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Strong and radiative decays of the doubly charmed baryons

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We have systematically studied the strong and radiative decays of the low-lying $1P$-wave doubly charmed baryons. Some interesting observations are: (i) The states Ξ^*_{cc} and Ω^*_{cc} with $J^P = 3/2^+$ have a fairly large decay rate into the $\Xi_{cc}\gamma$ and $\Omega_{cc}\gamma$ channels with a width ~15 and ~7 keV, respectively. (ii) The lowest lying excited doubly charmed baryons are dominated by the $1P$ ρ mode excitations, which should be quite narrow states. They decay into the ground state with $J^P = 1/2^+$ through the radiative transitions with a significant ratio. (iii) The total decay widths of the first orbital excitations of λ mode ($1P_\lambda$ states with $J^P = 1/2^-, 3/2^-, 5/2^-$) are about $\Gamma \sim 100$ MeV, and the ratio between the radiative and hadronic decay widths is about $\mathcal{O}(10^{-3})$.

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I. INTRODUCTION

In the past three decades, many singly heavy baryons were observed experimentally [1]. However, the experimental progress on the doubly heavy baryons remains very challenging. The SELEX Collaboration reported some evidence of two signals $\Xi^+_{cc}(3519)$ [2] and $\Xi^{++}_{cc}(3770)$ [3], which were not confirmed by other collaborations unfortunately. Very recently, the doubly heavy baryon $\Xi^{++}_{cc}(3621)$ was discovered in the $\Lambda^+_c K^- \pi^+ \pi^+$ mass spectrum by the LHCb collaboration [4]. Its mass was measured to be $3621.40 \pm 0.72(\mathrm{stat}) \pm 0.27(\mathrm{syst}) \pm 0.14$ MeV. The newly observed $\Xi_{cc}(3621)^{++}$ has attracted a great deal of attention from the hadron physics community [5–15].

The doubly heavy baryons provide a new platform to study the heavy quark symmetry and chiral dynamics simultaneously. There exist many theoretical calculations of the mass spectra of the doubly charmed baryons with various models in the literature [16–26]. The semileptonic decays of the doubly charmed baryons were also studied extensively [7,27–38]. Furthermore, there are a few discussions of the radiative transitions of the doubly charmed baryons in the literature [13,39–41]. In this work, we shall perform a systematical investigation of both strong and radiative decays of the low-lying $1P$-wave doubly charmed baryons. Their quark model classification, their allowed decay channels, and their predicted masses from Ref. [19] are summarized in Table I.

To deal with the pionic or kaonic decays of the doubly charmed baryons, we apply the chiral quark model [43], which was quite successful in the description of the hadronic decays of the heavy-light mesons and baryons [42,44–51] and light pseudoscalar meson productions [52–71]. The radiative decays of the doubly charmed baryons are analyzed within the constituent quark model. The same formalism was successfully applied to study the radiative decays of the $c\bar{c}$ and $b\bar{b}$ systems [72,73] and the newly observed Ω_c states [51].

The paper is structured as follows. In Sec. II we review the quark model description of the strong and radiative decays of the ccq system. We present the numerical results and some discussions in Sec. III and summarize our results in Sec. IV.

II. CHIRAL QUARK MODEL

In the chiral quark model, the effective low energy quark-pseudoscalar-meson coupling in the SU(3) flavor basis at tree level is described by [43]

$$H_m = \sum_j \frac{1}{f_m} \bar{\psi}_j \gamma^j_\mu \gamma^j_5 \psi_j \partial^\mu \phi_m, \tag{1}$$

where ψ_j stands for the jth quark field in a baryon. f_m is the pseudoscalar meson decay constant and ϕ_m is the pseudoscalar meson octet

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TABLE I. Masses and possible two body decay channels of the $1P$ doubly charmed baryons (denoted by $|N^{2S+1}L_\sigma J^P\rangle$), where $|N^{2S+1}L_\sigma J^P\rangle = \sum_{L_z+S_z=J_z}\langle LL_z, SS_z|JJ_z\rangle^N\Psi^\sigma_{LL_z}\chi_{S_z}\phi$ [42]. The masses (MeV) are taken from the relativistic quark model [19].

