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The $Y(4260)$ as an $\omega\chi_{c1}$ molecular state

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Abstract

It is suggested that the newly observed $Y(4260)$ by BaBar Collaboration is a molecular state composed of an ω and a χ_{c1}. Both the production and decay properties are discussed. A consequence for this molecular state, $Y(4260)$, is that it decays into $\pi^+\pi^-\pi^0\chi_{c1}$ with similar rate to $\pi^+\pi^-J/\psi$. It is also expected that $Y(4260)\to\pi^0\pi^0J/\psi$ is produced at half rate as $Y(4260)\to\pi^+\pi^-J/\psi$. These decay modes should be searched for in the B factories using initial state radiative return data and B decay data as well.

1. Introduction

Recently, in studying the initial state radiation events, $e^+e^-\to\gamma_{\rm ISR}\pi^+\pi^-J/\psi$ ($\gamma_{\rm ISR}$: initial state radiation photon) with 233 $\rm fb^{-1}$ data collected around $\sqrt{s}=10.58$ GeV, BaBar Collaboration observed an accumulation of events near 4.26 $\rm GeV/c^2$ in the invariant-mass spectrum of $\pi^+\pi^-J/\psi$ [1]. The fit to the mass distribution yields 125 ± 23 events with a mass of $4259\pm 8^{+2}_{-6}$ $\rm MeV/c^2$ and a width of $88\pm 23^{+6}_{-4}$ $\rm MeV/c^2$.

Since the resonance is produced in initial state radiation from e^+e^- collision, its quantum number $J^{PC}=1^{--}$. However, this new resonance seems rather different from the known charmonium states with $J^{PC}=1^{--}$ in the same mass scale, such as $\psi(4040)$, $\psi(4160)$, and $\psi(4415)$. Being well above the $D\bar{D}$ threshold, instead of decaying predominantly into $D\bar{D}$, the $Y(4260)$ shows strong coupling to $\pi^+\pi^-J/\psi$ final state. So this new resonance does not seem to be a usual charmonium state but rather an exotic. The strange properties exhibited by the $Y(4260)$ have triggered many theoretical discussions [2–8].

One suggestion is that the $Y(4260)$ is the first orbital excitation of a diquark–antidiquark state ($[cs][\bar{c}\bar{s}]$) [3]. By virtue of this scheme, the mass of such a state is estimated to be 4.28 $\rm GeV/c^2$, which is in good agreement with the observation. A crucial prediction of the scheme is that the $Y(4260)$ decays predominantly into $D_s\bar{D}_s$.

Zhu scrutinized many possible interpretations for the $Y(4260)$ and excluded the possibility of its being a conventional $c\bar{c}$ state, a $D\bar{D}$ or $\omega J/\psi$ molecule, or a glueball using the available experimental information [2]. As to the four-quark hypothesis, it is disfavored by its small total width and the non-observation of the $D\bar{D}$ decay mode. The author regarded a hybrid charmonium as the most plausible interpretation, which was consistent with all the experimental information by then. Some other work to explain the $Y(4260)$ as a hybrid were put forth afterwards [5,6]. In the light of the lattice inspired flux-tube model, the calculation shows that the decays of the hybrid meson to a pair of ground state 1S conventional mesons are suppressed [9,10].

Unlike the above models, Qiao proposed that the $Y(4260)$ might be a baryonium, containing charms, configured by the Λ_c–$\bar{\Lambda}_c$ [8]. This provides a natural explanation for the absence of $J/\psi K\bar{K}$ and $D\bar{D}$ in its decays. Moreover, this scheme predicts

$$\frac{\Gamma[Y(4260)\to\pi^0\pi^0J/\psi]}{\Gamma[Y(4260)\to\pi^+\pi^-J/\psi]}\approx 1, \tag{1}$$

which can be tested by the experiments.

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Besides the fore-mentioned various interpretations, there is another scheme which suggests that the $Y(4260)$ be a χ_c–ρ molecule [7]. The authors qualitatively explained that the decay rate of $Y(4260) \to \pi^+\pi^- J/\psi$ is greater than $Y(4260) \to D\bar{D}$, and pointed out that $Y(4260) \to \pi^0\pi^0 J/\psi$ must be suppressed since ρ^0 only decays into $\pi^+\pi^-$ but not $\pi^0\pi^0$.

In this Letter, we propose the $Y(4260)$ as a bound state composed of the vector meson $\omega(783)$ and the P-wave charmonium state $\chi_{c1}(3510)$. In this scenario, we discuss its decay into $\pi\pi J/\psi$, and expect that it decays into $\pi^+\pi^-\pi^0\chi_{c1}$ with considerably large rate. The search for the latter is experimentally reachable using the available data from the B-factories. In addition, based on our scenario, we present some predictions which are distinctive from those of other models.

