Possible molecule structure of the newly observed $Y(4260)$

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We suggest that the newly observed resonance $Y(4260)$ is a $\chi_c - \rho^0$ molecule, which is an isovector. In this picture, we can easily interpret why $Y(4260) \rightarrow \pi^+ \pi^- J/\psi$ has a larger rate than $Y(4260) \rightarrow D\bar{D}$ which has not been observed, and we also predict existence of the other two components of the isotriplet and another two possible partner states which may be observed in the future experiments. A direct consequence of this structure is that for this molecular structure $Y(4260) \rightarrow \pi^+ \pi^- J/\psi$ mode is more favorable than $Y(4260) \rightarrow K\bar{K}J/\psi$ which may have a larger fraction if other proposed structures prevail.

I. GENERAL DISCUSSION

The *BABAR* collaboration has recently announced that a very intriguing new state/structure $Y(4260) \rightarrow \pi^+ \pi^- J/\psi$ is observed in $e^+ e^- \rightarrow \mathrm{ISR}\pi^+ \pi^- J/\psi$, where ISR stands for Initial-State Radiation [1]. Their results indicate that $Y(4260)$ has spin-parity $J^{PC} = 1^{--}$. Its mass and width are

$$m = 4.26 \text{ GeV/c}^2 \quad \text{and} \quad \Gamma \sim 90 \text{ MeV/c}^2.$$

An enhancement near 4.26 GeV/c^2 is clearly observed in $e^+ e^- \rightarrow \mathrm{ISR}\pi^+ \pi^- J/\psi$ channel, but has not been observed in $e^+ e^- \rightarrow$ hadrons, especially not in the $D_{(s)}\bar{D}_{(s)}$ channel. It may imply that the branching ratio of $Y(4260) \rightarrow J/\psi\pi^+ \pi^-$ is much larger than that of $Y(4260) \rightarrow D\bar{D}$ [2].

Since its remarkable characteristics, this discovery stimulates intensive discussions about the structure of $Y(4260)$, especially if there is some new physics involved.

First, it exists in the energy-range of ψ family, and one may expect that it involves both c and $\bar{c}$ since in its strong-decay products there is no single charm (anticharm). On other aspects, $Y(4260) \rightarrow J/\psi\pi^+ \pi^-$ is a three-body decay whereas $Y(4260) \rightarrow D\bar{D}$ is a two-body decay, and usually the former is about two orders smaller than the later due to a suppression from the phase space of final state. However, the data indicate a reversed pattern. This characteristic challenges our theory and demands a plausible interpretation.

The newly observed resonance is very unlikely to be accommodated in the regular $c\bar{c}$ structure even with higher radial and/or orbital excitations. It may be a clear signal for a new structure. In Ref. [2–4], the authors analyze the characteristics of $Y(4260)$ and proposes that $Y(4260)$ is perhaps a hybrid charmonium. Different from this explanation, Maiani et al. consider that the new resonance $Y(4260)$ may be the first orbital excitation of a diquark-antidiquark state $[cs][\bar{c}\bar{s}]$ [5]. With a different point of view, instead of supposing $Y(4260)$ to be an exotic state, Llanes-Estrada [6] proposes that the experimental evidence is not compelling to declare this state an exotic, and can be fitted within a standard quarkonium scenario.

In this work, we propose an alternative possibility that $Y(4260)$ is an s-wave molecular state of $\rho - \chi_{c1}(1P)$, which is an isovector. In this framework, we can naturally explain why the branching ratio of $Y(4260) \rightarrow J/\psi\pi^+ \pi^-$ is larger than that of $Y(4260) \rightarrow D\bar{D}$. Meanwhile, we further predict existence of possible partner resonances of $Y(4260)$.

In next section we present our picture in detail and then we will draw our conclusion and make a discussion in the last section.

