Production of the spin partner of the $X(3872)$ in e^+e^- collisions

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Abstract

We study the production of the spin partner of the $X(3872)$, which is a $D^*\bar{D}^*$ bound state with quantum numbers $J^{PC} = 2^{++}$ and named $X_2(4012)$ here, with the associated emission of a photon in electron–positron collisions. The results show that the ideal energy region to observe the $X_2(4012)$ in e^+e^- annihilations is from 4.4 GeV to 4.5 GeV, due to the presence of the S-wave $\bar{D}^* D_1(2420)$ and $\bar{D}^* D_2(2460)$ thresholds, respectively. We also point out that it will be difficult to observe the $\gamma X(4012)$ at the e^+e^- center-of-mass energy around 4.26 GeV.

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In the heavy quarkonium mass region, the so called XYZ states have been observed, and many of these quarkonium-like states defy a conventional quark model interpretation. They are therefore suggested to be exotic. The $X(3872)$, discovered by the Belle Collaboration [1], is the one of the most interesting exotic states. As the mass of the $X(3872)$ is extremely close to the $D^0\bar{D}^{*0}$ threshold, it is regarded as one especially promising candidate for a hadronic molecule.

Effective field theory (EFT) can cope with the interaction between heavy mesons in bound state systems at low energies. For such a kind of systems, heavy quark symmetry is relevant due to the presence of the heavy quark/antiquark in the meson/antimeson. This fact leads to predictions of new states as partners of the observed XYZ states in the hadron spectrum. For example, with an EFT description of the heavy mesonic molecules, the heavy quark symmetry can be used to predict the existence of the spin and bottom partners of the $X(3872)$ [2,3].

The spin partner of the $X(3872)$, called $X_2(4012)$ hereafter, is predicted to exist as the S-wave bound state of $D^*\bar{D}^*$ with quantum numbers 2^{++} [2]. Such a state was also expected to exist in other models, see Refs. [4–8]. It is different from the $X(3872)$ in several aspects: first, being an isoscalar state it should decay into the $J/\psi\pi\pi\pi$ with a branching fraction much larger than that for the $J/\psi\pi\pi$ because the $J/\psi\rho$ and $J/\psi\omega$ thresholds are far below the mass of the $X_2(4012)$ (very different to the case of the $X(3872)$); second, it is expected to decay dominantly into open charm mesons, $D\bar{D}$, $D\bar{D}^*$ and $D^*\bar{D}$, in a D-wave with a width of the order of a few MeV [9]; third, its mass as set by the $D^*\bar{D}^*$ threshold is higher than the quark model prediction for the first radially excited χ_{c2} [10].

The significance of the $X_2(4012)$ state is that its mass should be approximately given by the

$$M_{X_2(4012)} \approx M_{X(3872)} + M_{D^*} - M_D \approx 4012\,\text{MeV} \tag{1}$$

as dictated by heavy quark spin symmetry for heavy-flavor hadronic molecules [3,11]. Notice that a state with the same quantum numbers 2^{++} was also predicted in the tetraquark model [12]. However, the fine splitting between the 2^{++} and 1^{++} tetraquarks, which was predicted to be 70 MeV in Ref. [12], is not locked to that between the D^* and D. Similarly, the splitting between the $2P\,c\bar{c}$ states in the Godfrey–Isgur quark model is 30 MeV [10], also much smaller than $M_{D^*} - M_D$. Therefore, if a 2^{++} state will be observed in experiments with a mass around 4012 MeV, the mass by itself would already be a strong support for the hadronic molecular nature of both the $X(3872)$ and the tensor state. As a result, searching for a 2^{++} state with a mass around 4012 MeV is very important even for understanding the nature of the $X(3872)$.