State		Ξ_{cc}			Ω_{cc}		
$N^{2S+1}L_\sigma J^P$	Wave function	Mass [19]	Decay channel	Observed state	Mass [19]	Decay channel	Observed state
$\lvert 0^2S\frac{1}{2}^+\rangle$	${}^0\Psi^S_{00}\chi^\lambda_{S_z}\phi$	3620		$\Xi(3621)$ [4]?	3778		?
$\lvert 0^4S\frac{3}{2}^+\rangle$	${}^0\Psi^S_{00}\chi^s_{S_z}\phi$	3727	$\Xi_{cc}\gamma$	?	3872	$\Omega_{cc}\gamma$	?
$\lvert 1^2P_\rho\frac{1}{2}^-\rangle$	${}^1\Psi^\rho_{1L_z}\chi^\rho_{S_z}\phi$	3838	$\Xi_{cc}\gamma$, $\Xi^*_{cc}\gamma$	?	4002	$\Omega_{cc}\gamma$,$\Omega^*_{cc}\gamma$	?
$\lvert 1^2P_\rho\frac{3}{2}^-\rangle$		3959	$\Xi_{cc}\gamma$, $\Xi^*_{cc}\gamma$	?	4102	$\Omega_{cc}\gamma$,$\Omega^*_{cc}\gamma$	?
$\lvert 1^2P_\lambda\frac{1}{2}^-\rangle$	${}^1\Psi^\lambda_{1L_z}\chi^\lambda_{S_z}\phi$	4136	$\Xi_{cc}\pi$, $\Xi^*_{cc}\pi$,$\Xi_{cc}\gamma$, $\Xi^*_{cc}\gamma$	?	4271	$\Xi_{cc}K$, $\Xi^*_{cc}K$, $\Omega_{cc}\gamma$, $\Omega^*_{cc}\gamma$	?
$\lvert 1^2P_\lambda\frac{3}{2}^-\rangle$		4196	$\Xi_{cc}\pi$, $\Xi^*_{cc}\pi$,$\Xi_{cc}\gamma$, $\Xi^*_{cc}\gamma$	?	4325	$\Xi_{cc}K$, $\Xi^*_{cc}K$, $\Omega_{cc}\gamma$, $\Omega^*_{cc}\gamma$	?
$\lvert 1^4P_\lambda\frac{1}{2}^-\rangle$	${}^1\Psi^\lambda_{1L_z}\chi^s_{S_z}\phi$	4053	$\Xi_{cc}\pi$, $\Xi^*_{cc}\pi$,$\Xi_{cc}\gamma$, $\Xi^*_{cc}\gamma$	?	4208	$\Xi_{cc}K$, $\Xi^*_{cc}K$, $\Omega_{cc}\gamma$, $\Omega^*_{cc}\gamma$	?
$\lvert 1^4P_\lambda\frac{3}{2}^-\rangle$		4101	$\Xi_{cc}\pi$, $\Xi^*_{cc}\pi$,$\Xi_{cc}\gamma$, $\Xi^*_{cc}\gamma$	?	4252	$\Xi_{cc}K$, $\Xi^*_{cc}K$, $\Omega_{cc}\gamma$, $\Omega^*_{cc}\gamma$	?
$\lvert 1^4P_\lambda\frac{5}{2}^-\rangle$		4155	$\Xi_{cc}\pi$, $\Xi^*_{cc}\pi$,$\Xi_{cc}\gamma$, $\Xi^*_{cc}\gamma$	?	4303	$\Xi_{cc}K$, $\Xi^*_{cc}K$, $\Omega_{cc}\gamma$, $\Omega^*_{cc}\gamma$	?

$$\phi_m = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & K^0 \\ K^- & \bar{K}^0 & -\sqrt{\frac{2}{3}}\eta \end{pmatrix}. \quad (2)$$

For the radiative decay under this model framework, we adopt the quark-photon electromagnetic interaction [74]:

$$H_e = -\sum_j e_j \bar{\psi}_j \gamma^j_\mu A^\mu(\mathbf{k}, \mathbf{r_j})\psi_j, \quad (3)$$

where $\mathbf{k}$ stands for the three-momentum of the photon with the field A^μ. $\mathbf{r}_j$ and e_j represent the coordinate and charge of the jth constituent quark, respectively. This model was successfully applied to discuss the radiative decay of doubly heavy mesons [72,73].

