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Understanding the newly observed $Y(4008)$ by Belle

Xiang Liu[a]

School of Physics, Peking University, Beijing 100871, P.R. China

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Abstract. Very recently a new enhancement around 4.05 GeV was observed by the Belle experiment. We discuss some possible assignments for this enhancement, i.e. the $\psi(3S)$ and $D^*\bar{D}^*$ molecular states. In these two assignments, $Y(4008)$ can decay into $J/\psi\pi^0\pi^0$ with a branching ratio comparable with that of $Y(4008)\to J/\psi\pi^+\pi^-$. Thus, one suggests high energy experimentalists to look for $Y(4008)$ in $J/\psi\pi^0\pi^0$ channel. Furthermore one proposes further experiments to search for the missing channels $D\bar{D}$, $D\bar{D}^*+\text{h.c.}$ and especially $\chi_{cJ}\pi^+\pi^-\pi^0$ and $\eta_c\pi^+\pi^-\pi^0$, which will be helpful to distinguish the $\psi(3S)$ and $D^*\bar{D}^*$ molecular state assignments for this new enhancement.

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Very recently the Belle Collaboration observed an enhancement with mass $m = 4008\pm 40^{+114}_{-28}$ MeV and width $\Gamma = 226\pm 44\pm 87$ MeV besides confirming $Y(4260)$ by studying the initial state radiation (ISR) process $e^+e^-\to\gamma_{\rm ISR}J/\psi\pi^+\pi^-$ [1]. The Belle experiment also indicated that a fit using two interfering Breit–Wigner shapes describes the data better than one that uses only $Y(4260)$ [1]. In this work, we called this new structure $Y(4008)$.

Recently, a series of observations of charmonium like states X, Y, Z [2–21] has challenged our understanding of non-perturbative QCD. At present how to understand this new structure is one of the intriguing and challenging topics.

This short note is dedicated to a discussion of the possible interpretations for $Y(4008)$.

1 A possible candidate for $\psi(3S)$?

In the known charmonium states listed in the Particle Data Book, only the mass of $\psi(4040)$ is close to that of $Y(4008)$ [22]. At present $\psi(4040)$ is usually considered as the candidate for $\psi(3S)$. The central value of the width of $Y(4008)$ is larger than that of $\psi(4040)$ around 100 MeV. However, due to the large error given by the Belle experiment, the mass and width of this new enhancement are consistent with that of $\psi(4040)$.

For $Y(4008)$, the Belle experiment also gave $B(J/\psi\pi^+\pi^-)\cdot\Gamma_{e^+e^-} = 5.0\pm 1.4^{+6.1}_{-0.9}$ eV and $12.4\pm 2.4^{+14.8}_{-1.1}$ eV, corresponding to two solutions in fitting the data [1]. As a candidate of $\psi(3S)$, the decay width of $\psi(4040)\to e^+e^-$ is 0.86 ± 0.07 keV [22]. Using the above values, we can roughly estimate $B[Y(4008)\to J/\psi\pi^+\pi^-] = 5.8\times 10^{-3}$ and 1.4×10^{-2} for the above two solutions if $Y(4008)$ is the $\psi(3S)$ state. Due to the large experimental errors, the central value of the former one does not contradict the upper limit of the branching ratio of $\psi(4040)\to J/\psi\pi^+\pi^-$ ($B[\psi(4040)\to J/\psi\pi^+\pi^-] < 4\times 10^{-3}$), though the former one is slightly larger than the upper limit of the branching ratio of $\psi(4040)\to J/\psi\pi^+\pi^-$.

At present, only $Y(4008)\to J/\psi\pi^+\pi^-$ values are reported by Belle [1]. If $Y(4008)$ is $\psi(3S)$, $B[Y(4008)\to J/\psi\pi^0\pi^0]$ is comparable with $B[Y(4008)\to J/\psi\pi^+\pi^-]$. Thus $Y(4008)$ can be found in the $J/\psi\pi^0\pi^0$ channel.

Although at present the experiments did not give a measurement for $\psi(3S)\to J/\psi\pi\pi, \psi(2S)\pi\pi$, the transition of $\psi(3S)$ to lower states, $\psi(nS)$ $(n<3)$, with two pions being emitted can be solved by the QCD multipole expansion (QCDME) method proposed by Gottfried, Yan and Kuang [23–27], which is depicted by Fig. 1.