However, although the $X(3872)$ has been observed by many other experiments after its discovery [13–18], no evidence for the existence of its spin partner has been reported. In Ref. [19], it is shown that the prompt production of the $X_2(4012)$ presents a significant discovery potential at hadron colliders. In this paper, we will investigate the production of the $X_2(4012)$ associated with the photon radiation in electron–positron collisions. This work presents an extension of the study on the production of the $X(3872)$ as a $D\bar{D}^*$ molecule in charmonia radiative transitions reported in Ref. [20]. In that paper, it was shown that the favorite energy regions for the $X(3872)\gamma$ production are around the $Y(4260)$ mass and 4.45 GeV. Later on, the BESIII Collaboration observed events for the process $Y(4260) \to X(3872)\gamma$ [21], which may be regarded as a support of the dominantly molecular nature of the $X(3872)$. Since the existence of the $D^*\bar{D}^*$ bound state, the $X_2(4012)$, is the consequence of the heavy quark spin symmetry of the molecular nature of the $X(3872)$, the production of the $X_2(4012)$ in e^+e^- collisions in the energy range of the BESIII experiment [22] thus provides an opportunity to search for new charmonium-like states on the one hand and can offer useful information towards understanding the $X(3872)$ on the other hand.

The production of the $X(3872)$ through the radiative decay of the $\psi(4160)$ charmonium is considered in Ref. [23] using heavy hadron chiral perturbation theory along with the X-EFT [24]. Then,
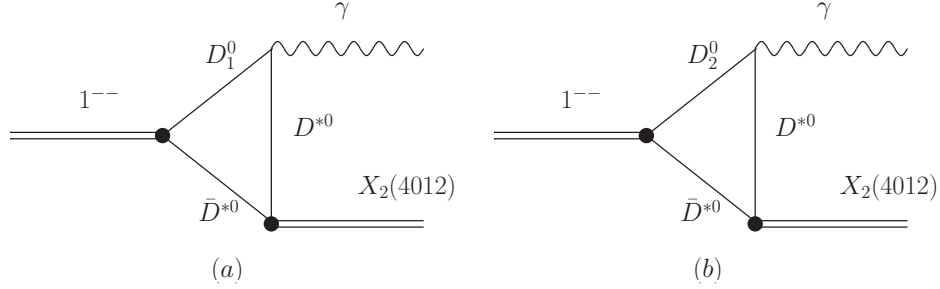
Figure 1: Relevant triangle diagrams for the production of the $X_2(4012)$ in vector charmonia radiative decays. The charge-conjugated diagrams are not shown here.

Ref. [20] studied the $X(3872)$ production by considering the contribution from intermediate charmed meson loops, and it was argued that the dominant mechanism is as follows: the initial charmonium is coupled to a pair of charmed mesons with one being S-wave with $s_\ell^P = \frac{1}{2}^-$, where s_ℓ is the total angular momentum of the light-flavor cloud in the charmed meson, and the other being P-wave with $s_\ell^P = \frac{3}{2}^+$, and the P-wave charmed meson radiatively transits to a $D(D^*)$ which coalesce with the other S-wave charmed meson, $\bar{D}^*(\bar{D})$, into the $X(3872)$. The spin partner of $X(3872)$, the $X_2(4012)$, can be produced by a similar mechanism as shown in Fig. 1. Notice that the $X_2(4012)$ couples to $D^*\bar{D}^*$ instead of $D\bar{D}^* + c.c.$, as it is in the case of the $X(3872)$. We will only consider the neutral charmed mesons in the loops because the photonic coupling between the P-wave and S-wave charmed mesons for the neutral ones is much larger than that for the charged. This is due to cancellation of contributions from the charm and down quarks in the charged mesons, see, e.g. [25]. In the loops, the $X_2(4012)$ couples to the $D^{*0}\bar{D}^{*0}$ pair in an S-wave. With the quantum numbers being 1^{--}, the initial charmonium can couple to one P-wave and one S-wave charmed meson in either S- or D-wave. Since both the initial charmonium and the $X_2(4012)$ in the final state are close to the corresponding thresholds of the charmed-meson pairs, we are able to use a power counting in velocity of the intermediate mesons. Following the power counting rules as detailed in Ref. [26] and presented in the case of interest in Refs. [20,27], the dominant contribution comes from the case when the coupling of the initial charmonium to the charmed mesons is in an S-wave. In this case, the initial charmonium should be a D-wave state in the heavy quark limit $m_c \to \infty$ as a consequence of heavy quark spin symmetry [28].

