Search for a $D\bar{D}$ bound state in the $\Lambda_b \to \Lambda D\bar{D}$ process

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We investigate the process of $\Lambda_b \to \Lambda D\bar{D}$, by taking into account the contributions from the s-wave $D\bar{D}$ interaction within the coupled-channel unitary approach, and the intermediate $\psi(3770)$ resonance. In addition to the peak of the $\psi(3770)$, an enhancement near the $D\bar{D}$ mass threshold is found in the $D\bar{D}$ invariant mass distributions, which should be the reflection of the $D\bar{D}$ bound state. We encourage our experimental colleagues to measure the $D\bar{D}$ invariant mass distribution of the $\Lambda_b \to \Lambda D\bar{D}$ process, which is crucial to search for the $D\bar{D}$ bound state and to understand the heavy-hadron heavy-hadron interactions.

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I. INTRODUCTION

Although the quark model was proposed by Gell-Mann and Zweig more than half century ago [1,2], it is still valid in classifying most of the known hadrons by now. Since the $X(3872)$ was observed by the Belle Collaboration in 2003 [3], many charmoniumlike states were reported experimentally [4], and most of them cannot be explained as the conventional mesons ($q\bar{q}$) or baryons (qqq) [5,6]. There are many explanations about those states, such as tetraquark states, molecular states, the conventional $c\bar{c}$ mesons, or the mixing between different components [7–11]. However, it is surprising that many resonant structures are observed around the thresholds of a pair of heavy hadrons, such as $X(3872)$ and $Z_c(3900)^{\pm}$ around the $D\bar{D}^*$ threshold, $Z_{cs}(3985)$ around the $\bar{D}_sD^*$ and $\bar{D}_s^*D$ thresholds, and $X(3930)$ around $D_s\bar{D}_s$ threshold. As discussed in Ref. [12], such structures should appear at any threshold of a pair of heavy-quark and heavy-antiquark hadrons which have attractive interaction at threshold. Thus, the experimental information about the threshold structures is crucial to deeply understand the heavy-hadron heavy-hadron interactions, and the internal structures of the hidden-charm states [13,14].

In Ref. [15], one new hidden charm resonance with mass around 3700 MeV [denoted as $X(3700)$ in this article] is predicted within the coupled channel unitary approach involving the D^+D^-, $D^0\bar{D}^0$, $D_s\bar{D}_s$, K^+K^-, $K^0\bar{K}^0$, $\pi^+\pi^-$, $\pi^0\pi^0$, $\eta\eta$, and $\pi^0\eta$ channels. Later it was suggested to search for this predicted $D\bar{D}$ bound state in several processes, such as $B \to D\bar{D}K$ [16], $\psi(3770) \to \gamma X(3700) \to \gamma\eta\eta'$, $\psi(4040) \to \gamma X(3700) \to \gamma\eta\eta'$, and $e^+e^- \to J/\psi X(3700) \to J/\psi\eta\eta'$ [17]. According to the studies of Refs. [18,19], the experimental data of $e^+e^- \to J/\psi D\bar{D}$ measured by the Belle Collaboration [20,21] are compatible with the existence of such a $D\bar{D}$ bound state around 3700 MeV, though other possibilities cannot be discarded due to the present quality of the Belle data. In Ref. [24], we have performed a global fit to the data of $\gamma\gamma \to D\bar{D}$ [22,23] and the $e^+e^- \to J/\psi D\bar{D}$ [21], by taking into account the s-wave $D\bar{D}$ final state interactions. Our results are consistent with the experimental data considering the uncertainties of the fitted parameters, and the modulus squared of the amplitude $|t_{D\bar{D}\to D\bar{D}}|^2$ show a peak around 3710–3740 MeV [24]. Recently, a $D\bar{D}$ bound state with binding energy $B = 4.0^{+5.0}_{-3.7}$ MeV was also predicted according to the lattice calculation in Ref. [25]. Furthermore, the potential proposed in Ref. [26] for a pair of heavy-antiheavy hadrons predicts the $X(3872)$ as an isoscalar $\bar{D}D^*$ molecular state, simultaneously, the existence of an isoscaler $\bar{D}D$ bound state is also predicted. Thus, it is crucial to search for the signal of this predicted state.

On the other hand, the decay of Λ_b is one of the important tools to study the hidden charm resonances [27], such as the processes of $\Lambda_b \to J/\psi\Lambda$, $\Lambda_b \to \psi(2S)\Lambda$ [28–30]. The process $\Lambda_b \to \Lambda X_c^0$ ($X_c^0 \equiv c\bar{c}u\bar{u}(d\bar{d}), c\bar{c}s\bar{s}$) is also proposed to search for the XYZ states in Ref. [31]. In this work, we will propose to search for the signal of the $D\bar{D}$ bound state in the process of $\Lambda_b \to \Lambda D\bar{D}$, which has not been measured

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experimentally. It should be pointed out that the $\Lambda_b \to \Lambda D\bar{D}$ process, involving the Cabibbo-Kobayashi-Maskawa (CKM) matrix element $V_{bc}V_{cs}$, is expected to be larger than the one of the process $\Lambda_b \to \Lambda K^+K^-$, involving $V_{bu}V_{us}$, with the branching fraction $\mathcal{B}(\Lambda_b \to \Lambda K^+K^-) = (15.9 \pm 1.2 \pm 1.2 \pm 2.0) \times 10^{-6}$ measured by the LHCb Collaboration [32].

Since the predicted mass of the $D\bar{D}$ bound state is lower than the $D\bar{D}$ threshold, it will manifest itself as an enhancement near the $D\bar{D}$ threshold, similarly as found in Refs. [16,33]. For instance, a peak observed in the $\phi\omega$ threshold in the $J/\psi \to \gamma\phi\omega$ reaction [34] was interpreted as the manifestation of the $f_0(1710)$ resonance below the $\phi\omega$ threshold [35]. In Ref. [36] the BESIII Collaboration has seen a bump structure close to threshold in the $K^{*0}\bar{K}^{*0}$ mass distribution of the $J/\psi \to \eta K^{*0}\bar{K}^{*0}$ decay, which can be interpreted as a signal of the formation of an h_1 resonance [37,38]. We expect there will be an enhancement near the threshold in the $D\bar{D}$ invariant mass distribution in the $\Lambda_b \to \Lambda D\bar{D}$ decay. On the other hand, since the $\psi(3770)$, with a mass close to the $D\bar{D}$ threshold, mainly decays into $D\bar{D}$ in the p wave, we will take into account the contribution from the $\psi(3770)$.

