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Exploring the threshold behavior and implications on the nature of $Y(4260)$ and $Z_c(3900)$

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We investigate several strong and radiative decay modes of $Y(4260)$, by assuming that $Y(4260)$ either is a $D_1\bar{D}$ molecular state, or has sizeable couplings with $D_0\bar{D}^*$ and $D_1'\bar{D}$. In such ansatzes, obvious threshold enhancements or narrow cusp structures appear quite naturally without introducing a genuine resonance. And we emphasize that the radiative decay modes may be useful for studying $D^{(*)}\bar{D}$ S-wave scattering.

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1. Introduction

The mysterious charmonium-like state $Y(4260)$ has many peculiar characterristics. First of all, there is no direct correspondence of $Y(4260)$ in naive quark model classifications. Furthermore, as a charmonium candidate, it has not been observed in the hidden charm decay channels. The R-value scan at BES around 4.26 GeV also appears to have a dip instead of a bump structure. Recently the observation of BESIII revives the discussion on the nature of $Y(4260)$. A charged charmonium-like resonance structure $Z_c(3900)$ is observed in the invariant mass spectrum of $J/\psi\pi^{\pm}$ from $Y(4260) \to J/\psi\pi^+\pi^-$ [1]. If the observed structure is a genuine particle, it obviously cannot be a conventional $c\bar{c}$ state. This experimental result was later confirmed by Belle [2]. One remarkable characteristic of the unconventional charmonium-like states is that many of them are observed at the thresholds of some charmed anti-charmed meson pairs. Therefore it is reasonable to interpret them as molecular states. In this work, we will assume that $Y(4260)$ is either a $D_1\bar{D}$ molecular state, or has sizeable couplings with $D_0\bar{D}^*$ and $D_1'\bar{D}$. Under such assumptions, a consistent description of many of the experimental observations can be obtained, such as its non-obersvation in open charm decays, and the observation of $Z_c(3900)$ [3, 4, 5]. We will mainly concentrate on the discussion of the threshold phenomena in several strong and radiative decay channels of $Y(4260)$ under such assumptions.

2. Threshold enhancement phenomena

If $Y(4260)$ is a $D_1\bar{D}+c.c.$ molecular state, its main decay channel would be $\bar{D}D^*\pi + c.c.$, as illustrated in Fig. 1(a). Since the momenta of the produced $\bar{D}D^*$ will be very small, the final state interactions (FSIs) can be expected to play a role when analyzing some decay processes. We illustrate the rescattering processes in Fig. 1(b). If FSIs are strong, they may significantly change the decay properties. Some non-analytical structures of the transition amplitude such as the cusp effect may occur. The transition amplitude will be estimated according to the heavy hadron chiral perturbation theory. The explicit formulae and details can be found in Ref. [4]. Concerning the rescattering process illustrated in Fig. 1(b), with some special kinematic configurations, all of the three intermediate states contained in the loop can be on-shell simultaneously. This is the so called triangle singularity (TS) or "two cut" condition [6]. Since this kind of singularities usually appears when the mass of the external particle is very close to the threshold of intermediate states, it may change the threshold behavior dramatically and show up directly as a bump in the amplitude.

2.1 $Y(4260) \to \bar{D}D^*\pi$

Taking AB in Fig. 1(b) as $\bar{D}D^*$, we will firstly discuss the $\bar{D}D^*\pi$ final states, and focus on

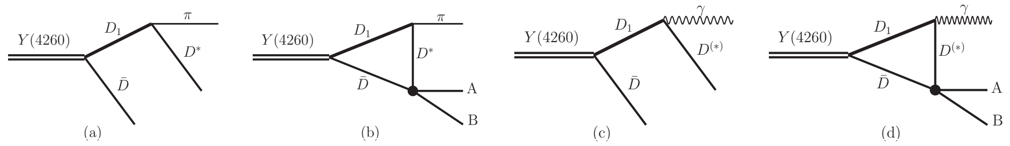

Figure 1: (a) and (c): Diagrams of $Y(4260)$ strong and radiative decay modes by supposing it is a $D_1\bar{D}$ molecular state. (b) and (d): The rescattering processes, where A and B are some specified final states.

