PROCEEDINGS OF SCIENCE

Investigating possible decay modes of $Y(4260)$ under the $D_1(2420)\bar{D}+c.c.$ molecular state ansatz

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By assuming that $Y(4260)$ is a $D_1(2420)\bar{D}+c.c.$ molecular state, we investigate some hidden-charm and charmed pair decay channels of $Y(4260)$ via intermediate $D_1\bar{D}$ meson loops with an effective Lagrangian approach. Through investigating the α dependence of branching ratio, we show that the intermediate $D_1\bar{D}$ meson loops are crucial for driving these transitions of $Y(4260)$ studied here. The coupled channel effects turn out to be more important in $Y(4260)\to D^*\bar{D}^*$, which can be tested in future experiments.

XV International Conference on Hadron Spectroscopy-Hadron 2013
4-8 November 2013
Nara, Japan

[*]Speaker.

[†]This work is supported in part by the National Natural Science Foundation of China (Grant Nos. 11035006, and 11275113), and in part by the China Postdoctoral Science Foundation (Grant No. 2013M530461).

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1. Introduction

During the past years, the experimental observation of so-called XYZ states has initiated tremendous efforts to explore their nature beyond the conventional quark model . $Y(4260)$ was reported by the *BABAR* collaboration in $\pi^+\pi^- J/\psi$ invariant spectrum in $e^+e^- \to \gamma_{ISR}\pi^+\pi^- J/\psi$ [1], which has been confirmed both by the CLEO and Belle collaborations [2, 3]. Its mass and total width are well determined as $m = 4263^{+8}_{-9}$ MeV and $\Gamma_Y = 95 \pm 14$ MeV, respectively [4]. The new datum from BESIII confirms the signal in $Y(4260) \to J/\psi\pi^+\pi^-$ with much higher statistics [5]. The mass of $Y(4260)$ does not agree to what is predicted by the potential quark model. Furthermore, the most mysterious fact is that as a charmonium state with $J^{PC} = 1^{--}$, it is only "seen" as a bump in the two pion transitions to J/ψ, but not in any open charm decay channels like $D\bar{D}$, $D^*\bar{D}+c.c.$ and $D^*\bar{D}^*$, or other measured channels.

Since the observation of the $Y(4260)$, many theoretical investigations have been carried out to explore the structure of $Y(4260)$, such as conventional $\psi(4S)$, tetraquark $c\bar{c}s\bar{s}$ state, charmonium hybrid, hadronic molecule of $D_1\bar{D}$, $\chi_{c1}\omega$, $\chi_{c1}\rho$, $J/\psi f_0$, a cusp or a non-resonance explanation etc (for a review see Ref. [6]). With the $D_1\bar{D}$ molecule ansatz, a consistent description of some of the experimental observations can be obtained, such as its non observation in open charm decays, or the observation of $Z_c(3900)$ as mentioned in Ref. [7], the threshold behavior in its decay channels are investigated in Ref. [8] and the production of $X(3872)$ is studied in the radiative decays of $Y(4260)$ [9]. In this proceeding, we report the hidden-charm and charmed pairs decays of $Y(4260)$ via $D_1\bar{D}$ loop with an effective Lagrangian approach under the $D_1\bar{D}$ molecule assumption.

2. The Model

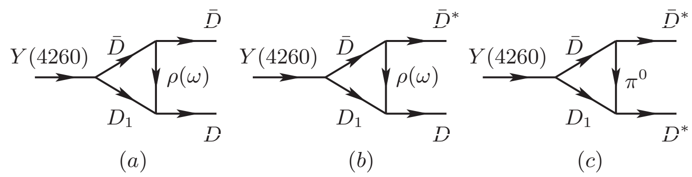

Figure 1: The hadron-level diagrams for $Y(4260) \to D^{(*)}\bar{D}^{(*)}$ with $D_1\bar{D}$ as the intermediate states.

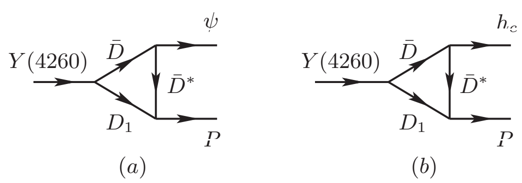

Figure 2: The hadron-level diagrams for hidden-charm decays of $Y(4260)$ with $D_1\bar{D}$ as intermediate states.