The paper is organized as follows: In Sec. II, we introduce our model for the process $\Lambda_b \to \Lambda D\bar{D}$. Numerical results for the $D\bar{D}$ invariant mass distribution and discussions are given in Sec. III, and a short summary is given in the last section.

II. FORMALISM

In analogy to Refs. [39–43], the mechanism of the decay $\Lambda_b \to \Lambda D\bar{D}$ ($D\bar{D} \equiv D^0\bar{D}^0, D^+D^-$) can happen via three steps: the weak decay, hadronization, and the final state interaction. In the first step as depicted in Fig. 1, the b quark of the initial Λ_b weakly decays into a c quark and a W^- boson, followed by the W^- boson decaying into a $\bar{c}s$ quark pair,

$$|\Lambda_b\rangle = \frac{1}{\sqrt{2}} b(ud - du)$$
$$\Rightarrow V_p c\bar{c} \frac{1}{\sqrt{2}} s(ud - du) = V_p c\bar{c}\Lambda, \qquad (1)$$

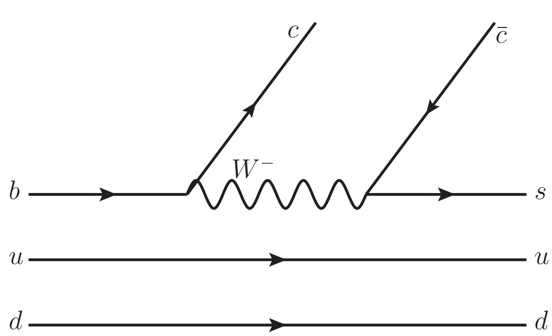

FIG. 1. The quark level diagram for the weak decay $\Lambda_b \to \Lambda c\bar{c}$.

where we take the flavor wave functions $\Lambda_b = b(ud - du)/\sqrt{2}$ and $\Lambda = s(ud - du)/\sqrt{2}$, and V_p is the strength of the production vertex that contains all dynamical factors.

In order to give rise to the final state $D^0\bar{D}^0\Lambda$ (or $D^+D^-\Lambda$), the quark c and antiquark $\bar{c}$ need to hadronize together with the $\bar{q}q$ ($\equiv \bar{u}u + \bar{d}d + \bar{s}s$) created from the vacuum with $J^{PC} = 0^{++}$, which could be expressed as the mechanisms of the internal W^- emission and external W^- emission, respectively shown in Figs. 2(a) and 2(b). Thus, we have

$$|H\rangle^{\rm in} = V_p \left| c(\bar{u}u + \bar{d}d + \bar{s}s)\bar{c}s \frac{1}{\sqrt{2}}(ud - du) \right\rangle$$
$$= V_p (D^0\bar{D}^0 + D^+D^- + D_s^+D_s^-)\Lambda, \qquad (2)$$

for the internal W^- emission mechanism of Fig. 2(a), and

$$|H\rangle^{\rm ex} = V_p \times C \times D_s^+D_s^-\Lambda, \qquad (3)$$

for the external W^- emission mechanism of Fig. 2(b). Here the color factor C accounts for the relative weight of the external W^- emission with respect to the internal W^- emission, and we take $C = 3$ in the case of color number $N_c = 3$ [44–46].

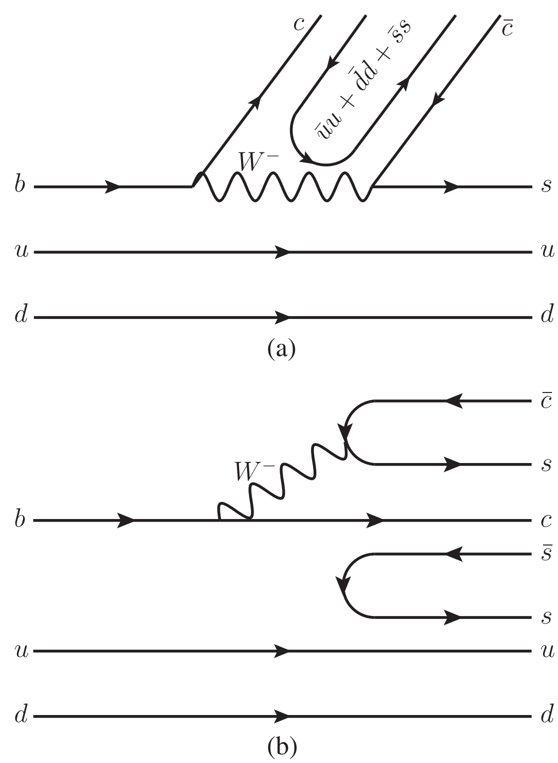

FIG. 2. The mechanisms of (a) the internal W^- emission and (b) the external W^- emission for the weak decay Λ_b and the hadronization of the $c\bar{c}$ through $\bar{q}q$ created from the vacuum.

The final states can also undergo the interaction of the $D\bar{D}$ and ΛD, which may generate dynamically the resonances. The interaction of the coupled channels including ΛD was studied within a unitary coupled-channel approach which incorporates heavy-quark spin symmetry, and two resonances $\Xi_c(2790)$ and $\Xi_c(2815)$ are identified as the dynamically generated resonances [47]. Since their masses are about 150–200 MeV below the ΛD threshold, their contributions do not affect the structure close to the $D\bar{D}$ threshold, which can be easily understood from the Dalitz plot of Fig. 3. Thus, we neglect the ΛD interaction in this work, because only the $D\bar{D}$ invariant mass distribution near the threshold is relevant for the $D\bar{D}$ bound state.