In a recent work [28], Ke et al. calculated the transitions of $\psi(3S)\to\psi(nS)\pi\pi$ to obtain

$$\Gamma[\psi(3S)\to J/\psi\pi\pi] = 589.91\,\text{keV}\,, \quad (1)$$
$$\Gamma[\psi(3S)\to \psi(2S)\pi\pi] = 14.96\,\text{keV} \quad (2)$$

by adopting the Cornell potential $V(r) = -\frac{\kappa}{r}+br$ [29, 30] and

$$\Gamma[\psi(3S)\to J/\psi\pi\pi] = 12.38\,\text{keV}, \quad (3)$$
$$\Gamma[\psi(3S)\to \psi(2S)\pi\pi] = 8.84\,\text{keV} \quad (4)$$

[a] e-mail: xiangliu@pku.edu.cn

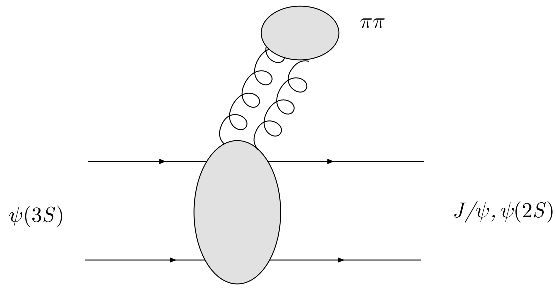

Fig. 1. The transition of $\psi(3S)$ to lower states $\psi(nS)$ $(n<3)$ with two pions being emitted

by adopting a modified Cornell potential, which includes a spin-related term [31]

$$V(r) = -\frac{\kappa}{r} + br + \frac{8\pi\kappa}{3m_q^2}\delta_\sigma(r)\mathbf{S}_q\cdot\mathbf{S}_{\bar{q}} + V_0\,,$$

where $\delta_\sigma(r) = (\frac{\sigma}{\sqrt{\pi}})^3 e^{-\sigma^2 r^2}$ and V_0 is the zero-point energy [28]. The above numerical results by two potentials show that there exists a large uncertainty for the estimate of $\psi(3S)\to J/\psi\pi\pi$ by the QCDME method, which is indicated in [28]. However, the estimate of $\psi(3S)\to\psi(2S)\pi\pi$ without spin-related term is consistent with that with spin-related term. If we trust the estimate of $\psi(3S)\to\psi(2S)\pi\pi$ by the QCDME method, one may hope to find $Y(4008)$ in the $\psi(2S)\pi\pi$ channel in future experiments.

Furthermore, if $Y(4008)$ is $\psi(3S)$, we know that $J/\psi\pi^+\pi^-$ is not its main decay channel. $Y(4008)$ may mainly decay into $D\bar{D}$ and $D\bar{D}^*+\mathrm{h.c.}$ Due to the fact that $Y(4008)$ has the wide decay width of about 200 MeV, $Y(4008)$ can also decay into $D^*\bar{D}^*$ through its mass tail.

2 A $D^*\bar{D}^*$ molecular state?

There has been a long history of discussion of the molecular structure of hadrons. To explain some phenomena that involve hard to find natural interpretations in the canonical framework, people have tried to search for new structure beyond it. The molecular structure is one of the possible candidates.

Because the mass of $Y(4008)$ is close to the threshold of $D^*\bar{D}^*$, and $Y(4008)$ is about 200 MeV in width, $Y(4008)$ can be assumed as a $D^*\bar{D}^*$ molecular state. In the past, Okun and Voloshin studied the interaction between charmed mesons and proposed possibilities of the molecular states involving charmed quarks [32]. Rujula, Georgi and Glashow once suggested $\psi(4040)$ as a $D^*\bar{D}^*$ molecular state [33]. In [34, 35], Dubynskiy and Voloshin proposed that there exists a possible new resonance at the $D^*\bar{D}^*$ threshold. Because $Y(4008)$ is observed along with $Y(4260)$, which has $J^{PC}=1^{--}$, the quantum numbers of $Y(4008)$ expected most are $J^{PC}=1^{--}$. Furthermore, $Y(4008)$ must be a p-wave $D^*\bar{D}^*$. At present one cannot use the experimental information to determine the quantum number I^G of $Y(4008)$. Thus $Y(4008)$ may be an isosinglet state with $I^G=0^-$ or an isovector state with $I^G=1^+$. If $Y(4008)$ is a $D^*\bar{D}^*$ molecular state, $Y(4008)$ falls apart into $D^*\bar{D}^*$ by its mass tail, which is depicted in Fig. 2.

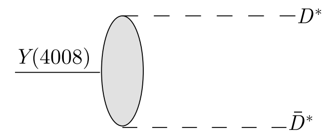

Fig. 2. The diagrams depicting the $Y(4008)\to D^*\bar{D}^*$ decay

In the following we will discuss its other possible decay modes.