the lineshape behavior of $\bar{D}D^*$ invariant mass spectrum. The $D_1 \to D^*\pi$ is a D-wave decay while the S-wave decay is forbidden according to the heavy quark spin symmetry, which is one of the main reasons why this D_1 is so narrow. Even if only the tree diagram is considered, there still appears an obvious threshold enhancement on the $\bar{D}D^*$ distribution, as illustrated in Fig. 2. Then it could be concluded that most of the $\bar{D}D^*$ events will be accumulated in the near threshold region, where we may expect strong FSIs. The numerical result corresponding to the rescattering diagram is displayed in Fig. 2, where an obvious threshold enhancement is also observed.

The states D_0 and D_1' are too broad to be taken as the components of a relatively narrower molecular state. However, since the thresholds of $D_0\bar{D}^*$ and $D_1'\bar{D}$ are very close to the mass of $Y(4260)$, it is still justifiable to assume larger couplings of $Y(4260)$ with these combinations. $D_0 \to D\pi$ and $D_1' \to D^*\pi$ are S-wave decays. Only the tree diagram itself can not lead to obvious threshold enhancement structures, as illustrated in Fig 2. After taking into account the rescattering processes, it seems that the threshold enhancement behavior is still not significant compared with the situation in $Y(4260) \to D_1\bar{D} \to \bar{D}D^*\pi$, and the larger width of intermediate state will lower the rescattering amplitude. These processes may offer some background for the pertinent decay channels.

2.2 $Y(4260) \to J/\psi(\psi')\pi\pi$

For the $J/\psi(\psi')\pi\pi$ final states, as mentioned in the previous section, the relatively larger $D^*\bar{D}$ yield in the vicinity of threshold will favor strong FSIs. In combination with the TS that may appear in the rescattering amplitude, there will be a strong enhancement in $J/\psi\pi$ ($\psi'\pi$) invariant mass spectrum which lies at the $D^*\bar{D}$ threshold. As illustrated in Fig. 3, only according to this semi-quantitative estimate, the line shape behavior is already very similar with the results observed by BESIII and Belle, and the "width" of this cusp structure can be compared with the width of "$Z_c(3900)$" to some extent. In $\psi'\pi\pi$ final states, as the kinematics changed, the reflection of the narrow cusp, which behaves as a bump, has been shifted to the tail of the phase space.

We also investigate $D_0\bar{D}^*$ and $D_1'\bar{D}$ combinations which may produce similar cusp structures.

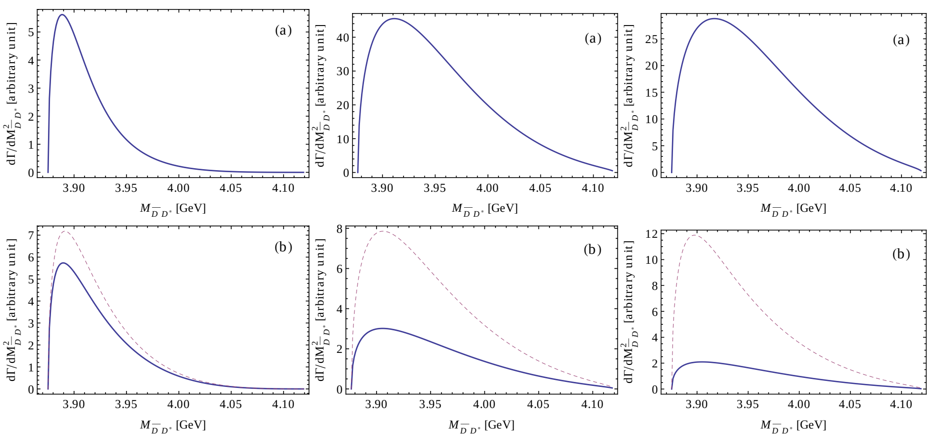

Figure 2: Invariant mass spectrum of $\bar{D}D^*$ in $Y(4260) \to D_1\bar{D} \to \bar{D}D^*\pi$ (first column), $Y(4260) \to \bar{D}_0D^* \to \bar{D}D^*\pi$(second column), and $Y(4260) \to D_1'\bar{D} \to \bar{D}D^*\pi$ (third column). (a) and (b) correspond to tree and loop diagrams, respectively. In (b), the solid (dashed) line corresponds to the result with (without) taking into account the width of intermediate state.