The next step is to consider the final state interaction of these channels to give $D^0\bar{D}^0$ (or D^+D^-) at the end. We can have the final states of $D^0\bar{D}^0$ (or D^+D^-) through the direct production in the Λ_b decay, or the rescattering of the primarily produced channels $D^0\bar{D}^0$, D^+D^-, or $D_s^+D_s^-$, as shown in Figs. 4(a) and 4(b), respectively. Apart from the three coupled channels $D^0\bar{D}^0$, D^+D^-, and $D_s^+D_s^-$, we only consider one light channel $\eta\eta$ to account for the width of the $D\bar{D}$ bound state, as in Refs. [16–18,24].

Then, the total amplitudes for the $\Lambda_b \to \Lambda D^0\bar{D}^0$ and $\Lambda_b \to \Lambda D^+D^-$ can be expressed as

$$t^{s\text{-wave}}_{\Lambda_b\to\Lambda D^0\bar{D}^0} = V_p[1 + G_{D^+D^-}t_{D^+D^-\to D^0\bar{D}^0} + G_{D^0\bar{D}^0}t_{D^0\bar{D}^0\to D^0\bar{D}^0} + (1+C)G_{D_s^+D_s^-}t_{D_s^+D_s^-\to D^0\bar{D}^0}], \quad (4)$$

$$t^{s\text{-wave}}_{\Lambda_b\to\Lambda D^+D^-} = V_p[1 + G_{D^+D^-}t_{D^+D^-\to D^+D^-} + G_{D^0\bar{D}^0}t_{D^0\bar{D}^0\to D^+D^-} + (1+C)G_{D_s^+D_s^-}t_{D_s^+D_s^-\to D^+D^-}], \quad (5)$$

where G_l is the loop function for the two-meson propagator in the lth channel,

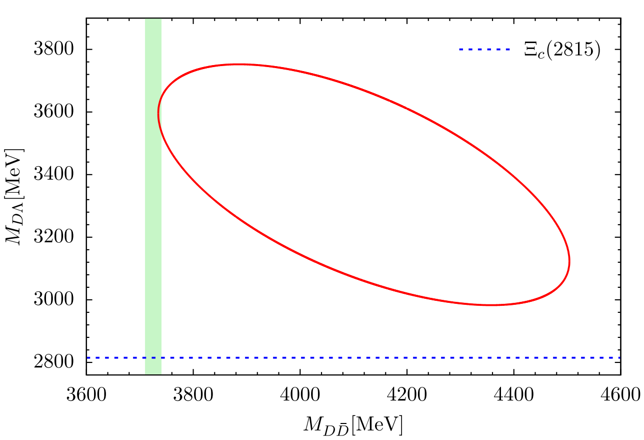

FIG. 3. The Dalitz plot for the $\Lambda_b \to \Lambda D\bar{D}$. The green band stands for the region of 3710–3740 MeV that the predicted $D\bar{D}$ bound state lies in.

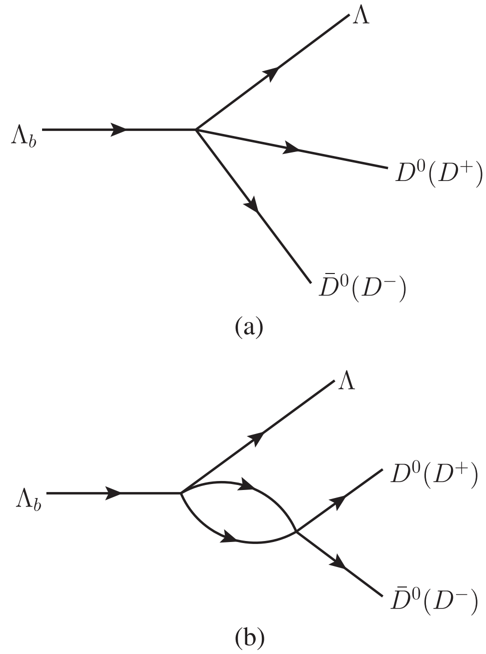

FIG. 4. The decays $\Lambda_b \to \Lambda D^0\bar{D}^0$ and $\Lambda_b \to \Lambda D^+D^-$, (a) direct production, (b) the rescattering of the channels $D^0\bar{D}^0$, D^+D^-, or $D_s^+D_s^-$.

$$G_l = i\int\frac{d^4q}{(2\pi)^4}\frac{1}{q^2-m_1^2+i\epsilon}\frac{1}{(P-q)^2-m_2^2+i\epsilon}$$
$$= \frac{1}{16\pi^2}\left[\alpha_l + \ln\frac{m_1^2}{\mu^2} + \frac{m_2^2-m_1^2+s}{2s}\ln\frac{m_2^2}{m_1^2} + \frac{p}{\sqrt{s}}\times\left(\ln\frac{s-m_2^2+m_1^2+2p\sqrt{s}}{-s+m_2^2-m_1^2+2p\sqrt{s}} + \ln\frac{s+m_2^2-m_1^2+2p\sqrt{s}}{-s-m_2^2+m_1^2+2p\sqrt{s}}\right)\right], \quad (6)$$

with the subtraction constant $\alpha_l = -1.3$ ($l = 1$, 2, 3, 4 correspond to the channels $D^0\bar{D}^0$, D^+D^-, $D_s^+D_s^-$, and $\eta\eta$, respectively) and $\mu = 1500$ MeV as Ref. [15]. $\sqrt{s} = M_{D\bar{D}}$ is the invariant mass of the two mesons in the lth channel. m_1 and m_2 are the masses of the two mesons in the lth channel. In Eq. (6), p is the momentum of the meson in the center of mass frame of the meson-meson system,

$$p = \frac{\lambda^{1/2}(s, m_1^2, m_2^2)}{2\sqrt{s}}, \quad (7)$$

with the Källen function $\lambda(x,y,z) = x^2 + y^2 + z^2 - 2xy - 2yz - 2zx$.