2.1 $Y(4008)$ as an isoscalar $D^*\bar{D}^*$ molecular state

By the $D^*\bar{D}^*$ rescattering effect, $Y(4008)$ with $I^G=0^-$ can decay into $J/\psi+\eta$, $J/\psi+\sigma$ and $J/\psi+f_0(980)$ by the mechanism depicted in Fig. 3, and into $\chi_{cJ}\omega$ $(J=0,1,2)$, $\eta_c\omega$ by Fig. 4. Here J/ψ may also be replaced by $\psi(2S)$ and $\psi(3770)$. By the same mechanism, $Y(4008)$ may also decay into $D\bar{D}$ and $D\bar{D}^*+\mathrm{h.c.}$ by exchanging π and ρ mesons between D^* and $\bar{D}^*$. In fact, as secondary decay, the branching ratio of $Y(4008)\to D^*\bar{D}^*\to D\bar{D}, D\bar{D}^*+\mathrm{h.c.}$ is comparable with that of $Y(4008)\to D^*\bar{D}^*\to J/\psi\eta, J/\psi\omega$.

Because σ and $f_0(980)$ dominantly decay into $\pi\pi$ according to isospin symmetry one can roughly estimate

$$\frac{B[Y(4008)\to J/\psi\pi^0\pi^0]}{B[Y(4008)\to J/\psi\pi^+\pi^-]}\sim\frac{1}{2}\,. \tag{5}$$

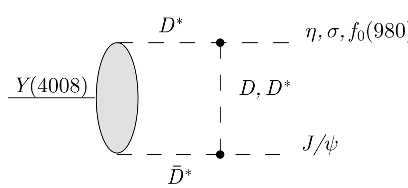

Fig. 3. The diagrams depicting the $Y(4008)\to J/\psi\eta, J/\psi\sigma, J/\psi f_0(980)$ decays

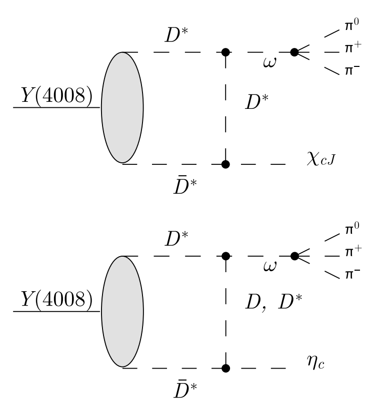

Fig. 4. The diagrams depicting the $Y(4008)\to\chi_{cJ}\omega, \eta_c\omega$ decays

Furthermore, the decay mechanism depicted by Fig. 3 can be tested in further experiments by analyzing the $\pi\pi$ invariant mass spectrum. If this mechanism is correct, the $\pi\pi$ invariant mass distribution should show the signature of σ or $f_0(980)$.

The branching ratio of $\omega \to \pi^+\pi^-\pi^0$ is almost 89.1%; thus, ω to $\pi^+\pi^-\pi^0$ is overwhelming. $\chi_{cJ}\pi^+\pi^-\pi^0$ and $\eta_c\pi^+\pi^-\pi^0$ are expected as special and main decay modes of $Y(4008)$. Meanwhile ω also decays into $\pi^+\pi^-$ and $\pi^0\gamma$ with the branching ratios $B(\omega \to \pi^+\pi^-) = 1.7\%$ and $B(\omega \to \pi^0\gamma) = 8.9\%$, respectively [22]. Thus $\chi_{cJ}\pi^+\pi^-$, $\chi_{cJ}\pi^0\gamma$, $\eta_c\pi^+\pi^-$ and $\eta_c\pi^0\gamma$ are important decay modes for $Y(4008)$.

The typical decay modes of $Y(4008)$ with the assignment of the $D^*\bar{D}^*$ molecular state ($I^G(J^{PC}) = 0^-(1^{--})$) mainly include $J/\psi\eta$, $J/\psi\pi\pi$, $\chi_{cJ}\pi^+\pi^-\pi^0$, $\chi_{cJ}\pi^0\gamma$, $\chi_{cJ}\pi^+\pi^-$, $\eta_c\pi^+\pi^-\pi^0$, $\eta_c\pi^0\gamma$, $\eta_c\pi^+\pi^-$, $D\bar{D}$ and $D\bar{D}^* +$ h.c. As one of the main decay modes, $\chi_{cJ}(\eta_c)\pi^+\pi^-\pi^0$ should be seen if $Y(4008)$ is a $D^*\bar{D}^*$ molecular state with $I^G = 0^-$. However, there exists the difficulty to distinguish $Y(4008) \to \chi_{cJ}(\eta_c)\pi^0\gamma$ in the experiment. Here the index J of χ_{cJ} may be $0, 1, 2$.