II. THE MOLECULAR STRUCTURE FOR Y(4260).

Actually, there has been a long history about the molecular structure of hadrons. To explain some phenomena which are hard to find natural interpretations in the regular valence quark structure, people have tried to look for new structures beyond it. The molecular structure is one of the possible candidates. Okun and Voloshin studied the interaction between charmed mesons and proposed possibilities of the molecular states involving charmed quarks [7]. Rujula, Geogi, and Glashow suggested that $\psi(4040)$ is a $D^*\bar{D}^*$ molecular state [8]. Moreover, the measured resonances $f_0(980)$, $a_0(980)$ may be reasonably interpreted as $K\bar{K}$ molecules [9]. It seems that at the energy region of charm, molecular structure might be more favorable than at other energy regions.

Therefore, before invoking some fancy structures, let us study possibility to construct a molecular state for $Y(4260)$ and see if it coincides with the observed characteristics.

From the Data-book [10], we find that three particles χ_{c0}, χ_{c1} and χ_{c2} in the $c\bar{c}$ meson spectrum may be candidates for the constituents in $Y(4260)$. The quantum numbers of χ_{c0}, χ_{c1} and χ_{c2} are $J^{PC} = 0^{++}$, 1^{++} and 2^{++} respectively. If combining them with ρ meson to construct $\chi_c - \rho$ systems, one can obtain states with spin-parity 1^{--}. Meanwhile, the masses of χ_{c0}, χ_{c1} and χ_{c2} are well measured as 3415.19 ± 0.34 MeV, 3510.59 ± 0.10 MeV and 3556.26 ± 0.11 MeV, thus we have that $M_{\chi_c} + M_\rho$ is 4185 MeV, 4280 MeV, and 4326 MeV, respectively, for χ_{c0}, χ_{c1} and χ_{c2}.

For an s-wave molecular state, one should expect that the sum of the constituent masses is closer to the mass of the resonance. The difference is due to the interaction between the constituents which in general results in a negative binding energy for s-wave. For the three-combinations $\rho - \chi_{c0}$, $\rho - \chi_{c1}$ and $\rho - \chi_{c2}$, one can observe that the mass sum of ρ and χ_{c1} is mostly close to the mass of $Y(4260)$. Based on the above considerations, we propose that $Y(4260)$ may be a molecular state of ρ and χ_{c1}. Namely the mass sum of ρ and χ_{c1} is about 20 MeV above 4260 MeV and the difference is paid to the negative binding energy.

The decay pattern of $Y(4260)$ is the most important issue to concern, because it may provide us the information about the structure of $Y(4260)$.

In the Fig. 1, we present the quark diagrams for $Y(4260) \to J/\psi \pi^+ \pi^-$ and $Y(4260) \to D\bar{D}$.

For Fig. 1(a) and 1(b), the transition matrix elements can be expressed as

$$\mathcal{M}(Y(4260) \to J/\psi \pi^+ \pi^-) = \langle \rho^0, J/\psi | \mathcal{H}_{\text{dis}} | Y(4260) \rangle$$
$$\times \langle \pi^+ \pi^- | \mathcal{H} | \rho^0 \rangle, \qquad (1)$$

$$\mathcal{M}(Y(4260) \to D\bar{D}) = \langle D\bar{D} | \mathcal{H}_{\text{cross}} | Y(4260) \rangle, \qquad (2)$$

where $\mathcal{H}_{\text{dis}}$ corresponds to the Hamiltonian which breaks the bound state $Y(4260)$ into free J/ψ and ρ^0 via exchanging σ meson (maybe, exchanges of multi-soft-gluons and even glueball of 0^{++} can also contribute, but definitely $\sigma -$ exchange plays the leading role), $\mathcal{H}$ is a strong interaction which causes ρ^0 decay into $\pi^+ \pi^-$. $\mathcal{H}_{\text{cross}}$ is an interaction, by which quarks (antiquarks) in χ_c and ρ^0 exchange and turn into hadronic D and $\bar{D}$, in the process quark lines cross with each other [see Fig. 1(b)].