2. $Y(4260)$ as $\omega\chi_{c1}$ molecular state

Since the $Y(4260)$ decays into $\pi^+\pi^- J/\psi$, it is very natural to consider that there is $c\bar{c}$ content in its wave function. We try to find a narrow charmonium state and a narrow light meson to form a $J^{PC} = 1^{--}$ state, with the sum of their masses slightly above the mass of the $Y(4260)$. There are not many such combinations, and we find that the one consisting of a 1^{--} state ω (mass 782.59 MeV/c^2 [11]) and a 1^{++} state χ_{c1} (mass 3510.59 MeV/c^2 [11]) satisfies the criteria. The sum of the masses, 4293 MeV/c^2, is higher than the mass of the $Y(4260)$ by 34 MeV/c^2, which is considered as the binding energy between the two constituents to form the bound state. The orbital angular momentum between ω and χ_{c1} can be zero to get the quantum number $J^{PC} = 1^{--}$. In contrast to the proposal of Ref. [7], here the $Y(4260)$ is an isoscalar particle and has no isospin partner.

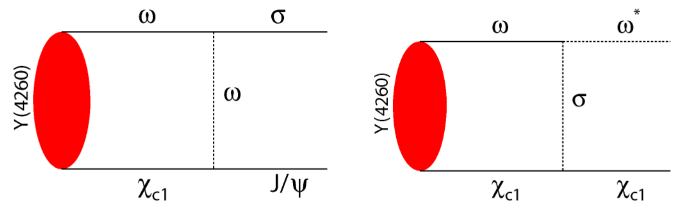
3. Decays of the $Y(4260)$

The decay of the $Y(4260)$ to the observed $\pi^+\pi^- J/\psi$ mode is illustrated in Fig. 1(a). In this picture, a virtual ω is exchanged between the two bound constituents, and a scalar particle like σ or $f_0(980)$, and a vector charmonium like J/ψ, $\psi(2S)$, or $\psi(3770)$ are produced. This decay mechanism can be verified by looking at the $\pi^+\pi^-$ invariant mass distribution in the BaBar data [1], which shows signature of σ at low mass side and of $f_0(980)$ at higher mass side. In this scenario, according to the isospin symmetry, we expect

$$\frac{\Gamma[Y(4260) \to \pi^0\pi^0 J/\psi]}{\Gamma[Y(4260) \to \pi^+\pi^- J/\psi]} \approx 0.5, \tag{2}$$

which is different from the predictions of being 1 in Ref. [8] (Eq. (1)) and being 0 in Ref. [7]. This provides a proof to our scenario.

The $Y(4260)$ also decays via the exchange of a scalar particle as illustrated in Fig. 1(b). In this case, the ω inside the $Y(4260)$ emits a scalar and turns into a photon or a virtual ω, which goes to $\pi^+\pi^-\pi^0$ in final states; while the χ_{c1} inside the $Y(4260)$, after absorbing the virtual scalar, becomes a real χ_{c1} particle, which decays to $\gamma J/\psi$ with about 30% branching fraction [11]. So a search for the $Y(4260)$ decays into $\gamma\chi_{c1} \to \gamma\gamma J/\psi$, or $\omega^*\chi_{c1} \to \pi^+\pi^-\pi^0\gamma J/\psi$, provides another test of our scenario.



(a) ω exchange (b) σ exchange

Fig. 1. Decay mechanism of the $Y(4260)$ into a charmonium together with light hadrons.

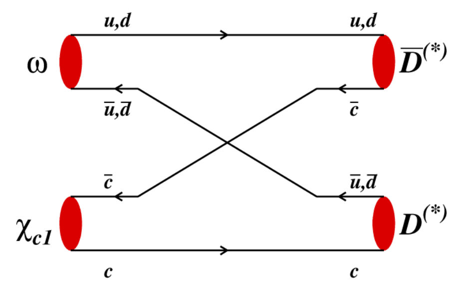


Fig. 2. Decay mechanism for $Y(4260) \to D^{(*)}\bar{D}^{(*)}$ final states.

The exchanges of light hadrons between the ω and χ_{c1} inside the molecular state shown in Fig. 1 require exchange of at least two or three gluons in the quark level and thus the processes are OZI suppressed [12], which in principle, will be smaller than the final states produced by changing quarks in the two constituents in the initial states directly, as shown in Fig. 2. However, in these decays of the $Y(4260)$ into $D^{(*)}\bar{D}^{(*)}$ (which indicates possible combinations such as $D\bar{D}$, $D^*\bar{D}$, $D\bar{D}^*$, and $D^*\bar{D}^*$), the rate is suppressed due to color reconnection. The decays of the $Y(4260)$ into charmed meson-pair with strange quarks have even lower rates since a strange quark pair must be created.