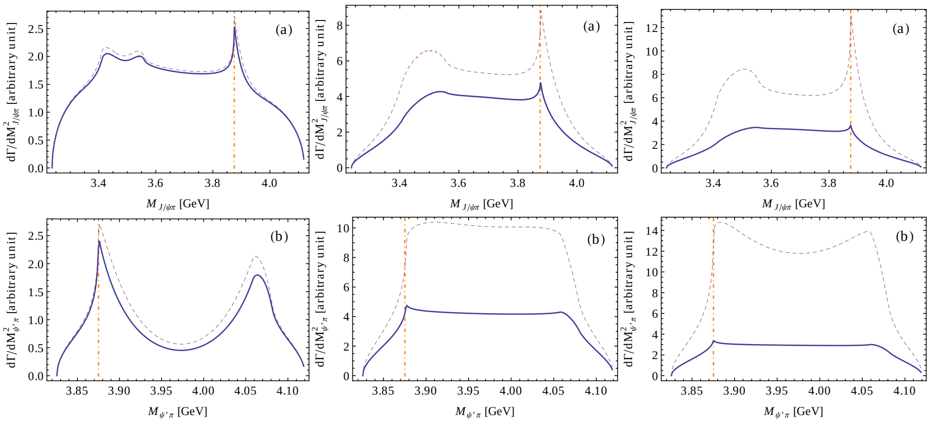

Figure 3: Invariant mass spectrum of $J/\psi\pi(\psi'\pi)$ in $Y(4260) \to J/\psi(\psi')\pi\pi$ via $D_1\bar{D}$(first column), $D_0\bar{D}^*$(second column) and $D_1'\bar{D}$(third column) intermediate states respectively. Solid (dashed) line corresponds to the result with (without) taking into account the width of intermediate states. The vertical dot-dashed line indicates the threshold of $\bar{D}D^*$.