χ_{c1} is a 1^{++} axial vector, J/ψ is a 1^{--} vector and both of them are isosinglet, the couplings of $\chi_{c1} - \pi(\rho) - \chi_{c1}$ and $\chi_{c1} - \pi(\rho) - J/\psi$ are forbidden by the isospin conservation, and only σ of 0^{++} can be exchanged and is the main contribution to the potential which holds the constituents in a molecule. The interactions of $\chi_{c1} - \sigma - \chi_{c1}$ and $\chi_{c1} - \sigma - J/\psi$ are obviously OZI suppressed [11], so cannot be very large. One may write down the effective Lagrangians

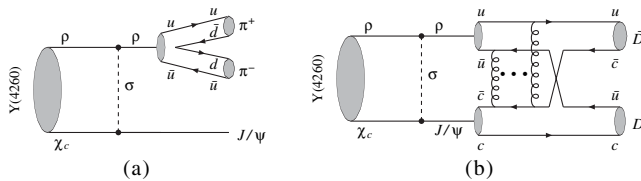$$L_1 = g_1 A_{1\mu} A_1^\mu \sigma, \quad \text{for } \chi_{c1} - \sigma - \chi_{c1},$$

FIG. 1. (a) and (b) correspond to $Y(4260) \to J/\psi \pi^+ \pi^-$ and the $Y(4260) \to D\bar{D}$ decays, respectively.

and

$$L_2 = g_2 \tilde{F}_{1\mu\nu} F_2^{\mu\nu} \sigma, \quad \text{for } \chi_{c1} - \sigma - J/\psi,$$

where

$$\tilde{F}_{1\mu\nu} \equiv \frac{1}{2} \epsilon_{\mu\nu\alpha\beta} F_1^{\alpha\beta},$$

and $A_{1\mu}$, $A_{2\mu}$ correspond to axial vector χ_{c1} and vector J/ψ respectively.

It is supposed that the σ exchange provides an attractive potential $\propto -e^{-m_\sigma r}/r$ between χ_{c1} and ρ to construct a bound state. Apparently, the coupling is OZI suppressed, and the binding is relatively loose.

More concretely, in Fig. 1(a), χ_c may convert into J/ψ mainly via exchanging σ particle with the constituent ρ meson. It is noted that L_2, which turns χ_{c1} into J/ψ is a p-wave interaction and proportional to the linear momentum to guarantee the parity match. The differentiation may result in an opposite sign to the potential between χ_{c1} and ρ^0 and provide an effective repulsion. Then the bound state dissolves into free J/ψ and ρ, and then a strong decay of $\rho^0 \to \pi^+ \pi^-$ follows. Here, for a general discussion, we ignore all the dynamical details and make only an estimate on the order of magnitude. Since the branching ratio of $\rho^0 \to \pi^+ \pi^-$ is almost 100%, we can suppose that the transition of the constituent of $Y(4260)$, i.e. ρ^0 to $\pi^+ \pi^-$ is overwhelming.

The total width is then,

$$\Gamma(Y(4260) \to J/\psi \pi^+ \pi^-) = \frac{1}{2M} \int \frac{d^3 p_{J/\psi}}{(2\pi)^3} \frac{1}{2E_{J/\psi}} \frac{d^3 p_\rho}{(2\pi)^3} \frac{1}{2E_\rho}$$
$$\times (2\pi)^4 \delta^4(M - P_{J/\psi} - P_\rho)$$
$$\cdot |\mathcal{M}(Y(4260) \to J/\psi + \rho^0)|^2$$
$$\times BR(\rho^0 \to \pi^+ \pi^-), \qquad (3)$$

where M is the mass of $Y(4260)$ and $P_{J/\psi}$, $p_{J/\psi}$, P_ρ, p_ρ are the four- and three-momenta of J/ψ and ρ respectively.