With the isospin doublets $(D^+, -D^0)$, $(\bar{D}^0, D^-)$, we have,

$$|D^+D^-\rangle = \frac{1}{\sqrt{2}}|D\bar{D}, I=0, I_3=0\rangle + \frac{1}{\sqrt{2}}|D\bar{D}, I=1, I_3=0\rangle, \tag{8}$$

$$|D^0\bar{D}^0\rangle = \frac{1}{\sqrt{2}}|D\bar{D}, I=0, I_3=0\rangle - \frac{1}{\sqrt{2}}|D\bar{D}, I=1, I_3=0\rangle. \tag{9}$$

Taking the averaged mass of D meson in Eqs. (4) and (5), it is easy to find that only the isospin $I=0$ component of the $D\bar{D}$ has the contribution to the $\Lambda_b \to \Lambda D\bar{D}$ process,[1]

$$G_{D^+D^-}t_{D^+D^-\to D^0\bar{D}^0} + G_{D^0\bar{D}^0}t_{D^0\bar{D}^0\to D^0\bar{D}^0} = G_{D\bar{D}}t^{I=0}_{D\bar{D}\to D\bar{D}}, \tag{10}$$

$$G_{D^+D^-}t_{D^+D^-\to D^+D^-} + G_{D^0\bar{D}^0}t_{D^0\bar{D}^0\to D^+D^-} = G_{D\bar{D}}t^{I=0}_{D\bar{D}\to D\bar{D}}. \tag{11}$$

The scattering matrices $t_{i\to j}$ in Eqs. (4) and (5) are obtained by solving the Bethe-Salpeter equation in coupled channels,

$$t = [1 - VG]^{-1}V, \tag{12}$$

where the elements of the diagonal matrix G are the loop functions of Eq. (6), and the matrix element $V_{i,j}$ is the transition potential of the ith channel to the jth channel. The transition potentials $V_{i,j}$ $(i, j = D^0\bar{D}^0, D^+D^-, D_s^+D_s^-)$ are tabulated in the Appendix A of Ref. [15]. We introduce the potentials of $\eta\eta \to D^0\bar{D}^0$ and $\eta\eta \to D^+D^-$ with a dimensionless strength $a = 50$ to give the width of the $D\bar{D}$ bound state, and the transition potentials of $\eta\eta \to \eta\eta$ and $\eta\eta \to D_s^+D_s^-$ are not relevant and are taken as zero [16–18,24]. Both the G_l and $t_{i\to j}$ in Eqs. (4) and (5) are the functions of the $D\bar{D}$ invariant mass $M_{D\bar{D}}$.

The obtained modulus squared of the transition amplitude $|t_{D^+D^-\to D^+D^-}|^2$ and $|t_{D^+D^-\to D_s^+D_s^-}|^2$ are shown in Fig. 5, and one can find a peak around 3720 MeV, which could be associated to the $D\bar{D}$ bound state. On the other hand, from Fig. 5, the $|t_{D^+D^-\to D^+D^-}|^2$ is two times larger than $|t_{D^+D^-\to D_s^+D_s^-}|^2$, which indicates that the $X(3700)$ state couples mostly to $D\bar{D}$ channel.

In addition, we also take into account the decays $\Lambda_b \to \Lambda D^0\bar{D}^0$ and $\Lambda_b \to \Lambda D^+D^-$ via the intermediate resonance $\psi(3770)$, which is depicted in Fig. 6. The amplitude can be

[1]One can also see this conclusion from Figs. 2(a) and (b), since $c\bar{c}$ has isospin $I=0$ and no has $D_s\bar{D}_s$.

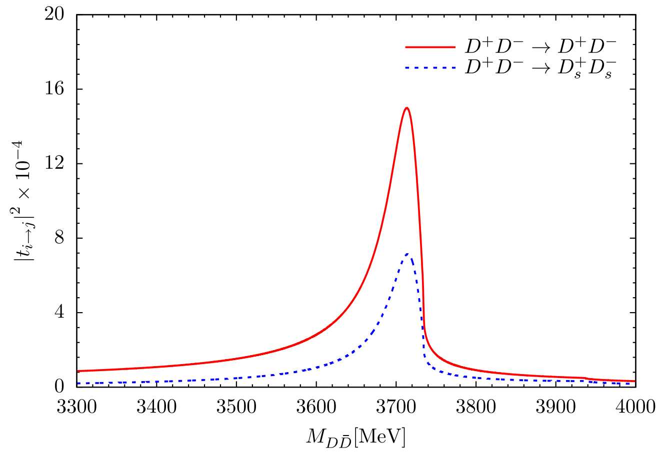

FIG. 5. The modulus squared of the transition amplitudes $|t_{D^+D^-\to D^+D^-}|^2$ and $|t_{D^+D^-\to D_s^+D_s^-}|^2$ calculated with Eq. (12).

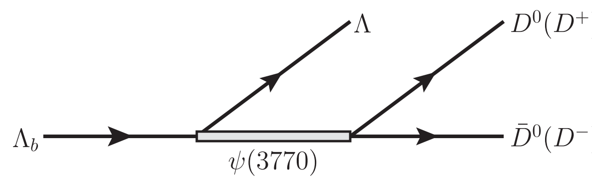

FIG. 6. The microscopic diagram for the decays $\Lambda_b \to \Lambda D^0\bar{D}^0$ and $\Lambda_b \to \Lambda D^+D^-$.

written as

$$t^{p\text{-wave}} = \frac{\beta V_p \times M_{\psi(3770)}\tilde{p}_D}{M^2_{D\bar{D}} - M^2_{\psi(3770)} + iM_{\psi(3770)}\tilde{\Gamma}_{\psi(3770)}}, \tag{13}$$

where the normalization factor V_p is the same as the one in Eqs. (4) and (5), and we introduce the parameter β to account for the relative weight of the $\psi(3770)$ strength with respect to the s-wave contribution of Eqs. (4) and (5). $\tilde{p}_D$ is the momentum of the D^0 (or D^+) in the rest frame of the $D^0\bar{D}^0$ (or D^+D^-) system,

$$\tilde{p}_D = \frac{\lambda^{1/2}(M^2_{D\bar{D}}, M^2_D, M^2_{\bar{D}})}{2M_{D\bar{D}}}. \tag{14}$$

We take the width for $\psi(3770)$ energy dependent, which is given by

$$\tilde{\Gamma}_{\psi(3770)} = \Gamma_{\psi(3770)} \times \frac{\sqrt{M^2_{D\bar{D}} - 4M^2_D}}{\sqrt{M^2_{\psi(3770)} - 4M^2_D}}, \tag{15}$$

with $M_{\psi(3770)} = 3773.7$ MeV, $\Gamma_{\psi(3770)} = 27.2$ MeV, and $M_D = (M_{D^+} + M_{D^0})/2 = 1867.24$ MeV [4].

