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Structure of the Hidden-Charm Exotic Vector Mesons

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We study the $q\bar{q}c\bar{c}$ $J^{PC} = 1^{--}$ isospin 0 systems using a quark hadron hybrid model, where the 14 relevant two-meson channels are coupled, while the quark degrees of freedom appear in the short range region. We find a pole near the $\omega\chi_{c1}$, $\overline{D}D_1$ and $\overline{D}D_1'$ thresholds with a very small width. We further estimate the effects of the coupling between this two-meson hadronic molecular state and the the $\psi(3S)$ and $\psi(4S)$ states and find it reduces the molecule mass a little. Although the calculated mass of this molecular state is still considerably higher than the observed $Y(4260)$, we argue that it can be a part of the $Y(4260)$ components.

KEYWORDS: exotic hadron, $Y(4260)$, hadronic molecule

1. Introduction

The $Y(4260)$ (or $\psi(4260)$) state was first observed by *BABAR* in the initial state radiation (ISR) process of e^+e^- collision at B factory with the invariant mass of $\pi^+\pi^- J/\psi$ [2]. It was confirmed by the CLEO [3] and Belle [4] collaborations in the same process. Recently, BESIII measured the $e^+e^- \to \pi^+\pi^- J/\psi$ cross section at center-of-mass energies from 3.77 to 4.60 GeV precisely and reported two clear resonance structures at (4222.0±3.1±1.4) MeV and (4320.0±10.4±7.0) MeV [5]. The former resonance agrees with the $Y(4260)$ though the mass is lighter than that of the previous experiments. The latter one agrees with $Y(4360)$, which had been observed only in the $\pi^+\pi^-\psi(2S)$ final state. Since it is produced from the e^+e^- annihilation, the quantum number of the Y states is $J^{PC} = 1^{--}$. The world average of the mass and width of the $Y(4260)$ are (4230±8) MeV and (55±19) MeV, respectively [6]. As for the decay mode, there are three noteworthy features: (1) the open charm decay modes have not been observed so far, even the $Y(4260)$ mass is well above the open charm threshold, (2) the exotic candidate $Z_c(3900)^\pm$ has been observed in the decay, $Y(4260) \to Z_c(3900)^\pm\pi^\mp$, (3) it has a radiative decay mode to another exotic candidate $X(3872)$.

Since there is always J/ψ (or η_c) found in the decay products, the $Y(4260)$ is considered to contain a charm-anti-charm quark pair. Simple $c\bar{c}$ charmonium states have been studied in the quark potential models theoretically [7]. They assigned the 1^{--} charmonia as $J/\psi(3097)\,(1^3S_1)$, $\psi(3686)\,(2^3S_1)$, $\psi(3770)\,(1^3D_1)$, $\psi(4040)\,(3^3S_1)$, $\psi(4160)\,(2^3D_1)$ and $\psi(4415)\,(4^3S_1)$. The $Y(4260)$ and $Y(4360)$ are sitting in between $\psi(4160)\,(2^3D_1)$ and $\psi(4415)\,(4^3S_1)$, where no corresponding charmonium state exists. This situation suggests that the Y states are not simple charmonia but exotic meson candidates [8]. Not that, the observed ψ states assigned above are not a pure $c\bar{c}$ states either. One has to consider

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the mixing to the exotic states and those ψ states.

Since the charmonium in the potential model does not fit to the $Y(4260)$, the natural extension is to introduce a light quark pair into the system. Introducing additional light quark pairs changes the parity, which can reduce the orbital angular momentum by one. We have applied this approach to the the LHCb pentaquarks, P_c, and found that the color octet uud in the $uudc\bar{c}$ configuration gives rise to resonances around $\Sigma_c^{(*)}\overline{D}^*$ thresholds [9]. When one restricts the quark degrees of freedom at the short range of the two hadrons, the model becomes a hadron model [10]. Here we investigate the J^{PC}=1^{--} $q\bar{q}c\bar{c}$ systems, employing a quark hadron hybrid model [1]. In this model, the asymptotic states are two mesons. In the short-range region, where the two mesons are close to each other, the quark degrees of freedom appears with the rearrangement between the $q\bar{q}$-$c\bar{c}$ and the $q\bar{c}$-$c\bar{q}$ channels. These quark effects can be expressed as a two-hadron interaction in this model, which enables us to solve rather complicated systems. As we will show later, we have found this model can produce a resonance for the J^{PC}=1^{--} $q\bar{q}c\bar{c}$ system. We further studied the effects of the mixing of the $q\bar{q}c\bar{c}$ and the $c\bar{c}$, which is found to be important for the $X(3872)$ [11, 12].