The charmed mesons can be classified according to the total angular momentum of the light degrees of freedom s_ℓ and collected in doublets with total spin $J = s_\ell \pm \frac{1}{2}$ in the heavy quark limit. The $s_\ell^P = \frac{1}{2}^-$ states correspond to charmed mesons in the doublet $(0^-, 1^-)$, here denoted as (P, V), whereas the $s_\ell^P = \frac{3}{2}^+$ states correspond to charmed mesons in the doublet $(1^+, 2^+)$, denoted as (P_1, P_2). To describe these heavy mesons, we choose the two-component notation introduced in Ref. [29]. The notation uses 2×2 matrix fields, and is convenient for nonrelativistic calculations. The fields for the relevant heavy meson states are

$$H_a = \vec{V}_a \cdot \vec{\sigma} + P_a,$$
$$T_a^i = P_{2a}^{ij}\sigma^j + \sqrt{\frac{2}{3}}\, P_{1a}^i + i\sqrt{\frac{1}{6}}\, \epsilon_{ijk}P_{1a}^j\sigma^k, \tag{2}$$

for the $s_\ell^P = \frac{1}{2}^-$ (S-wave) and $s_\ell^P = \frac{3}{2}^+$ (P-wave) heavy mesons, respectively, where $\vec{\sigma}$ are the Pauli matrices, and a is the flavor index for the light quarks. In Eq. (2), P_a and V_a annihilate the pseudoscalar

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and vector heavy mesons, respectively, and P_{1a} and P_{2a} annihilate the excited axial-vector and tensor heavy mesons, respectively. Under the same phase convention for charge conjugation specified in Ref. [20], the fields annihilating the mesons containing an anticharm quark are [30]

$$\bar{H}_a = -\vec{\bar{V}}_a \cdot \vec{\sigma} + \bar{P}_a,$$
$$\bar{T}_a^i = -\bar{P}_{2a}^{ij}\sigma^j + \sqrt{\frac{2}{3}}\,\bar{P}_{1a}^i - i\sqrt{\frac{1}{6}}\,\epsilon_{ijk}\bar{P}_{1a}^j\sigma^k. \tag{3}$$

In nonrelativistic limit, the field for the D-wave 1^{--} charmonium state can be written as [23]

$$J^{ij} = \frac{1}{2}\sqrt{\frac{3}{5}}\left(\psi^i\sigma^j + \psi^j\sigma^i\right) - \frac{1}{\sqrt{15}}\delta^{ij}\,\vec{\psi}\cdot\vec{\sigma}, \tag{4}$$

where ψ annihilates the D-wave vector charmonium, and the spin-0 and spin-2 states irrelevant for our study are not shown. In order to calculate the triangle diagrams in Fig. 1, we need the Lagrangian for coupling the D-wave charmonia to the $\frac{1}{2}^{-}$-$\frac{3}{2}^{+}$ charmed-meson pair as well as that for the E1 radiative transitions between the charmed mesons [20]

$$\mathcal{L} = \frac{g_4}{2}\mathrm{Tr}\left[\left(\bar{T}_a^{j\,\dagger}\sigma^i H_a^\dagger - \bar{H}_a^\dagger\sigma^i T_a^{j\,\dagger}\right)J^{ij}\right] + \sum_a \frac{c_a}{2}\,\mathrm{Tr}\left[T_a^i H_a^\dagger\right]E^i + \mathrm{H.c.}, \tag{5}$$

where in the first term the Einstein summation convention is used while for the latter we distinguish the coupling constants for different light flavors because there is no isospin symmetry in the electromagnetic interaction. Moreover, we parametrize the coupling of the $X_2(4012)$ to the pair of vector charm and anticharm mesons as

$$\mathcal{L}_{X_2} = \frac{x_2}{\sqrt{2}}X_2^{ij\,\dagger}\left(D^{*0\,i}\bar{D}^{*0\,j} + D^{*+\,i}D^{*-\,j}\right) + \mathrm{H.c.}. \tag{6}$$