The effective Lagrangians relevant to charmnium, the light vector mesons, and the light pseudoscalar mesons can be obtained by using heavy quark symmetry [10], the hidden gauge symmetry approach [11] or invariance under both heavy quark spin-flavor transformation and chiral transformation [12, 13]. The explicit expression of the effective Lagrangians and the coupling constants can be found in Ref. [14].

By assuming $Y(4260)$ is a $D_1\bar{D}$ molecular state, the effective Lagrangian is constructed as

$$\mathscr{L}_{Y(4260)D_1D} = i\frac{y}{\sqrt{2}}(\bar{D}_a^{\dagger}Y^{\mu}D_{1a}^{\mu\dagger} - \bar{D}_{1a}^{\mu\dagger}Y^{\mu}D_a^{\dagger}) + H.c., \quad (2.1)$$

which is an S-wave coupling. Since the mass $Y(4260)$ is slightly below the $D_1\bar{D}$ threshold, the effective coupling $g_{Y(4260)D_1D}$ can be related to the binding energy, $\delta E = m_D + m_{D_1} - m_Y$ [15, 16, 9],

$$g_{\rm NR}^2 \equiv 16\pi(m_D + m_{D_1})^2\sqrt{\frac{2\delta E}{\mu}}[1 + \mathscr{O}(\sqrt{2\mu\varepsilon r})] \,, \quad (2.2)$$

where $\mu = m_D m_{D_1}/(m_D + m_{D_1})$ and r is the reduced mass and the range of the forces. The coupling constants in Eq. (2.1) are given by the first term in the above equation. With the masses of the $Y(4260)$, D, and D_1 mesons [4], we obtain

$$|y| = 14.62^{+1.11}_{-1.25} \pm 6.20 \text{ GeV} \quad (2.3)$$

where the first errors are from the uncertainties of the binding energies, and the second ones are due to the approximate nature of Eq. (2.2).

The transition amplitudes in Figs. 1 and 2 can be expressed in a general form as follows:

$$\mathscr{M}_{fi} = \int \frac{d^4q_2}{(2\pi)^4}\sum_{D^*\text{ pol.}}\frac{T_1T_2T_3}{a_1a_2a_3}\mathscr{F}(m_2, q_2^2) \,, \quad (2.4)$$

where a dipole form factor,

$$\mathscr{F}(m_2, q_2^2) \equiv \left(\frac{\Lambda^2 - m_2^2}{\Lambda^2 - q_2^2}\right)^2 \,, \quad (2.5)$$

is introduced in order to compensate the off-shell effects from the intermediate exchanged particle. The cut-off energy is chosen as $\Lambda = m_2 + \alpha\Lambda_{QCD}$ with $\Lambda_{QCD} = 0.22$ GeV.

3. Numerical Results

Since $Y(4260)$ has a large width 95 ± 14 MeV, one has to take into account the mass distribution of the $Y(4260)$ when calculating its decay widths. The decay width are as follows [17]:

$$\Gamma(Y(4260))_{2-\text{body}} = \frac{1}{W}\int_{(m_Y-2\Gamma_Y)^2}^{(m_Y+2\Gamma_Y)^2} ds\frac{(2\pi)^4}{2\sqrt{s}}\int d\Phi_2|\mathscr{M}|^2\frac{1}{\pi}\text{Im}(\frac{-1}{s - m_Y^2 + im_Y\Gamma_Y}). \quad (3.1)$$

Although the mass distribution is largely dependent on the parametrization scheme which reflects the nature of Y(4260) as shown in Ref. [18], it dose not change too much due to the convolution in Eq. 3.1. That means the simple Breit-Wigner formula in Eq. (3.1) can give the similar result as that of the $D_1\bar{D}$ bubble diagram. This is the reason why the bubble diagrams with the $D_1\bar{D}$ loop are not considered here.

In Table 1, we list the predicted branching ratios of $Y(4260)$ at different α values, and the errors are from the uncertainties of the coupling constants in Eq. (2.3). We have checked that including the width for D_1 only causes a minor change of about 1%-3%.