With the amplitudes of Eqs. (4), (5), and (13), we can write the differential decay width for the decays $\Lambda_b \to \Lambda D^0 \bar{D}^0$ and $\Lambda_b \to \Lambda D^+ D^-$,

$$\frac{d\Gamma}{dM_{D^0\bar{D}^0}} = \frac{\tilde{p}_{D^0} p_\Lambda M_\Lambda M_{\Lambda_b}}{(2\pi)^3 M_{\Lambda_b}^2}[|t^{s\text{-wave}}|^2 + |t^{p\text{-wave}}|^2], \quad (16)$$

$$\frac{d\Gamma}{dM_{D^+D}} = \frac{\tilde{p}_{D^+} p_\Lambda M_\Lambda M_{\Lambda_b}}{(2\pi)^3 M_{\Lambda_b}^2}[|t^{s\text{-wave}}|^2 + |t^{p\text{-wave}}|^2], \quad (17)$$

with

$$p_\Lambda = \frac{\lambda^{1/2}(M_{\Lambda_b}^2, M_\Lambda^2, M_{D\bar{D}}^2)}{2M_{\Lambda_b}}. \quad (18)$$

Here we distinguish the masses of D^0 and $D^\pm$ when the momenta $\tilde{p}_{D^0}$ and $\tilde{p}_{D^+}$ are calculated with Eq. (14).

III. NUMERICAL RESULTS AND DISCUSSION

In our model, we have three free parameters, the global normalization V_p, the color factor C, and β. V_p is a global factor and its value does not affect the shapes of the $D^0\bar{D}^0$ and D^+D^- invariant mass distributions. β represents the relative weight of the $\psi(3770)$ strength with respect to the one of the s waves, and we take its value $\beta = 0.15$ to give the contributions from the s-wave $D\bar{D}$ interaction and the $\psi(3770)$ with the same order of magnitude. Next, we show the results with the color factor $C = 3$ and $V_p = 1$, and will present the results for different values of C and β.

We show the $D^0\bar{D}^0$ and D^+D^- invariant mass distributions in Fig. 7. One can find a clear enhancement near the $D^0\bar{D}^0$ threshold in the $D^0\bar{D}^0$ invariant mass distribution of the $\Lambda_b \to \Lambda D^0\bar{D}^0$, due to the presence of the $X(3700)$ resonance below the $D\bar{D}$ threshold. The enhancement structure near the threshold is a little weaker for the D^+D^- invariant mass distribution of the $\Lambda_b \to \Lambda D^+D^-$, because the D^+D^- threshold is higher than the $D^0\bar{D}^0$ one and farther away from the peak of $X(3700)$.

In Fig. 8, we show the $D^0\bar{D}^0$ and D^+D^- invariant mass distributions with the different values of color factor $C = 3.0, 2.5, 2.0$. One can find that the mass distributions near the threshold do not change too much, since the value of color factor C only affects the contribution from the $D_s^+D_s^-$ loop of Fig. 4(b), which is smaller than the contributions from the D^+D^- and $D^0\bar{D}^0$. On the other hand, the $s\bar{s}$ production in vacuum of Fig. 2(a) is slightly suppressed with respect to the $u\bar{u}$ and $d\bar{d}$ production, when the effect of SU(3) breaking is taking into account.

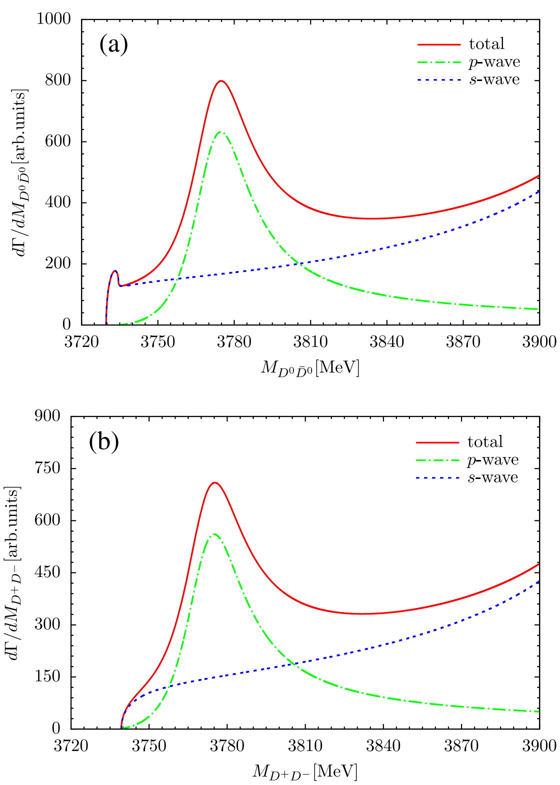

FIG. 7. The $D^0\bar{D}^0$ (a) and D^+D^- (b) invariant mass distributions of the processes $\Lambda_b \to \Lambda D^0\bar{D}^0$ and $\Lambda_b \to \Lambda D^+D^-$. The blue dashed curve shows the contribution from the meson-meson interaction in the s wave, the green dash-dotted curve corresponds to the results for the intermediate meson $\psi(3770)$, and the red solid curve shows the total contributions.