2. Quark Hadron Hybrid Model

First we classify the $q\bar{q}c\bar{c}$ $J^{PC} = 1^{--}$ systems with the orbital $(0s)^2 0p$ configuration by mapping them onto two-meson states. The two-meson states we consider here consist of the $L = 0$ and 1 quark-antiquark mesons: those of $^1S_0(J^{PC} = 0^{-+})$, $^3S_1(1^{--})$, $^1P_1(1^{+-})$, and $^3P_J(J^{++})$. Combining the $q\bar{q}$ and the $c\bar{c}$ states of the above quantum numbers, one can make ten $q\bar{q}c\bar{c}$ $(0s)^2 0p$ 1^{--} states as listed in Table I.

Table I. $q\bar{q}c\bar{c}$ spin flavor orbital classification. S is the meson spin, and L_r is the relative meson orbital angular momentum.

$q\bar{q}$	$c\bar{c}$	S	L_r	J^{PC}	mesons	$q\bar{q} \leftrightarrow c\bar{c}$
$^1S_0$	$^1P_1$	1	0	1^{--}	$\eta\, h_{c1}$	$h_1\, \eta_c$
$^3S_1$	^3P_J	1	0	1^{--}	$\omega\, \chi_{cJ}$	$f_J\, J/\psi$
$^1S_0$	$^3S_1$	1	1	1^{--}	$\eta\, J/\psi$	$\omega\, \eta_c$

There are two independent color configurations for the totally color-singlet $q\bar{q}c\bar{c}$ system. One is the configuration in which both of the $q\bar{q}$ and $c\bar{c}$ are color-singlet, which we denote $(q\bar{q})_1(c\bar{c})_1$. The other is the one where both of them are color-octet, $(q\bar{q})_8(c\bar{c})_8$. The former can be mapped onto the two-meson states directly, but the latter cannot. It is necessary to apply a quark rearrangement in the color spin orbital space in order to map it onto the two-meson states:

$$(q\bar{q})_8(c\bar{c})_8 \quad = \quad \sqrt{\frac{9}{8}}T^{-1}(q\bar{c})_1(c\bar{q})_1 - \sqrt{\frac{1}{8}}(q\bar{q})_1(c\bar{c})_1 \;, \qquad (1)$$

where T is the transfer matrix of the ten channels in the spin orbital space. There are also ten $(q\bar{c})_1(c\bar{q})_1$ states for 1^{--} systems:

$$\begin{aligned} &[\overline{D}D_1]_-,\ [\overline{D}D_1']_+,\ [\overline{D}^*D_0]_+,\ [\overline{D}^*D_1]_-,\ [\overline{D}^*D_1']_+,\ [\overline{D}^*D_2]_+ \quad \text{for relative } S \text{ wave} \\ &\overline{D}D,\ [\overline{D}D^*]_-,\ (\overline{D}^*D^*)|_{S=0,2} \quad \text{for relative } P \text{ wave} \end{aligned} \qquad (2)$$

where $[\bar{A}B]_\pm$ stands for $(\bar{A}B \pm \bar{B}A)/\sqrt{2}$. Here we would like to emphasize that, suppose one of the $(q\bar{q})_8(c\bar{c})_8$ states plays an important role, it is necessary to take many two-meson channels into account in order to see the effects. Let us point out also that these 20 1^{--} two-meson states are independent but not orthogonal to each other as seen from eq. (1). The $\overline{D}D_1$ state is orthogonal to the $\overline{D}D_1'$, for example. The $\overline{D}D_1$ and $\omega\chi_{c1}$ states, for example, however, are independent but not orthogonal to each other due to the quark degrees of freedom.