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Final states	$\alpha=0.5$	$\alpha=1.0$	$\alpha=1.5$	$\alpha=2.0$
$D\bar{D}$	$(3.54^{+3.71}_{-2.34})\times 10^{-5}$	$(4.21^{+4.41}_{-2.78})\times 10^{-4}$	$(1.62^{+1.70}_{-1.07})\times 10^{-3}$	$(3.94^{+4.13}_{-2.60})\times 10^{-3}$
$D^*\bar{D}+c.c.$	$(9.86^{+10.33}_{-6.51})\times 10^{-6}$	$(1.22^{+1.28}_{-0.80})\times 10^{-4}$	$(4.82^{+5.05}_{-3.18})\times 10^{-4}$	$(1.20^{+1.28}_{-0.79})\times 10^{-3}$
$D^*\bar{D}^*$	$(1.41^{+1.48}_{-0.93})\times 10^{-3}$	$(2.78^{+2.91}_{-1.83})\times 10^{-2}$	$(16.24^{+17.01}_{-10.72})\%$	$(52.21^{+54.69}_{-34.48})\%$
$J/\psi\eta$	$(7.43^{+7.78}_{-4.91})\times 10^{-6}$	$(8.19^{+8.58}_{-5.41})\times 10^{-5}$	$(2.95^{+3.09}_{-1.95})\times 10^{-4}$	$(6.80^{+7.12}_{-4.49})\times 10^{-4}$
$J/\psi\pi^0$	$(3.04^{+3.18}_{-2.01})\times 10^{-9}$	$(3.32^{+3.48}_{-2.19})\times 10^{-8}$	$(1.19^{+1.24}_{-0.78})\times 10^{-7}$	$(2.72^{+2.85}_{-1.79})\times 10^{-7}$
$\psi'\eta$	$(4.34^{+4.54}_{-2.84})\times 10^{-6}$	$(2.71^{+2.84}_{-1.79})\times 10^{-5}$	$(6.50^{+6.81}_{-4.29})\times 10^{-5}$	$(1.10^{+1.15}_{-0.73})\times 10^{-4}$
$\psi'\pi^0$	$(1.76^{+1.84}_{-1.16})\times 10^{-7}$	$(9.71^{+10.17}_{-6.41})\times 10^{-7}$	$(2.14^{+2.24}_{-1.41})\times 10^{-6}$	$(3.43^{+3.59}_{-2.26})\times 10^{-6}$
$h_c\eta$	$(3.87^{+4.05}_{-2.55})\times 10^{-3}$	$(2.99^{+3.13}_{-1.97})\times 10^{-2}$	$(8.20^{+8.59}_{-5.41})\times 10^{-2}$	$(15.26^{+15.98}_{-10.08})\%$
$h_c\pi^0$	$(1.27^{+1.33}_{-0.84})\times 10^{-4}$	$(9.50^{+9.95}_{-6.27})\times 10^{-4}$	$(2.54^{+2.66}_{-1.67})\times 10^{-3}$	$(4.62^{+4.83}_{-3.05})\times 10^{-3}$

Table 1: The predicted branching ratios of $Y(4260)$ decays with different α values. The uncertainties are dominated by the use of Eq. (2.3).

As shown in this table, at the same α, the intermediate $D_1\bar{D}$ meson loops turns out to be more important in $Y(4260)\to D^*\bar{D}^*$ than that in $Y(4260)\to D\bar{D}$ and $D^*\bar{D}+c.c.$ This behavior can also be seen from Table. 1. As a result, a smaller value of α is favored in $Y(4260)\to D^*\bar{D}^*$. For the decay $Y(4260)\to D^*\bar{D}^*$, the off-shell effects of intermediate mesons $D_1D(\pi)$ are not significant, which makes this decay favor a relatively smaller α value. For the decay $Y(4260)\to D\bar{D}$ and $D^*\bar{D}+c.c.$, since the exchanged mesons of the intermediate meson loops are ρ and ω, which makes their off-shell effects relatively significant, this decay favor a relatively larger α value.