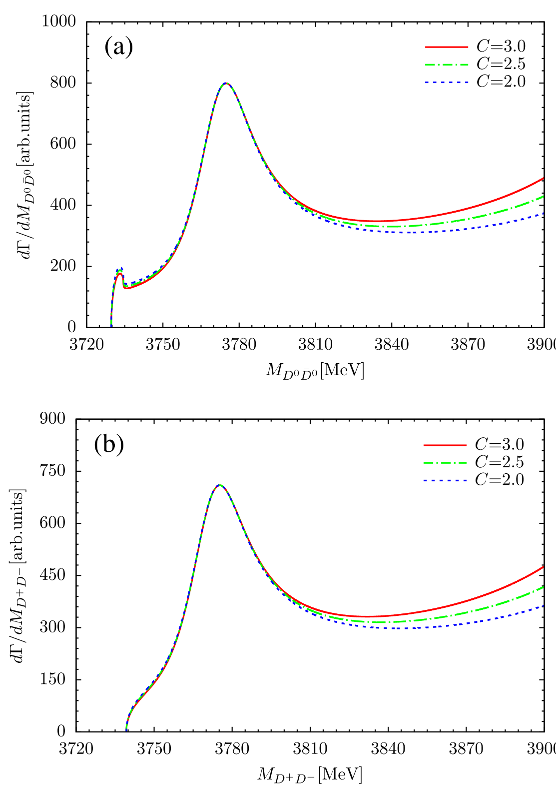

FIG. 8. The $D^0\bar{D}^0$ (a) and D^+D^- (b) invariant mass distributions of the processes $\Lambda_b \to \Lambda D^0\bar{D}^0$ and $\Lambda_b \to \Lambda D^+D^-$ with different values of $C = 3.0, 2.5, 2.0$.

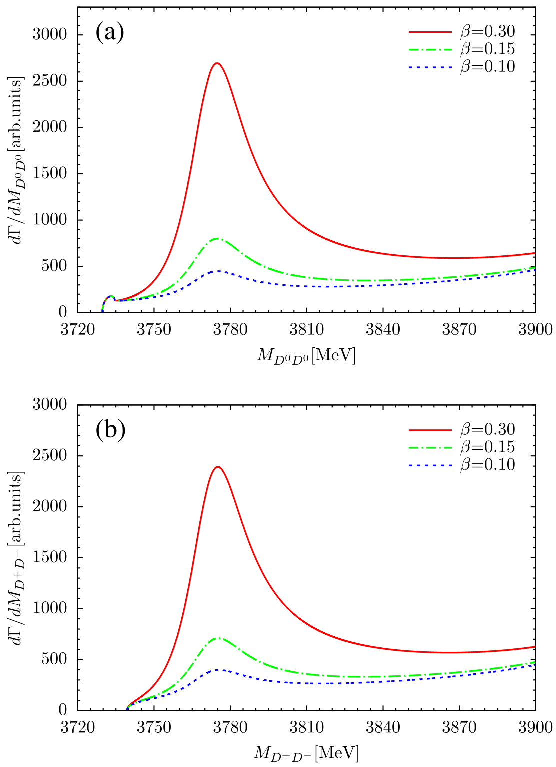

FIG. 9. The $D^0\bar{D}^0$ (a) and D^+D^- (b) invariant mass distributions of the processes $\Lambda_b \to \Lambda D^0\bar{D}^0$ and $\Lambda_b \to \Lambda D^+D^-$ with different values of $\beta = 0.30,\ 0.15,\ 0.10$.

However, the suppressed effect of the $s\bar{s}$ production can be absorbed by changing the value of C, which almost does not affect the $D\bar{D}$ invariant mass distribution close to the $D\bar{D}$ threshold.

We also present our results for the different values of $\beta = 0.30,\ 0.15,\ 0.10$ in Fig. 9. One can see that the enhancement near the threshold will be identified difficultly for the larger value of β. Indeed, the $\psi(3770)$ would provide the dominant contribution for the $\Lambda_b \to \Lambda D\bar{D}$ process; however, it is still expected to find an enhancement near the $D\bar{D}$ threshold, especially the $D^0\bar{D}^0$ one, if the $D\bar{D}$ bound state do exist, as predicted in Refs. [15,25]. Furthermore, since the $\psi(3770)$ state couples to $D\bar{D}$ in the p wave, the partial wave analysis of this reaction would be helpful to test the existence of the $D\bar{D}$ bound state.

As we known, the absolute branching fraction is useful. In our model, the exact value of V_p is difficult to be obtained even in terms of the effective Hamiltonian [48], which inevitably introduces additional unknown parameters. As we discussed in the introduction, the branching fraction of this process is expected to be larger than the one of $\Lambda_b \to \Lambda K^+K^-$, and could be precisely measurable by the updated LHCb. At present, the LHCb Collaboration has accumulated a large number of Λ_b events, thus, we would like to call the attention of the experimentalists to measure the $\Lambda_b \to \Lambda D\bar{D}$ decay, which should be useful to confirm the existence of $X(3700)$ and to understand its nature.

IV. CONCLUSIONS

The study of the charmoniumlike states is crucial to understand the heavy-hadron heavy-hadron interactions, and also the internal structures of the hidden-charm states. One $D\bar{D}$ bound state around 3700 MeV was predicted within the coupled channel unitary approach [15], and also the lattice investigation of the $D\bar{D}$ and $D_s\bar{D}_s$ scattering [24]. Although our previous studies on the $e^+e^- \to J/\psi D\bar{D}$ and $\gamma\gamma \to D\bar{D}$ data support the existence of the $D\bar{D}$ bound state, the other possibilities cannot be discarded due to the present quality of the experimental data [18,24]. Investigating the processes involving the s-wave $D\bar{D}$ system could provide the information about the existence of the $D\bar{D}$ bound state.

In this paper, we have investigated the processes $\Lambda_b \to \Lambda D^0\bar{D}^0$ and $\Lambda_b \to \Lambda D^+D^-$ within the coupled channel unitary approach, by taking into account the s-wave meson-meson interactions and the contribution from the intermediate resonance $\psi(3770)$. The $D^0\bar{D}^0$ and D^+D^- invariant mass distributions in the $\Lambda_b \to \Lambda D\bar{D}$ reaction are investigated, and our results show an enhancement structure near the $D\bar{D}$ threshold, which should be the reflection of the $D\bar{D}$ bound state. Therefore, we strongly encourage our experimental colleagues to measure the $\Lambda_b \to \Lambda D\bar{D}$ process, which would be crucial to confirm the existence the $X(3700)$ resonance, and to understand the heavy-hadron heavy-hadron interactions.

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[1] M. Gell-Mann, A schematic model of baryons and mesons, Phys. Lett. **8**, 214 (1964).