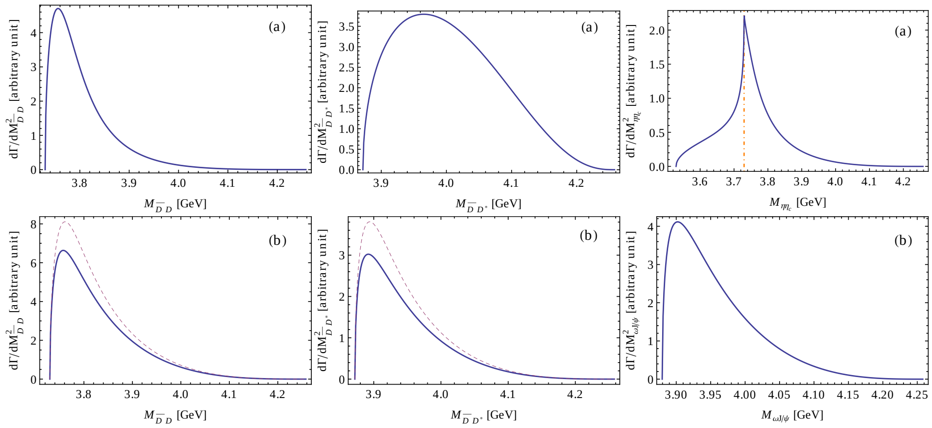

Figure 4: First column: $\bar{D}D$ distribution in $Y(4260) \to D_1\bar{D} \to \gamma D\bar{D}$. Second column: $\bar{D}D^*$ distribution in $Y(4260) \to D_1\bar{D} \to \gamma D^*\bar{D}$. Third column (a): $\eta_c\eta$ distribution in $Y(4260) \to D_1\bar{D}[D] \to \gamma\eta_c\eta$. Third column (b): $J/\psi\omega$ distribution in $Y(4260) \to D_1\bar{D}[D^*] \to \gamma J/\psi\omega$. (a) and (b) correspond to the tree and loop diagrams respectively. Solid (dashed) line corresponds to the result with (without) taking into account the width of D_1. The vertical dot-dashed line corresponding to the threshold $2m_D$.

As displayed in Fig. 3, it seems that there will also be obvious cusp structures in the $J/\psi\pi\pi$ decay mode if the larger width of intermediate states is ignored. But for the $\psi'\pi\pi$ final states, the cusp structures are flattened to some extent. Therefore this channel could be taken as a criterion to test which combination is more favorable to be taken as the main component of $Y(4260)$.

2.3 Threshold behavior in $Y(4260)$ radiative decays

Radiative decay modes are very useful for understanding the intrinsic structures of hadrons. By assuming $Y(4260)$ is a $D_1\bar{D}$ molecule, we try to investigate some of its radiative decay properties under this scenario, as illustrated in Fig. 1. According to the results estimated by utilizing quark model, the radiative decay width of $D_1^0 \to \gamma D^{(*)0}$ is much larger than that of $D_1^\pm \to \gamma D^{(*)\pm}$. This

PoS(Hadron 2013)041

may imply that the ratio $R \equiv \Gamma(Y(4260) \to \gamma D^{(*)0}\bar{D}^0)/\Gamma(Y(4260) \to \gamma D^{(*)+}D^-)$ will be much larger than 1, and the rescattering will mainly happen between neutral charmed mesons. Taking the final states AB in Fig. 1 as $D\bar{D}$ and $D^*\bar{D}$ respectively, the numerical results without taking into account interference are displayed in Figs. 4. It can be noticed that in both of these two decay modes, the rescattering process can give obvious threshold enhancement. If taking AB as $\eta\eta_c$ and $\omega J/\psi$ respectively, and assuming an S-wave coupling, a narrow cusp structure is obtained at the $D\bar{D}$ as illustrated in Fig. 4. Since the threshold of $\omega J/\psi$ is a little higher than that of $D^*\bar{D}$, there is only a threshold enhancement at Fig. 4. These resonance-like structures do not result from some genuine resonances with quantum numbers $J^P = 0^+$ and $J^P = 1^+$. Especially for the narrow cusp structure in the vicinity of $D\bar{D}$ threshold, since there is no scalar charmonium state with the mass of about $2m_D$ that has ever been observed, this radiative decay mode can be taken as a criterion to test whether such a structure is some kind of molecular state or just a cusp structure results from FSIs.

3. Summary

By assuming $Y(4260)$ is a $D_1\bar{D}$ molecular state, we investigate several decay modes which are related with this assumption. More $\bar{D}D^*$ events will be accumulated in the vicinity of the threshold under this ansatz. Therefore, strong FSIs will be expected. With some special kinematic configurations, TS may occur in the transition amplitude, which will significantly change the threshold behavior and manifest itself as some cusp structures. The process $Y(4260) \to J/\psi(\psi')\pi\pi$ results from $\bar{D}D^*$ rescattering is investigated, where the cusp structure is very similar with the experimental observations. This is the result without introducing a genuine resonance, such as $Z_c(3900)$. However, we should also claim this effect just offer a possible dynamical mechanism to describe such a resonance-like structure. The existence of a genuine resonance is not excluded. Some radiative decay modes of $Y(4260)$ in the molecule ansatz are also discussed, and we emphasize that the strong $D\bar{D}$ S-wave interaction will lead to a narrow cusp structure in the process $Y(4260) \to D_1\bar{D}[D] \to \gamma\eta_c\eta$, which may behave as a scalar charmonium resonance.

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