With the above preparations, we can now proceed to calculate quantitatively the production of the $\gamma X_2(4012)$ in electron–positron collisions. Although in the heavy quark limit the production of the D-wave vector heavy quarkonium or the pair of $\frac{1}{2}^{-}$ and $\frac{3}{2}^{+}$ heavy mesons are suppressed due to spin symmetry [28], we can expect a large spin symmetry breaking in the charmonium mass region above 4 GeV. This may be seen from similar values of electronic widths of the excited vector charmonia. Thus, we will assume that the production of the $\gamma X_2(4012)$ occurs through the D-wave charmonia or the D-wave components of excited vector charmonia. Without any detailed information about the values of the coupling constants, we can predict the energy regions with the maximal production cross sections. In Fig. 2, we show the dependence of the decay width of a D-wave charmonium into the $\gamma X_2(4012)$, divided by $(g_4 x_2)^2$, on the mass of the D-wave charmonium or the center-of-mass energy of the e^+e^- collisions. The value of the photonic coupling c_u does not affect the shape of the dependence either. Nevertheless, we took $c_u = 0.4$ which is a typical value evaluated from various quark model predictions for the decay widths $\Gamma(D_1^0 \to \gamma D^{(*)0})$ [31–33]. In the figure, the dashed curve is obtained neglecting the widths of the D_1 and D_2 states, and the solid curve is the result of evaluating the triangle loop integrals with constant widths for the D_1 and D_2 as done in Ref. [20]. The maximum around 4.447 GeV and the local minimum around 4.492 GeV of the dashed curve are due to the presence of Landau singularities [34] of triangle diagrams in the complex plane at $(4.447 \pm i\,0.003)$ GeV (for the D_1 loop) and $(4.492 \pm i\,0.003)$ GeV (for the D_2 loop), respectively (for a discussion of the Landau singularities in the triangle diagrams of heavy quarkonium transitions, we refer to Ref. [27]). The two cusps on both sides of the shoulders of the peak show up at the thresholds of the $D_1\bar{D}^*$ and $D_2\bar{D}^*$.
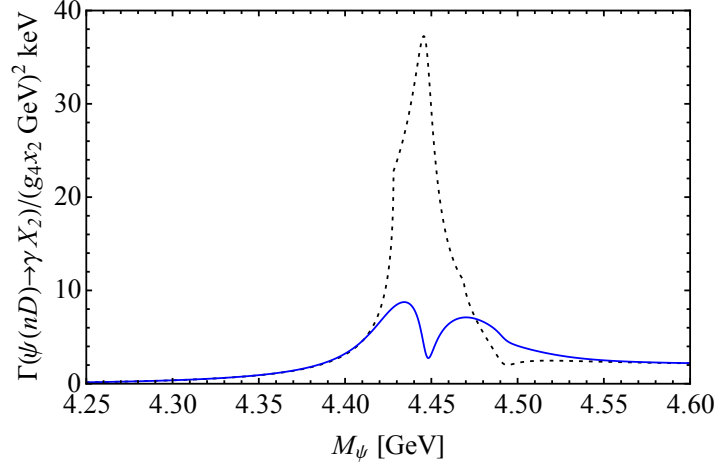
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Figure 2: Dependence of the partial decay width of a D-wave charmonium into $\gamma X_2(4012)$ on the mass of the charmonium. The solid and dotted curves are obtained with and without taking into account the widths of the $D_1(2420)$ and $D_2(2460)$, respectively. Here, $c_u = 0.4$ is used.