Comparing with Fig. 1(a), Fig. 1(b) involves an extra color recombination process which leads to a suppression, this suppression factor is

$$\frac{|\mathcal{M}(Y(4260) \to D\bar{D})|}{|\mathcal{M}(Y(4260) \to J/\psi \pi^+ \pi^-)|} \propto \alpha = \frac{1}{3}. \qquad (4)$$

There may be a numerical factor g coming from dynamics and it is completely a nonperturbative QCD factor. For a rough estimate it can be approximated as unity.

$Y(4260) \to J/\psi \pi^+ \pi^-$ seems to be a three-body decay, thus there could be a suppression from the phase space of final states. However, in our picture of molecular state, it is not a real three-body decay, instead, it is a two-step process, namely, first $Y(4260)$ dissolves into J/ψ and ρ^0 and then ρ^0 transits into $\pi^+ \pi^-$. Since the total width is proportional to a two-body decay rate multiplied by the branching ratio of $\rho^0 \to \pi^+ \pi^-$ which is 100% almost,

there does not exist the phase space suppression factor at all.

Because of the color rematching factor, one can expect that the decay rate of $Y(4260) \to J/\psi \pi^+ \pi^-$ is about one order larger than that of $Y(4260) \to D\bar{D}$. The concrete dynamics may change this ratio more or less, but here we just take this value from estimate of order of magnitude. This value qualitatively coincides with the experimental results.

III. MORE DISCUSSIONS AND CONCLUSION

We suggest that the observed $Y(4260)$ is an s-wave molecular state of χ_{c1} and ρ^0. It is natural to consider another two partner molecular states, namely $\chi_{c0} + \rho^0$ and $\chi_{c2} + \rho^0$ in s-wave. Their spin-parity can be different, but which one is dominant depends on the concrete dynamics. For the simplest case, supposing they are also 1^{--}, we may expect that the molecular state of $\chi_{c2} + \rho^0$ is only 40 MeV above 4260 MeV (supposing it has the same binding energy as that for $\chi_{c1} + \rho^0$), on other side, the total width of $Y(4260)$ is 90 MeV, thus this molecular state might be hidden in the observed peak of $Y(4260)$, in other words, the experimentally observed peak $Y(4260)$ may cover two close states. Meanwhile, the molecular state of $\chi_{c0} + \rho^0$ could be 100 MeV below the central value of the peak and thus corresponds to a new state which can be used as a test of the model. Namely, if this partner resonance is observed in the future experiments, one can claim that the molecular structure postulation may be correct, otherwise, we need to consider other possible mechanisms to suppress its production rate from dynamics or abandon the molecular state interpretation. Moreover, the molecule of $\chi_{c1} - \rho^0$ is a component of an isovector, so there may exist another two components of the isotriplet, i.e. $\chi_{c1} - \rho^\pm$ which may decay into $J/\psi \pi^\pm \pi^0$ with comparable rates of $Y(4260) \to J/\psi \pi^+ \pi^-$. They may be experimentally observable. For the molecular structure, σ exchange between χ_{c1} and ρ^0 may result in an attractive potential which binds them into a molecule. Since the coupling is OZI suppressed, the binding is relatively loose.

In our scenario, the favorable decay mode of $Y(4260)$ is $Y(4260) \to J/\psi \pi^+ \pi^-$. The molecular structure of $Y(4260)$ results in different decay pattern from $\psi(3770)$ which is supposed to be a pure $c\bar{c}$ charmonium. Namely if we take the $D\bar{D}$ mode as a standard, the rate of $Y(4260) \to J/\psi \pi^+ \pi^-$ is larger than that of $Y(4260) \to D\bar{D}$ by an order.