2.2 $Y(4008)$ as an isovector $D^*\bar{D}^*$ molecular state

For the isovector $D^*\bar{D}^*$ molecular state, $Y(4008)$ may decay into $\pi^0 J/\psi$, $\rho^0\chi_{cJ}$ ($J = 0, 1, 2$) and $\rho^0\eta_c$, which are depicted in Fig. 5. The branching ratio of $\rho^0 \to \pi^+\pi^-$ is almost 100% [22]. Thus, the typical decay modes of $Y(4008)$ as an isovector $D^*\bar{D}^*$ molecular state are $\pi^0 J/\psi$, $\chi_{cJ}\pi^+\pi^-$ and $\eta_c\pi^+\pi^-$. Besides these decays, of course $Y(4008)$ can also decay into $D\bar{D}$ and $D\bar{D}^* +$ h.c. Because $J/\psi\pi^+\pi^-$ is forbidden for an isovector $D^*\bar{D}^*$ molecular state, one may exclude the assignment of the isovector $D^*\bar{D}^*$ molecular state for $Y(4008)$.

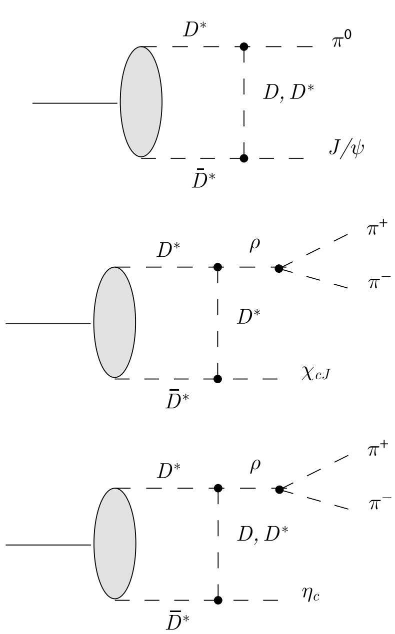

Fig. 5. The diagrams depicting the $Y(4008) \to \chi_{cJ}\rho, \eta_c\rho$ decays

3 Brief conclusion

In the above sections, we discuss the possible assignments for $Y(4008)$: the $\psi(3S)$ and $D^*\bar{D}^*$ molecular states. In these two possible pictures, one finds that the branching ratio of $Y(4008) \to J/\psi\pi^0\pi^0$ is comparable with that of $Y(4008) \to J/\psi\pi^+\pi^-$. Thus one suggests further experiments to search for $Y(4008)$ in the $J/\psi\pi^0\pi^0$ invariant mass distribution.

How to distinguish these two assignments becomes a key problem. In the following we will illustrate the differences of the $Y(4008)$ decays for the two assignments, which will be helpful to distinguish the $\psi(3S)$ and $D^*\bar{D}^*$ molecular state pictures.

(1) Search for the $D\bar{D}$ and $D\bar{D}^* +$ h.c. decay channels. If $Y(4008)$ is $\psi(3S)$, $D\bar{D}$ and $D\bar{D}^* +$ h.c. are the main decay channels. If $Y(4008)$ is a $D^*\bar{D}^*$ molecular state, $D\bar{D}$ and $D\bar{D}^* +$ h.c., as the secondary decay modes, are comparable with $\chi_{cJ}\pi^+\pi^-\pi^0$ and $\eta_c\pi^+\pi^-\pi^0$. Thus one suggests experiments to search for these missing decay channels.
(2) Search for the $\chi_c\pi^+\pi^-\pi^0$ and $\eta_c\pi^+\pi^-\pi^0$ decay channels. In the picture of the $D^*\bar{D}^*$ molecular state, $\chi_{cJ}\pi^+\pi^-\pi^0$ and $\eta_c\pi^+\pi - \pi^0$ are the main decay modes. However, as $\psi(3S)$, besides decaying to $D\bar{D}$, $D\bar{D}^* +$ h.c. and $D^*\bar{D}^*$, $Y(4008)$ mainly decays into $J/\psi\pi\pi$.

It will be a decisive factor to distinguish the $\psi(3S)$ and $D^*\bar{D}^*$ molecular state assignments if the $Y(4008) \to \chi_{cJ}\pi^+\pi^-\pi^0, \eta_c\pi^+\pi^-\pi^0$ can be found in further experiments. We strongly urge our experimental colleagues to design more accurate experiments to find $Y(4008) \to \chi_{cJ}\pi^+\pi^-\pi^0, \eta_c\pi^+\pi^-\pi^0$.

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