We employ a quark Hamiltonian which has the kinetic term and the two-body interaction terms: the central, the spin-spin, the spin-orbit, and the tensor terms. They are considered to come from the confinement force and one-gluon exchange force as those in the conventional quark model. We assume that all the interaction terms of the present model have the color factor, $\lambda \cdot \lambda$. Since we only consider the quark degrees of freedom within the orbital $(0s)^2 0p$ configuration, it is enough to determine the size of the matrix elements of the interaction with respect to the $0s$ or $0p$ configurations; we do not have to assume the potential function shape in the orbital space. So, let us just consider the matrix elements of the quark Hamiltonian with respect to the 0ℓ $q\overline{q}$ or qq state:

$$\langle H_q \rangle = \sum_i (m_q + \langle K_q \rangle) + \sum_{i<j} \lambda_i \cdot \lambda_j (c^c_{0\ell} + c^{\sigma\sigma}_{0\ell} \sigma_i \cdot \sigma_j + c^{LS}_{0\ell} O^{LS}_{ij} + c^{ALS}_{0\ell} O^{ALS}_{ij} + c^T_{0\ell} O^T_{ij}), \tag{3}$$

where $c_{0\ell}$'s are the matrix elements, and O's are the noncentral operators of the quarks.

We obtain the c's from the hadron mass spectra assuming that the orbital part of the $q\overline{q}$ mesons or q^3 baryons can also be approximated by the $0s$ or $0p$ configuration of the same size parameters as those in the above $(0s)^2 0p$ configuration. This assumption is valid when one takes the size parameter to be $b_{red} = \sqrt{x_0^2/m_{red}}$, where x_0 is a constant (~ 0.6 fm$^{1/2}$) and m_{red} is the reduced mass of the relevant quarks [9]. The b_{red} between $u\overline{u}$, $c\overline{u}$, or $c\overline{c}$ is 0.69, 0.53, or 0.29 fm, respectively.

The matrix elements for the interaction between c and $\overline{c}$, $c^O_{0\ell}(c\overline{c})$, can be determined from the $c\overline{c}$ meson masses straightforwardly. We use not all the light hadron masses as they are, however, in order to determine the c's because some of the light mesons are not regarded as a simple $q\overline{q}$ meson. We take $(m_\omega + \frac{64}{3} c^{\sigma\sigma}_{0s}(uu))$ for the $u\overline{u}(^1S_0)$ mass with $c^{\sigma\sigma}_{0s}(uu) = -\frac{1}{32}(2m_{\Sigma_c^*} + m_{\Sigma_c} - 3m_{\Lambda_c}) = -19.70$ MeV. As for the qc or qs interaction, we use the same c's for the ones between $q\overline{c}$ or $q\overline{s}$ except for the $c^{\sigma\sigma}_{0s}$, which we obtain from the baryon mass spectra: we use $c^{\sigma\sigma}_{0s}(us) = -\frac{1}{16}(m_{\Sigma^*} - m_\Sigma) = -11.96$ MeV. Using $-\frac{3}{32}(2m_{\Xi_c^*} - m_{\Xi_c'} - m_{\Xi_c}) = c^{\sigma\sigma}_{0s}(us) + c^{\sigma\sigma}_{0s}(uc) + c^{\sigma\sigma}_{0s}(sc)$ and assuming $c^{\sigma\sigma}_{0s}(uc) = c^{\sigma\sigma}_{0s}(sc)$, we have $c^{\sigma\sigma}_{0s}(uc) = -5.47$ MeV. Moreover, we assume that $D_1(2420)$ $[D_1'(2430)]$ corresponds to the $c\overline{q}$ state where the light quark spin with the angular momentum, $j_{\overline{q}} = s_{\overline{q}} + \ell$, is $\frac{3}{2}$ $[\frac{1}{2}]$.

Now let us define the two-meson interaction arising from the quark degrees of freedom, by taking the matrix elements of the quark Hamiltonian with respect to the quark configuration. Nonzero values appear only in the off-diagonal part where the rearrangement of quarks occurs, from which we define the two-meson potential as:

$$\Big\langle (q\overline{q})_1 (c\overline{c})_1(\alpha); (0s)^2 0p \Big| (H_q - E) \Big| (q\overline{c})_1 (c\overline{q})_1(\beta); (0s)^2 0p \Big\rangle = V_{\alpha\beta}(E) \tag{4}$$

The potential $V_{\alpha\beta}(E)$ depends on the energy because the overlapping term which proportional to E survives due to the rearrangement.

