the production of the D and $\bar{D}_1$ pair. It is shown that the heavy quark spin symmetry (HQSS) breaking due to a finite charm quark mass is important in this case [18]. We also discuss the challenges that both interpretations still face.

In Ref. [15], Li and Voloshin stressed that in the heavy quark limit the production of a heavy state in e^+e^-–collisions proceeds via the electromagnetic current $\bar{c}\gamma_\mu c$ leading to a $c\bar{c}$ pair in a ${}^3S_1$ state with the spin of the heavy system $S_H = 1$. At the same time, the total angular momentum of the light degrees of freedom should be $S_L = 0$. In the heavy quark limit, both S_H and S_L are conserved. However, the light quark total angular momenta in the S-wave states $D_1D^{(*)}$ and D_2D^*, $S_L = 3/2$ and $S_L = 1/2$, cannot combine to $S_L = 0$. Consequently, the S-wave production of $D_1D^{(*)}$ and D_2D^* pairs with $J^{PC} = 1^{--}$ in electron-positron collisions breaks the HQSS and thus would be forbidden if the charm quark were infinitely heavy.

This can also be understood using the angular momentum decomposition of the heavy and light degrees of freedom. The $J^{PC} = 1^{--}$ states with $(\frac{3}{2})^+$ and $(\frac{1}{2})^-$ components can be decomposed into the following states [15,19,20]:

$$\psi_{mn} \equiv \frac{1}{\sqrt{2}}([[c\bar{c}]^m, [\bar{q}_l q]^n]^1 - [[\bar{c}c]^m, [q_l\bar{q}]^n]^1),$$

where the subscript l denotes the orbital angular momentum carried by the light quark in the D_1 or $\bar{D}_1$. As a result, the D_1D wave function projected to the proper quantum numbers reads [15]

$$|D_1D({}^3S_1)\rangle^{1^{--}} = \frac{1}{2}\psi_{01} + \frac{1}{2\sqrt{2}}\psi_{11} + \frac{\sqrt{5}}{2\sqrt{2}}\psi_{12}. \quad (1)$$

[1]Here, D_1D is a short notation for $D_1\bar{D}$ + c.c. For brevity, the same convention will be used for the D_1D^* and D_2D^* below.

Since ψ_{10} is absent, in the heavy quark limit, the D_1D state should not couple to the photon. In addition, in Ref. [15], it was shown that neither the rescattering due to the process $D^*\bar{D}^* \to D_1\bar{D}$ nor the mixing of the $D_1(2420)$ with the $D_1(2430)$ can evade the above-mentioned suppression. In Ref. [15], also an attempt was made to quantify a possible kinematic effect that might increase the amount of HQSS violation by estimating at the square of the ratio of the D-wave amplitude to the S-wave one [15],

$$\left|\frac{D}{S}\right|^2 = \frac{(E-2m_c)^2}{2(E+m_c)^2}, \tag{2}$$

which turns out to be about 0.02 at $E = 4.26$ GeV, although the energy is already well above $2m_c$. Thus, they conclude that the S-wave production of the $(3/2)^+$ and $(1/2)^-$ charmed meson pairs is heavily suppressed.

In what follows, we will demonstrate that the presence of the suppression described above does not allow one to exclude that the $Y(4260)$ is a D_1D bound system. On the contrary, all properties of the $Y(4260)$ are consistent with its molecular interpretation in the presence of a suppressed production in e^+e^- collisions.