[2] G. Zweig, An $SU(3)$ model for strong interaction symmetry and its breaking. Version 2, Report No. CERN-TH-412, Developments in the quark theory of hadrons, edited by D. Lichtenberg and S. Rosen (1964), Vol. **1**, pp. 22–101.

[3] S. K. Choi *et al.* (Belle Collaboration), Observation of a narrow charmoniumlike state in exclusive $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}J/\psi$ decays, Phys. Rev. Lett. **91**, 262001 (2003).

[4] P. A. Zyla *et al.* (Particle Data Group), Review of particle physics, Prog. Theor. Exp. Phys. **2020**, 083C01 (2020).

[5] N. Brambilla, S. Eidelman, C. Hanhart, A. Nefediev, C. P. Shen, C. E. Thomas, A. Vairo, and C. Z. Yuan, The XYZ states: Experimental and theoretical status and perspectives, Phys. Rep. **873**, 1 (2020).

[6] S. L. Olsen, T. Skwarnicki, and D. Zieminska, Nonstandard heavy mesons and baryons: Experimental evidence, Rev. Mod. Phys. **90**, 015003 (2018).

[7] H. X. Chen, W. Chen, X. Liu, and S. L. Zhu, The hidden-charm pentaquark and tetraquark states, Phys. Rep. **639**, 1 (2016).

[8] Y. R. Liu, H. X. Chen, W. Chen, X. Liu, and S. L. Zhu, Pentaquark and tetraquark states, Prog. Part. Nucl. Phys. **107**, 237 (2019).

[9] A. Hosaka, T. Iijima, K. Miyabayashi, Y. Sakai, and S. Yasui, Exotic hadrons with heavy flavors: X, Y, Z, and related states, Prog. Theor. Exp. Phys. **2016**, 062C01 (2016).

[10] F. K. Guo, C. Hanhart, U. G. Meißner, Q. Wang, Q. Zhao, and B. S. Zou, Hadronic molecules, Rev. Mod. Phys. **90**, 015004 (2018).

[11] W. Hao, G. Y. Wang, E. Wang, G. N. Li, and D. M. Li, Canonical interpretation of the $X(4140)$ state within the $^3P_0$ model, Eur. Phys. J. C **80**, 626 (2020).

[12] X. K. Dong, F. K. Guo, and B. S. Zou, Explaining the Many Threshold Structures in the Heavy-Quark Hadron Spectrum, Phys. Rev. Lett. **126**, 152001 (2021).

[13] E. Wang, J. J. Xie, L. S. Geng, and E. Oset, The $X(4140)$ and $X(4160)$ resonances in the $e^{+}e^{-} \to \gamma J/\psi\phi$ reaction, Chin. Phys. C **43**, 113101 (2019).

[14] E. Wang, J. J. Xie, L. S. Geng, and E. Oset, Analysis of the $B^{+} \to J/\psi\phi K^{+}$ data at low $J/\psi\phi$ invariant masses and the $X(4140)$ and $X(4160)$ resonances, Phys. Rev. D **97**, 014017 (2018).

[15] D. Gamermann, E. Oset, D. Strottman, and M. J. V. Vacas, Dynamically generated open and hidden charm meson systems, Phys. Rev. D **76**, 074016 (2007).

[16] L. R. Dai, J. J. Xie, and E. Oset, $B^0 \to D^0\bar{D}^0K^0$, $B^{+} \to D^0\bar{D}^0K^{+}$, and the scalar $D\bar{D}$ bound state, Eur. Phys. J. C **76**, 121 (2016).

[17] C. W. Xiao and E. Oset, Three methods to detect the predicted $D\bar{D}$ scalar meson $X(3700)$, Eur. Phys. J. A **49**, 52 (2013).

[18] E. Wang, W. H. Liang, and E. Oset, Analysis of the $e^{+}e^{-} \to J/\psi D\bar{D}$ reaction close to the threshold concerning claims of a $\chi_{c0}(2P)$ state, Eur. Phys. J. A **57**, 38 (2021).

[19] D. Gamermann and E. Oset, Hidden charm dynamically generated resonances and the $e^{+}e^{-} \to J/\psi D\bar{D}, J/\psi D\bar{D}^{*}$ reactions, Eur. Phys. J. A **36**, 189 (2008).

[20] P. Pakhlov *et al.* (Belle Collaboration), Production of new charmoniumlike states in $e^{+}e^{-} \to J/\psi D^{(*)}\bar{D}^{(*)}$ at $s^{1/2} \sim 10$ GeV, Phys. Rev. Lett. **100**, 202001 (2008).

[21] K. Chilikin *et al.* (Belle Collaboration), Observation of an alternative $\chi_{c0}(2P)$ candidate in $e^{+}e^{-} \to J/\psi D\bar{D}$, Phys. Rev. D **95**, 112003 (2017).

[22] S. Uehara *et al.* (Belle Collaboration), Observation of a χ'_{c2} Candidate in $\gamma\gamma \to D\bar{D}$ Production at BELLE, Phys. Rev. Lett. **96**, 082003 (2006).

[23] B. Aubert *et al.* (*BABAR* Collaboration), Observation of the $\chi_{c2}(2P)$ Meson in the Reaction $\gamma\gamma \to D\bar{D}$ at BABAR, Phys. Rev. D **81**, 092003 (2010).

[24] E. Wang, H. S. Li, W. H. Liang, and E. Oset, Analysis of the $\boldsymbol{\gamma\gamma \to D\bar{D}}$ reaction and the $D\bar{D}$ bound state, Phys. Rev. D **103**, 054008 (2021).

[25] S. Prelovsek, S. Collins, D. Mohler, M. Padmanath, and S. Piemonte, Charmoniumlike resonances with $J^{PC} = 0^{++}$, 2^{++} in coupled $D\bar{D}$, $D_s\bar{D}_s$ scattering on the lattice, arXiv:2011.02542.

[26] X. K. Dong, F. K. Guo, and B. S. Zou, A survey of heavy-antiheavy hadronic molecules, Prog. Phys. **41**, 65 (2021).