From the figure, it is clear that the ideal energy regions for producing the $\gamma X_2(4012)$ in e^+e^- collisions are around the $D_1\bar{D}^*$ and $D_2\bar{D}^*$ thresholds, i.e. between 4.4 GeV and 4.5 GeV. It is also clear that the mass region of the $Y(4260)$ is not good for the production of the $\gamma X_2(4012)$, contrary to the case of the $\gamma X(3872)$. In order to quantify the relative production rate of the $\gamma X_2(4012)$ with respect to the $\gamma X(3872)$, we require the $Y(4260)$ to couple to the $\frac{1}{2}^-$-$\frac{3}{2}^+$ meson pair as follows

$$\mathcal{L}_Y = \frac{y}{\sqrt{2}} Y^{i\dagger} \left(D_{1a}^i \bar{D}_a - D_a \bar{D}_{1a}^i \right) + i \frac{y'}{\sqrt{2}} \epsilon^{ijk} Y^{i\dagger} \left(D_{1a}^j \bar{D}_a^{*k} - D_a^{*k} \bar{D}_{1a}^j \right)$$
$$+ \frac{y''}{\sqrt{2}} Y^{i\dagger} \left(D_{2a}^{ij} \bar{D}_a^{*j} - D_a^{*j} \bar{D}_{2a}^{ij} \right) + \text{H.c.}, \tag{7}$$

where we have assumed isospin symmetry in the couplings and the flavor index a runs over up and down quarks. Notice that if the $Y(4260)$ is a pure $D_1\bar{D}$ (here and in the following the charge conjugated channels are dropped for simplicity) molecule [35, 36], it would not couple to the $D_1\bar{D}^*$ and $D_2\bar{D}^*$ as given by the y' and y'' terms, and thus cannot decay into the $\gamma X_2(4012)$. These two terms are included to allow the decay to occur.[1] Because the $X_2(4012)$ is the spin partner of the $X(3872)$, for a rough estimate, we can assume that x_2 takes the same value as the coupling constant of the $X(3872)$ to the $D\bar{D}^*$. We also assume that the values of y' and y'' are related to y by a spin symmetry relation for D-wave charmoinia. Comparing Eq. (5) with Eq. (7) one obtains $y' = -y/2$ and $y'' = \sqrt{6}y/10$. Then, the ratio of the partial decay widths of the $Y(4260)$ to the $\gamma X_2(4012)$ and the $\gamma X(3872)$ can be estimated parameter-free, and is

$$\frac{\Gamma(Y(4260) \to \gamma X_2(4012))}{\Gamma(Y(4260) \to \gamma X(3872))} \approx 10^{-2} . \tag{8}$$

In the above ratio, whether or not to take into account the finite widths of the P-wave charmed mesons only results in a minor change of 2%. It is clear that unless the $Y(4260)$ couples to the $D_1\bar{D}^*$ and/or

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[1]The possibility of the $Y(4260)$ to have $D_1\bar{D}^*$ and $D_2\bar{D}^*$ components was discussed in Ref. [37].

$D_2\bar{D}^*$ with a coupling much larger than that for the $D_1\bar{D}$, which is less possible, the branching fraction of the $Y(4260) \to \gamma X_2(4012)$ is much smaller than that of the $Y(4260) \to \gamma X(3872)$. Given that the number of events for the latter process as observed at BESIII is the order of 10 [21], it is unlikely to make an observation of the $\gamma X_2(4012)$ at an energy 4.26 GeV at BESIII.

To summarize, it is generally expected that the $X(3872)$ as a hadronic molecule has a spin partner close to the $D^*\bar{D}^*$ threshold. In this paper, we have investigated the production of the $\gamma X_2(4012)$ in e^+e^- collisions. According to our calculation, we strongly suggest to search for the $X_2(4012)$ associated with a photon in the energy region between 4.4 GeV and 4.5 GeV in e^+e^- collisions. Besides, the width ratio of the $Y(4260)$ decaying to $\gamma X_2(4012)$ and $\gamma X(3872)$ is quite small, at the order of 10^{-2}. Thus observing the $\gamma X_2(4012)$ at an energy around 4.26 GeV would be unlikely in the BESIII experiment according to the current result of $Y(4260) \to \gamma X(3872)$.

Acknowledgments

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