To match the nonrelativistic harmonic oscillator spatial wave function ${}^N\Psi_{LL_z}$ in this work, we adopt a nonrelativistic form of the quark-pseudoscalar and quark-photon EM couplings. The nonrelativistic form of Eq. (1) reads [55–57]

$$H^{nr}_m = \sum_j \left\{ \frac{\omega_m}{E_f + M_f}\boldsymbol{\sigma}_j \cdot \mathbf{P}_f + \frac{\omega_m}{E_i + M_i}\boldsymbol{\sigma}_j \cdot \mathbf{P}_i \right. \quad (4)$$

$$\left. -\boldsymbol{\sigma}_j \cdot \mathbf{q} + \frac{\omega_m}{2\mu_q}\boldsymbol{\sigma}_j \cdot \mathbf{p}'_j \right\} I_j \phi_m, \quad (5)$$

where the $\boldsymbol{\sigma}_j$ and μ_q stands for the Pauli spin vector and the reduced mass of the jth quark in the initial and final baryons, respectively. $\varphi_m = e^{-i\mathbf{q}\cdot\mathbf{r}_j}$ for emitting a meson, and $\varphi_m = e^{i\mathbf{q}\cdot\mathbf{r}_j}$ for absorbing a meson. $\mathbf{p}'_j = \mathbf{p}_j - (m_j/M)\mathbf{P}_{c.m.}$ is the internal momentum of the jth quark in the baryon rest frame. ω_m and $\mathbf{q}$ are the energy and three-vector momentum of the meson, respectively. I_j is the isospin operator associated with the pseudoscalar meson

$$I_j = \begin{cases} a^\dagger_j(u)a_j(s) & \text{for } K^-, \\ a^\dagger_j(d)a_j(s) & \text{for } K^0, \\ a^\dagger_j(u)a_j(d) & \text{for } \pi^-, \\ a^\dagger_j(d)a_j(u) & \text{for } \pi^+, \\ \frac{1}{\sqrt{2}}[a^\dagger_j(u)a_j(u) - a^\dagger_j(d)a_j(d)] & \text{for } \pi^0. \end{cases} \quad (6)$$

The nonrelativistic form of Eq. (3) reads [55–57,72–74]

$$H^{nr}_e = \sum_j \left[e_j \mathbf{r}_j \cdot \boldsymbol{\epsilon} - \frac{e_j}{2m_j}\sigma_j \cdot (\boldsymbol{\epsilon} \times \hat{\mathbf{k}}) \right] e^{-i\mathbf{k}\cdot\mathbf{r}_j}, \quad (7)$$

where the $\boldsymbol{\epsilon}$ is the polarization vector of the photon.

For the emission of a light pseudoscalar meson, the partial decay width is

$$\Gamma_m = \left(\frac{\delta}{f_m}\right)^2 \frac{(E_f + M_f)|q|}{4\pi M_i} \frac{1}{2J_i + 1} \sum_{J_{iz}J_{fz}} |M_{J_{iz},J_{fz}}|^2, \quad (8)$$

where $M_{J_{iz},J_{fz}}$ is the transition amplitude, J_{iz} and J_{fz} stand for the third components of the total angular momenta of the initial and final baryons, respectively. Accounting for the strength of the quark-meson coupling, δ is a global parameter which has been determined in previous study of the strong decays of the charmed baryons and heavy-light mesons [42,44]. Here, we fix its value the same as that in Refs. [42,44], i.e., $\delta = 0.557$.