[27] E. Oset, W. H. Liang, M. Bayar, J. J. Xie, L. R. Dai, M. Albaladejo, M. Nielsen, T. Sekihara, F. Navarra, L. Roca *et al.*, Weak decays of heavy hadrons into dynamically generated resonances, Int. J. Mod. Phys. E **25**, 1630001 (2016).

[28] R. Aaij *et al.* (LHCb Collaboration), Measurement of the ratio of branching fractions of the decays $\Lambda_b^0 \to \psi(2S)\Lambda$ and $\Lambda_b^0 \to J/\psi\Lambda$, J. High Energy Phys. 03 (2019) 126.

[29] V. M. Abazov *et al.* (D0 Collaboration), Measurement of the production fraction times branching fraction $f(b \to \Lambda_b) \cdot \mathcal{B}(\Lambda_b \to J/\psi\Lambda)$, Phys. Rev. D **84**, 031102 (2011).

[30] G. Aad *et al.* (ATLAS Collaboration), Measurement of the branching ratio $\Gamma(\Lambda_b^0 \to \psi(2S)\Lambda^0)/\Gamma(\Lambda_b^0 \to J/\psi\Lambda^0)$ with the ATLAS detector, Phys. Lett. B **751**, 63 (2015).

[31] Y. K. Hsiao, P. Y. Lin, L. W. Luo, and C. Q. Geng, Fragmentation fractions of two-body b-baryon decays, Phys. Lett. B **751**, 127 (2015).

[32] R. Aaij *et al.* (LHCb Collaboration), Observations of $\Lambda_b^0 \to \Lambda K^{+}\pi^{-}$ and $\Lambda_b^0 \to \Lambda K^{+}K^{-}$ decays and searches for other Λ_b^0 and Ξ_b^0 decays to $\Lambda h^{+}h'^{-}$ final states, J. High Energy Phys. 05 (2016) 081.

[33] G. Y. Wang, M. Y. Duan, E. Wang, and D. M. Li, Enhancement near the $\bar{p}\Lambda$ threshold in the $\chi_{c0} \to \bar{p}K^{+}\Lambda$ reaction, Phys. Rev. D **102**, 036003 (2020).

[34] M. Ablikim *et al.* (BES Collaboration), Observation of a Near-Threshold Enhancement in the $\omega\phi$ Mass Spectrum from the Doubly OZI Suppressed Decay $J/\psi \to \gamma\omega\phi$, Phys. Rev. Lett. **96**, 162002 (2006).

[35] A. M. Torres, K. P. Khemchandani, F. S. Navarra, M. Nielsen, and E. Oset, The role of $f_0(1710)$ in the $\phi\omega$ threshold peak of $J/\Psi \to \gamma\phi\omega$, Phys. Lett. B **719**, 388 (2013).

[36] M. Ablikim *et al.* (BES Collaboration), Study of J/ψ decays into $\eta K^{*0}\bar{K}^{*0}$, Phys. Lett. B **685**, 27 (2010).

[37] L. S. Geng and E. Oset, Vector meson-vector meson interaction in a hidden gauge unitary approach, Phys. Rev. D **79**, 074009 (2009).

[38] J. J. Xie, M. Albaladejo, and E. Oset, Signature of an h_1 state in the $J/\psi \to \eta h_1 \to \eta K^{*0}\bar{K}^{*0}$ decay, Phys. Lett. B **728**, 319 (2014).

[39] J. X. Lu, E. Wang, J. J. Xie, L. S. Geng, and E. Oset, The $\Lambda_b \to J/\psi K^0 \Lambda$ reaction and a hidden-charm pentaquark state with strangeness, Phys. Rev. D **93**, 094009 (2016).

[40] E. Wang, H. X. Chen, L. S. Geng, D. M. Li, and E. Oset, Hidden-charm pentaquark state in $\Lambda_b^0 \to J/\psi p\pi^-$ decay, Phys. Rev. D **93**, 094001 (2016).

[41] H. S. Li, L. L. Wei, M. Y. Duan, E. Wang, and D. M. Li, Search for the scalar meson $a_0(980)$ in the single Cabibbo-suppressed process $\Lambda_c \to \pi^0\eta p$, arXiv:2009.08600.

[42] Z. Wang, Y. Y. Wang, E. Wang, D. M. Li, and J. J. Xie, The scalar $f_0(500)$ and $f_0(980)$ resonances and vector mesons in the single Cabibbo-suppressed decays $\Lambda_c \to pK^+K^-$ and $p\pi^+\pi^-$, Eur. Phys. J. C **80**, 842 (2020).

[43] W. Y. Liu, W. Hao, G. Y. Wang, Y. Y. Wang, E. Wang, and D. M. Li, Resonances $X(4140)$, $X(4160)$, and $P_{cs}(4459)$ in the decay of $\Lambda_b \to J/\psi\Lambda\phi$, Phys. Rev. D **103**, 034019 (2021).

[44] M. Y. Duan, J. Y. Wang, G. Y. Wang, E. Wang, and D. M. Li, Role of scalar $a_0(980)$ in the single Cabibbo suppressed process $D^+ \to \pi^+\pi^0\eta$, Eur. Phys. J. C **80**, 1041 (2020).

[45] Y. Zhang, E. Wang, D. M. Li, and Y. X. Li, Search for the $D^*\bar{D}^*$ molecular state $Z_c(4000)$ in the reaction $B^- \to J/\psi\rho^0K^-$, Chin. Phys. C **44**, 093107 (2020).

[46] L. R. Dai, G. Y. Wang, X. Chen, E. Wang, E. Oset, and D. M. Li, The $B^+ \to J/\psi\omega K^+$ reaction and $D^*\bar{D}^*$ molecular states, Eur. Phys. J. A **55**, 36 (2019).

[47] O. Romanets, L. Tolos, C. Garcia-Recio, J. Nieves, L. L. Salcedo, and R. G. E. Timmermans, Charmed and strange baryon resonances with heavy-quark spin symmetry, Phys. Rev. D **85**, 114032 (2012).

[48] H. Y. Cheng and C. K. Chua, Bottom baryon decays to pseudoscalar meson and pentaquark, Phys. Rev. D **92**, 096009 (2015).