From the above discussions, we see that the two decay mechanisms, as shown in Figs. 1 and 2, may have comparable decay rates. The decays of the $Y(4260)$ into a charmonium state together with a photon or some light mesons like pions will be better tagging modes due to the clear signature and clean environment; while the decays of the $Y(4260)$ to the charmed mesons, have not been discovered experimentally by now because of the small branching fractions of the D decay modes.

4. Production of the $Y(4260)$

The production of the $Y(4260)$ in e^+e^- collision occurs via the so-called hairpin mechanism [13] which is shown in Fig. 3. Since the ω is produced from the gluons emitted by the $c\bar{c}$ quarks, the production rate is small relative to the ψ states above 4 GeV/c^2. The ω may be produced from a photon emitted from $c\bar{c}$ quarks too, but this amplitude is even smaller since it is proportional to the QED fine structure constant α.

The $Y(4260)$ was also found in B decays in association with a K meson [14]. It may be produced via a spectator diagram, as shown in Fig. 4(a) and (c), and via a hairpin diagram, as shown in Fig. 4(b) and (d). Although in the hairpin mechanism, the ω is produced from the gluons emitted by the quarks, so its amplitude is thought to be suppressed, but there is indication from the weak decays of charmed mesons that such suppression is not severe: the experiments measured [11] $\mathcal{B}(D^0 \to \phi \bar{K}^0) = (9.4 \pm 1.1) \times 10^{-3}$ and $\mathcal{B}(D_s^+ \to \omega\pi^+) = (2.8 \pm 1.1) \times 10^{-3}$ can be explained by the hairpin diagrams [15] shown in Fig. 5. They are smaller by only about an order of magnitude compared to the signature modes which go through spectator diagrams without color reconnection: $\mathcal{B}(D^0 \to \rho^+ K^-) = (10.1 \pm 0.8)\%$ and $\mathcal{B}(D_s^+ \to \phi\pi^+) = (3.6 \pm 0.9)\%$ [11]. If this is extended to the weak decays of B mesons, one may expect that the diagrams of Fig. 4(b) and (d) be important in the production of the $Y(4260)$ in B decays.

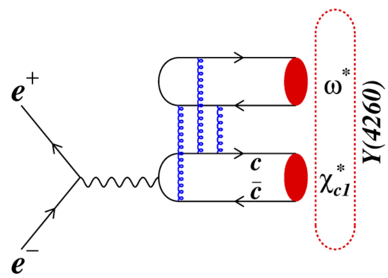


Fig. 3. Production mechanism of the $Y(4260)$ in e^+e^- annihilation. The particle with "∗" is virtual.

5. Discussions

Although the above discussions are limited to the $\omega\chi_{c1}$ bound state, the scenario can be naturally extended to other bound states consisting of a light meson and a charmonium state. If the bound state of χ_{c1} and ω exists, by the same mechanism, a χ_{c0} or a χ_{c2} can also form a bound state with an ω. At the same time, besides ω, other $SU(3)$ singlet light hadrons, like ϕ, η, and η', can also form bound states with charmonia, such