Naively, the HQSS breaking effect is characterized as $\mathcal{O}(\Lambda_{\rm QCD}/m_Q)$, which presents a significant suppression when $m_Q \gg \Lambda_{\rm QCD}$. There is no ambiguity if the heavy quark mass m_Q is much larger than $\Lambda_{\rm QCD}$ so that a finite numerical factor would not change the suppression much. However, this is not the case for the charm quark. For the production of the D_1 and $\bar{D}$ pair around the energy 4.26 GeV, the excess energy $E_e = E - 2m_c$ is not small compared with the charm quark mass and might cause a large HQSS breaking. Equation (2) discussed in Ref. [15] only represents the D/S ratio for the free charm quark pair. However, HQSS breaking could happen after this in the nonperturbative hadronization process. For instance, we may think of the light quark and antiquark pair being produced through bremsstrahlung gluons radiated from the charm quark. If the gluons carry an energy which is not negligible compared with the charm quark mass, the spin of the charm quark has a certain probability to be flipped due to the chromomagnetic interaction $\bar{c}\vec{B}\cdot\vec{\sigma}c/m_c$, where $B^i = \epsilon^{ijk}\partial^j A^k$ and A^k are the gluon fields and $\vec{\sigma}$ are the Pauli matrices. Thus, the HQSS breaking amplitude should be proportional to E_g/m_c, where E_g is the gluon energy. The effect in question could reach $E_g/m_c \sim (M_{D_1} - m_c)/m_c \sim 0.6$ in the production amplitude,[2] which is numerically larger than $\Lambda_{\rm QCD}/m_c$ by a factor of 2 or 3, and ~0.3–0.4 in the cross section. Therefore, the suppression in the S-wave production of the D_1D pair in e^+e^- collisions does not need to be as strong as reported in Ref. [15].

[2] In a perturbative estimate, one would need to multiply the estimate with α_s/π. However, at the energy just estimated α_s is already large.

TABLE I. Electron widths of the vector charmonium states [22].

Resonance	Γ_{ee} (keV)
J/ψ	5.55 ± 0.14
$\psi(3686)$	2.35 ± 0.04
$\psi(3770)$	0.262 ± 0.018
$\psi(4040)$	0.86 ± 0.07
$\psi(4160)$	0.83 ± 0.07
$\psi(4415)$	0.58 ± 0.07

In line with the expectation that the HQSS breaking could be sizeable when the excess energy $E_e = E - 2m_c$ is not small in comparison with the charm quark mass, HQSS is indeed badly broken in many cases for the charmonium states above the open-charm thresholds. One good example is the electron decay widths Γ_{ee} of the vector charmonium states. In the heavy quark limit, only the S-wave heavy quarkonium states are allowed to decay into an electron-positron pair via a virtual photon. Thus, the value of Γ_{ee} of a D-wave heavy quarkonium, which corresponds to the ψ_{12} state in the decomposition in Eq. 1, should be much smaller than that of an S-wave state corresponding to ψ_{10}. From Table I, one can see that the Γ_{ee} value of the $\psi(3770)$ is 1 order of magnitude smaller than that of the $\psi(3686)$, which is consistent with the fact that the $\psi(3770)$ and $\psi(3686)$ are mainly a D-wave state and an S-wave state, respectively. However, all the three states above 4 GeV, among which at least one is a D-wave state, have similar Γ_{ee}. This indicates a strong HQSS breaking effect in this energy range, which could be caused by either a mixing between S-wave and D-wave states (see, e.g., Ref. [21]) or due to enhancement resulting from nearby thresholds [19].[3] The mixing angle between the $2D$ and $3S$ states could be as large as 34° in Ref. [21].

Another observation supporting that spin symmetry violations are potentially significant for the $Y(4260)$ is that $|(M_{D_1} + M_D) - M_Y| \sim 30$ MeV, $|(M_{D_1} + M_{D^*}) - M_Y| \sim 160$ MeV, and $|(M_{D_2} + M_{D^*}) - M_Y| \sim 200$ MeV—in the heavy quark limit, all mentioned thresholds were degenerate.