So, we have the Hamiltonian for the two meson systems as:

$$H_h^{\alpha\beta} = (M_1^\alpha + M_2^\alpha + K^\alpha)\delta_{\alpha\beta} + |0\ell\rangle V_{\alpha\beta}(E) \langle 0\ell| \tag{5}$$

Here, the M_1^α and M_2^α are the mass of each of the two mesons and the K^α term comes from the relative meson kinetic energy. The $|0\ell\rangle$ is a projection operator to the orbital 0ℓ configuration.

This Hamiltonian can be used also for the long range region, where the system is free. There is no interaction among the $c\overline{c}$-$q\overline{q}$ channels, nor among the $\overline{D}D$ channels. The Hamiltonian has the interaction of a range of the hadron size, which appears only between the $c\overline{c}$-$q\overline{q}$ and the $\overline{D}D$ channels. In this work, we further restrict ourselves to use the channels whose relative orbital momentum is S-wave: we take the channels where $0\ell = 0s$ in eq. (5). The above meson interaction becomes a simple gaussian separable potential, which enables us to solve the many-channel coupled systems rather easily. Let us remark that we replace the reduced mass in the denominator with that of the real meson masses in the kinetic term of the above equation, K^α, in order to make the kinematics of the system realistic. Let us also note that we ignore the kinetic term which operates over the rearrangement part of the normalization in eq. (5).

In the $c\bar{c}q\bar{q}$ 1^{--} systems, we have found a pole with an energy of $4293.37 - 0.23i$ MeV. The width of this resonance is very small, 0.5 MeV, and the real part of the energy is very close to the two-meson thresholds: the $\overline{D}^+ D_1^-$ threshold, 4292.85 MeV, the $\omega\chi_{c1}$, 4293.32 MeV, and the $\overline{D}^+ D_1'^-$, 4296.65 MeV. Since the resonance is close to the thresholds, the components of this resonance are mostly these three two-meson states. The resonance does not correspond directly to the observed $Y(4260)$, because it requires an additional attraction to reduce the mass by about 60 MeV. It, however, strongly suggests that this resonance, or the quark rearrangement, induces the exotic mesons like $Y(4260)$.

There is a model ambiguities which comes from the meson assignments, or level mixing of the mesons, in the process of obtaining the matrix elements c's. The decay widths of some of the mesons which construct the two-meson states, *e.g.*, the D_1 or D_1' mesons, are large, and should be included when one performs more realistic calculation. Moreover, it is probably necessary to include the pion exchange effects in the $\overline{D}D$ channels. It is also interesting to see the effects from the coupling to the $c\bar{c}$ mesons, such as $\psi(3S)$ or $\psi(4S)$, with an annihilation of the light quark pair.

Since $Y(4260)$ is produced by the e^+e^- experiments, it should have an $c\bar{c}$ component. So, We estimate the effect of the mixing of $\psi(3S)$ and $\psi(4S)$, the energetically closest two charmonia, into the $\overline{D}D_1$ hadronic molecule by a separable potential in the same manner as in [11]. We assume that the coupling strength of the $\psi(3S)$ and the $\overline{D}D_1$ is the same as that of the $\psi(4S)$ and the $\overline{D}D_1$. The size of the coupling strength is chosen so that this mixing alone reproduces the observed $\psi(4S)$ width. Since the $\overline{D}D_1$ threshold is located in the middle of $\psi(3S)$ and $\psi(4S)$ masses, the mixing effect on the molecular pole is rather small due to the cancellation. We found that the mixing of the ψ states reduces the pole energy by less than 10 MeV.

3. Summary

In this work, we investigate the $q\bar{q}c\bar{c}$ $J^{PC} = 1^{--}$ system by employing a quark hadron hybrid model. We introduce the 14 relevant two-meson channels, whose short range includes the quark degrees of freedom. We find a pole just around the $\omega\chi_{c1}$, $\overline{D}D_1$, and $\overline{D}D_1'$ thresholds with a very narrow width. The results strongly suggest that the $q\bar{q}c\bar{c}$ configuration contribute largely to form the observed exotic mesons like $Y(4260)$. The method employed in the present work can be applied to the charged multiquark system, such as $u\bar{d}c\bar{c}$, or to the system with different flavors, such as $s\bar{s}c\bar{c}$, which we are now working on.

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