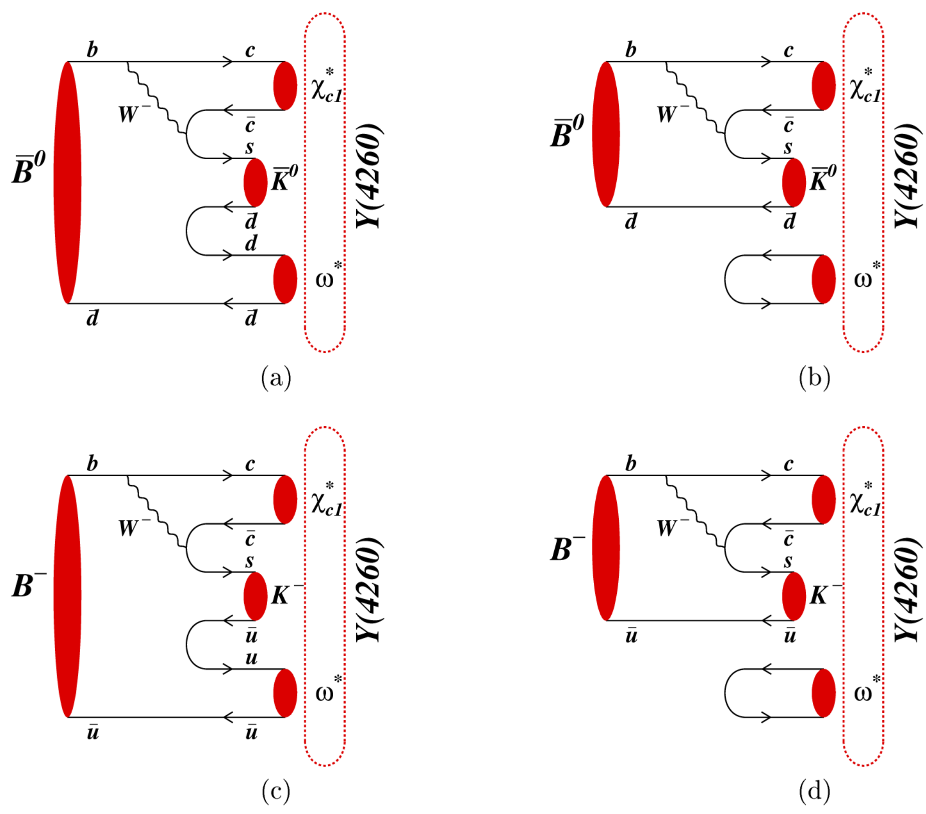


Fig. 4. Production mechanism of the $Y(4260)$ in B decays. (a) and (b) are for $\bar{B}^0$ decays, and (c) and (d) are for B^- decays. The particle with "∗" is virtual.

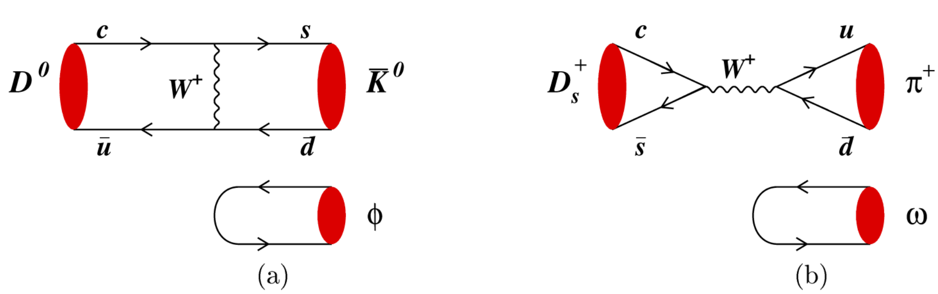


Fig. 5. Hairpin diagrams for $D^0 \to \bar{K}^0\phi$ (a) and $D_s^+ \to \pi^+\omega$ (b) decays.

Table 1
The sum of the masses (in MeV/c^2) of a light meson and a charmonium state. A bound state of each possible combination could be produced by emitting a few or a few ten MeV binding energy. The numbers underlined may correspond to the states which have been observed experimentally

	J/ψ	χ_{c0}	χ_{c1}	χ_{c2}	h_c
η	3645	<u>3963</u>	4058	4104	4073
η'	4055	4373	4468	4514	4483
ω	<u>3880</u>	4198	<u>4293</u>	4339	4308
ϕ	4116	4435	4530	4576	4544

as J/ψ, $\psi(2S)$, χ_{c0}, χ_{c1}, χ_{c2} and h_c. Table 1 gives the sum of the masses of a light hadron (η, η', ω and ϕ) and a charmonium state (J/ψ, χ_{c0}, χ_{c1}, χ_{c2} and h_c). Considering a binding energy of a few to a few ten MeV in forming the bound state, we can see the newly observed states $X(3872)$ [16] could be interpreted as an $\omega J/\psi$ bound state, the $Y(3940)$ [17] could be an $\eta\chi_{c0}$ bound state. Furthermore, there are many other possible combinations which have no experimental evidence yet. Their decay properties can be analyzed in the same way as in this Letter, and the production of these bound states in e^+e^- collision (if it is a $J^{PC} = 1^{--}$ state) and in B decays follows the similar mechanisms described in previous sections. These bound states should be searched for by the B-factories both in ISR data and in B decays.

6. Summary

The $Y(4260)$ observed by the BaBar Collaboration is proposed as an $\omega\chi_{c1}$ molecular state, which may decay into a charmonium state together with some light particles, with comparable rates as for the decays to open charm final states. A few predictions are made and could be tested in the B-factories. The decays of $Y(4260) \to \pi^+\pi^-\pi^0\chi_{c1}$ or $\gamma\chi_{c1}$ should be searched for in high priority.

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