Having established that in the 4 GeV region one should expect a significant violation of heavy spin symmetry that thus allows for the production of the $Y(4260)$ in e^+e^- collisions even if it is a D_1D molecule, we now collect arguments that the data currently available are actually in favor of this molecular interpretation while they pose a challenge to the hadro-charmonium picture:

(1) The $Y(4260)$ decays into both the $\pi^+\pi^-J/\psi$ and $\pi^+\pi^-h_c$, and the cross sections for the processes $e^+e^- \to \pi^+\pi^-h_c$ and $e^+e^- \to \pi^+\pi^-J/\psi$ at 4.26 GeV are similar [5], which implies a large HQSS

[3] In principle, these two different scenarios are not independent because coupling to the nearby open-charm channels can induce mixing.

breaking. Especially, the data show that a large part of the cross section for the $\pi^+\pi^- h_c$ is not from the Z_c states. This is natural in the $D_1 D$ molecular picture, as both the J/ψ and h_c couple to the charmed and anticharmed meson pair. Furthermore, once the $D_1 D$ pair is produced, the decay into the $\pi^+\pi^- h_c$ will be facilitated by the charmed meson loops. This is because both the $Y(4260)D_1\bar{D}$ and the $h_c D^*\bar{D}$ vertices are S wave, and in this case, there is a large enhancement factor $1/v^3$ with $v \ll 1$ being the velocity of the intermediate charmed mesons (for detailed discussions, we refer to Refs. [13,23,24]). In the hadro-charmonium picture, Li and Voloshin explain the decays of the $Y(4260)$ into both the $\pi^+\pi^- J/\psi$ and $\pi^+\pi^- h_c$ channels by mixing two hadro-charmonium states for which the cores are a $^1P_1$ and $^3S_1$ charmonium, respectively, into the $Y(4260)$ and $Y(4360)$ [18]. However, the former and the latter states were observed in the $J/\psi\pi^+\pi^-$ and in the $\psi'\pi^+\pi^-$ channels, respectively—although current data do not fully exclude that both states are seen in both transitions due to limited statistics. Because the nonrelativistic wave functions of the J/ψ and ψ' do not overlap, the hadro-charmonium interpretation faces the difficulty to explain why the $Y(4260)$ and $Y(4360)$ are not observed in the same final states.

Also in the molecular picture, it would be natural if the $Y(4360)$ and the $Y(4260)$ were close relatives —after all, the distance of $Y(4260)$ to the $D_1 D$ threshold is very similar to the distance of $Y(4360)$ to the $D_1 D^*$ threshold and D and D^* are spin partners. It remains to be seen if the rates discussed above are consistent with such a picture or not. To address this issue requires a microscopic calculation that we are currently working on.

(2) There is a dip in the measured R values around the mass of the $Y(4260)$. As is most clearly demonstrated in Ref. [25], the dip in this region emerges after summing up the two-body channels $D^{(*)}\bar{D}^{(*)}$ and the three-body channels $D\bar{D}^{(*)}\pi$—none of the individual cross sections shows a prominent dip. In the hadronic molecular model where the main component of the $Y(4260)$ is $D_1 D$, we expect that the $Y(4260)$ decays mainly into the $D\bar{D}^*\pi + \mathrm{c.c.}$ through the decays of the D_1 meson. Therefore, the dip behavior that emerges in the inclusive cross section from the rise of the $DD^*\pi$ rates beyond 4.2 GeV is fully in line with the hadronic molecular scenario since the $Y(4260)$ acts as a doorway for the three-body final states. Furthermore, the model does not contradict the upper limit $\mathcal{B}(Y(4260) \to D^0 D^{*-}\pi^+)/\mathcal{B}(Y(4260) \to \pi^+\pi^- J/\psi) < 9$ [26]. On the other hand, in the hadro-charmonium picture, there is no suppression for $e^+e^- \to Y(4260)$, and the $Y(4260)$ decay dominantly into a charmonium and two pions. Therefore, one would expect a pronounced peak in the R ratio around the mass of the $Y(4260)$. Especially in this case, the R values should not be saturated by the open charm channels at this energy. Further measurements in the $D\bar{D}^*\pi$ channel would be very helpful to distinguish between the two models since in the hadro-charmonium model such decays are not expected to be important.