By contraries, in the hybrid charmonium structure [2–4], where a color-octet $c\bar{c}$ system is bound with an octet valence gluon, since gluon is flavor-blind, it has the same coupling to $q\bar{q}(q = u, d)$ and $s\bar{s}$, thus besides a small suppression from the phase space, $Y(4260) \to J/\psi \pi^+ \pi^-$ and $Y(4260) \to J/\psi K\bar{K}$ should be comparable unless there exist certain mechanisms to suppress $K\bar{K}$ production. In the diquark-anti-diquark picture of $[cs][\bar{c}\bar{s}]$, the mode

$Y(4260) \to J/\psi K\bar{K}$ overwhelms $Y(4260) \to J/\psi \pi^+ \pi^-$. In our picture of molecular state, the mode of $Y(4260) \to J/\psi K\bar{K}$ can only be realized via final state interaction $\pi^+ \pi^- \to K\bar{K}$, so that the rate of $Y(4260) \to J/\psi K\bar{K}$ is much smaller than that of $Y(4260) \to J/\psi \pi^+ \pi^-$.

Let us turn to a subtle and difficult subject, the production of $Y(4260)$ in $e^+ e^-$ collisions. The production may occur via the so-called hairpin mechanism [12] which does not suffer from the suppression due to color matching. It seems that it has a larger production rate than the direct (nonresonant) production of $D\bar{D}$ at first glimpse. However, a detailed analysis indicates that unless the energy $\sqrt{s}$ of $e^+ e^-$ collisions can be precisely tuned to 4260 MeV, the energy conservation demands production of other hadrons such as pions in company with $Y(4260)$, and the constraint from the final product phase space would greatly suppress its production rate. To achieve concrete values one must carry out model-dependent calculations and it is beyond the scope of this work.

One more observation is that ρ^0 only decays into $\pi^+ \pi^-$, but not $\pi^0 \pi^0$, therefore, if the molecular picture is right, the mode of $Y(4260) \to J/\psi \pi^0 \pi^0$ must be very suppressed. Moreover, since in our picture $\pi^+ \pi^-$ are produced from the real ρ^0 − meson, the measured invariant-mass spectrum of $\pi^+ \pi^-$ should peak up at m_ρ. Looking at the figure (Fig. 3 of [1]), the dipion mass distribution of $Y(4260) \to J/\psi \pi^+ \pi^-$ seems to show some fine structures. Since the spectrum is due to $\rho^0 \to \pi^+ \pi^-$ decay, it is a p-wave structure. The authors of Ref. [1] indicate that the observed $\pi\pi$ spectrum is somehow rather an s-wave comparing with the Monte Carlo results, thus the molecular interpretation offers a nonstandard interpretation for the bump. More precise experiments in the future may give a decisive conclusion. Thus the possibility that $Y(4260)$ is a molecular state, is indeed worth careful studies.

Now let us draw a brief conclusion. We propose that the newly observed $Y(4260)$ is a molecular state of χ_{c1} and ρ^0, and our analysis indicates that this picture qualitatively coincides with the experimental data. We naturally explain why the rate of $Y(4260) \to \pi^+ \pi^- J/\psi$ is larger than that of $Y(4260) \to D\bar{D}$, namely, why $Y(4260)$ is only observed in $e^+ e^- \to \text{ISR}\pi^+ \pi^- J/\psi$, but not in $Y(4260) \to D\bar{D}$. We have also made predictions on existence of two other components of the isotriplet, $\chi_{c1} - \rho^\pm$ which may be observed in channels $J/\psi \pi^\pm \pi^0$, and the extra partner resonances $\chi_{c0(c2)} - \rho^0$ along with their isotriplet components. It is suggested that the state of $\chi_{c0} + \rho^0$ may be distinguished from $Y(4260)$ and can be experimentally measured, so should serve as a test of the model. The future experiments will collect more data and confirm or negate the various theoretical models as well as ours. For such experiments besides the B-factories, BES and CLEO are also ideal places.

In our model, we only discuss the qualitative characteristics and make estimate of order of magnitude, but ignore

all the dynamics. Definitely all the details of dynamics may change the numbers quite much, but we hope that the qualitative conclusion and analysis would remain unchanged, because they are independent of the dynamical details.

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