Corresponding to the diagrams in Figs. 2(a) and 2(b), the amplitudes for $Y(4260)\to J/\psi\pi^0$ ($J/\psi\eta$, $\psi'\pi^0$, $\psi'\eta$) and $Y(4260)\to h_c\pi^0$ ($h_c\eta$) scale as

$$\frac{v^5}{(v^2)^3}q^3\frac{\Delta}{v^2}\sim\frac{q^3\Delta}{v^3}\,, \tag{3.2}$$

$$\frac{v^5}{(v^2)^3}q^2\frac{\Delta}{v^2}\sim\frac{q^2\Delta}{v^3}\,, \tag{3.3}$$

respectively. v and q are the average velocity of the intermediate charmed meson and the momentum of the outgoing pseudoscalar meson, respectively. Δ denotes the charmed meson mass difference. For the π^0 and η production processes, the factors Δ are about $M_{D^+}+M_{D^-}-2M_{D^0}$ and $M_{D^+}+M_{D^0}-2M_{D_s}$, respectively. According to Eqs. (3.2) and (3.3), it can be concluded that the contributions of the coupled channel effects would be significant here since the amplitudes scale as $\mathscr{O}(1/v^3)$. And the branching ratio of $Y(4260)\to h_c\pi^0$ is expected to be larger than that of $Y(4260)\to J/\psi\pi^0$, because the corresponding amplitudes scale as $\mathscr{O}(q^2)$ and $\mathscr{O}(q^3)$, respectively. However, the momentum q in $Y(4260)\to J/\psi\pi^0$ is larger than that in $Y(4260)\to h_c\pi^0$, which may compensate for this discrepancy to some extent.

For the hidden-charm transitions $Y(4260)\to J/\psi\eta(\pi^0)$, some points can be learned from this table: (1) The branching ratios are not drastically sensitive to the cutoff parameter. (2) The leading contributions to the $Y(4260)\to J/\psi\pi^0$ are given by the differences between the neutral and charged charmed meson loops and also from the π^0-η mixing through the loops contributing to the eta transition. (3) At the same α, the branching ratios for the $Y(4260)\to J/\psi\eta$ transition are 2-3 orders of magnitude larger than that of $Y(4260)\to J/\psi\pi^0$. It is because there are no cancellations between the charged and neutral meson loops.

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For $Y(4260) \to \psi'\eta$ and $\psi'\pi^0$, since the mass of ψ' is closer to the thresholds of $\bar{D}D^*$ than J/ψ, it should give rise to more important threshold effects in $Y(4260) \to \psi'\eta(\pi^0)$ than in $Y(4260) \to J/\psi\eta(\pi^0)$. At the same α value, the branching ratio of $Y(4260) \to \psi'\pi^0$ is larger than that of $Y(4260) \to J/\psi\pi^0$. The three-momentum of final η is only about 167 MeV in $Y(4260) \to \psi'\eta$, which leads to a smaller branching rations in $Y(4260) \to J/\psi\eta$ than in $Y(4260) \to J/\psi\eta$ at the same α value. The branching ratios for $Y(4260) \to h_c\pi^0(\eta)$ are larger than that of $Y(4260) \to J/\psi\pi^0(\eta)$ and $\psi'\pi^0(\eta)$, which is consistent with the power counting analysis in Eqs. (3.2) and (3.3).

4. Summary

In this proceeding, we report the hidden-charmonium decays of $Y(4260)$ and the decays $Y(4260) \to D\bar{D}$, $D\bar{D}^*$ and $D^*\bar{D}^*$ in an effective Lagrangian approach. with $Y(4260)$ being the $D_1\bar{D}$ molecular state. For the hidden charmonium decays, we also carried out the power counting analysis and our results for these decays in ELA are qualitatively consistent with the power counting analysis. For the decay $Y(4260) \to D^*\bar{D}^*$, the exchanged meson π is almost on-shell, so the coupled channel effects are more important than $D\bar{D}$ and $D\bar{D}^*$ channels studied here. We expect the experiments to search for the hidden-charm and charmed meson pair decays of $Y(4260)$, which will help us investigate the nature and decay mechanisms of $Y(4260)$ deeply.

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