(3) From the discussion above, we expect Γ_{ee} of $Y(4260)$ to be in the range of 1%–10% of $\Gamma_{ee}(J/\psi) = 5.55$ KeV. Unfortunately, the electron width of the $Y(4260)$ cannot be calculated model independently. We may estimate it by assuming that the photon coupling to the ψ_{12} component of the $D_1 D$ molecule is the same as that to the2^3D_1 charmonium state which is the closest D-wave state. If we take $\Gamma_{ee}(2^3D_1) = 0.059$ keV calculated in Ref. [21], taking into account the decomposition given in Eq. (1), we have $\Gamma_{ee}(Y(4260)) \simeq \frac{5}{8}\Gamma_{ee}(2^3D_1) = 37$ eV, which is much smaller than the existing upper limit 580 eV [27], about 10% of the e^+e^- decay width of J/ψ. Alternatively, we can extract the upper limit of $\Gamma_{ee}(Y(4260))$ from the formula $\sigma_{e^+e^-\to D^0 D^{*-}\pi^+} = 12\pi\Gamma_{ee}(Y(4260))\Gamma_{Y(4260)\to D^0 D^{*-}\pi^+}|G_Y(s)|^2$ with $G_Y(s)$ [28] the propagator of $Y(4260)$. Using the experimental cross section 0.1–0.8 nb for $e^+e^- \to Y(4260) \to D^0 D^{*-}\pi^+$ from Belle [26] and $\Gamma_{Y(4260)\to D^0 D^{*-}\pi^+} = \Gamma_{Y(4260)}/6 \simeq 18$ MeV [22], we estimate $\Gamma_{ee}(Y(4260)) \simeq 100 \sim 800$ eV, which again is within the range of values estimated above.

(4) In a molecular picture for the $Y(4260)$, it appears natural that the $Z_c(3900)$ is observed in the decay [8], in line with observations. On the other hand, in the hadro-chamonium scenario, where the $Y(4260)$ is predominantly a compact charmonium state surrounded by an isoscalar pion cloud, it appears difficult to understand why the decay into its building blocks should run via an isovector intermediate state. Analogously, within the molecular picture for the $Y(4260)$ in Ref. [13], it was predicted that the $X(3872)$ should be produced in $Y(4260)$ radiative decays. Also, this transition would be difficult to explain within the hadro-charmonium interpretation. It should be mentioned that there are preliminary data available from BESIII, where the observation of $Y(4260) \to \gamma X(3872)$ was reported [29].

(5) In the hadronic molecule picture, one expects that the decay chain $Y(4260) \to D\bar{D}_1 \to D\bar{D}^*\pi$ is very important. This would lead to a prominent peak at the upper end of the $D^*\pi$ invariant mass spectrum due to the intermediate D_1 [28]. In contrast, one would not expect the same feature in the hadro-charmonium picture.

(6) The data for $e^+e^- \to D^*\bar{D}^*\pi$ [4], which is only a factor of 2–3 below those for $e^+e^- \to D^*\bar{D}\pi$ at 4260 MeV, provide a challenge to both pictures for the $Y(4260)$ hadro-charmonium as well as the molecule. Analogously to the remark at the end of item 1 above, a microscopic calculation of (D_1, D_2) scattering off (D, D^*) is necessary in order to see if the molecular ansatz is consistent with the data.

In summary, although the $(3/2)^+ + (1/2)^-$ charmed meson pair production vanishes in the heavy quark limit [15], we claim that the resulting suppression for the physical charm quark mass is not in conflict with the interpretation that the main component of the $Y(4260)$ is a D_1D molecule. The HQSS breaking effects at above 4 GeV can be large. We have examined known experimental constraints on the $Y(4260)$ and found that the hadronic molecular model does not contradict these constraints. On the other hand, we argue that phenomenology challanges the hadro-charmonium interpretation. Further high luminosity measurement at BESIII will help us to gain more insights into the nature of the $Y(4260)$ and to strengthen the statements given above. Especially, a measurement in the $D\bar{D}^*\pi$ channel with improved statistics will help to distinguish the hadronic molecular model from the hadro-charmonium one.

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