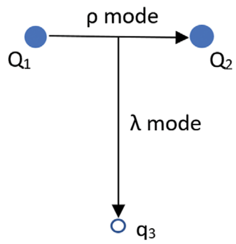

FIG. 1. The $\rho-$ and $\lambda-$ mode excitations of the ccq system where ρ and λ are the Jacobi coordinates defined as $\rho = \frac{1}{\sqrt{2}}(\mathbf{r}_1 - \mathbf{r}_2)$ and $\lambda = \frac{1}{\sqrt{6}}(\mathbf{r}_1 + \mathbf{r}_2 - 2\mathbf{r}_3)$, respectively. Q_1 and Q_2 stand for the charm quark, and q_3 stands for the light (u, d, s) quark.

Meanwhile, the partial radiative decay widths are [72,73]

$$\Gamma_\gamma = \frac{|\mathbf{k}|^2}{\pi}\frac{2}{2J_i+1}\frac{M_f}{M_i}\sum_{J_{iz}J_{fz}}|A_{J_{iz},J_{fz}}|^2, \tag{9}$$

where $A_{J_{iz},J_{fz}}$ stands for the EM transition amplitude.

In the calculation, the standard quark model parameters are adopted. Namely, we set $m_u = m_d = 330$ MeV, $m_s = 450$ MeV, and $m_c = 1480$ MeV for the constituent quark masses. The decay constants for π and K mesons are taken as $f_\pi = 132$ MeV, $f_K = 160$ MeV, respectively. The masses of the resonances are then from the predictions with the relativistic quark model [19]. The mass of the ground-state $|\Xi_{cc}{}^2S\frac{1}{2}^+\rangle$ is adopted the experimental measurement, $M = 3621$ MeV. The harmonic oscillator parameter α_ρ in the spatial wave function of the ρ-mode excitation between the two charm quarks (see Fig. 1) is taken as $\alpha_\rho = 0.66$ GeV as in the charmonium system, which is significantly larger than that of the ρ-mode excitation between the two strange quarks ($\alpha_\rho = 0.44$ GeV) adopted in [51]. Another harmonic oscillator parameter α_λ is estimated with the relation:

$$\alpha_\lambda = \left(\frac{3m_q}{2m_Q + m_q}\right)^{1/4}\alpha_\rho. \tag{10}$$

In the simplified case of the harmonic oscillator potential, the ρ and λ degrees of freedom decouple,

$$H = \frac{1}{2m_\rho}\mathbf{p}_\rho^2 + \frac{1}{2m_\lambda}\mathbf{p}_\lambda^2 + \frac{3}{2}K(\rho^2 + \lambda^2), \tag{11}$$

where

$$m_\rho = m_Q, \qquad m_\lambda = \frac{3m_Q m_q}{2m_Q + m_q} \tag{12}$$

and the oscillator frequencies ω_ρ and ω_λ are defined as

$$\omega_\rho = (3K/m_\rho)^{1/2}, \qquad \omega_\lambda = (3K/m_\lambda)^{1/2}. \tag{13}$$

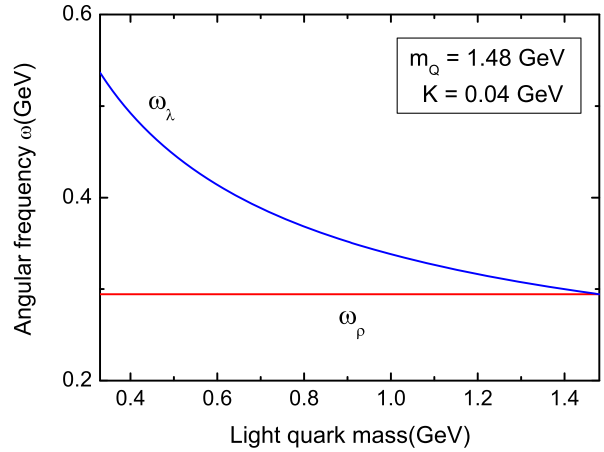

FIG. 2. Light-quark mass dependence of the excitation energy of the λ mode (blue solid line) and the ρ mode (red solid line) in Eq. (13).

The ratio of the $1P$ ρ and λ excitation energies reads

$$\frac{\omega_\lambda}{\omega_\rho} = \sqrt{\frac{1}{3} + \frac{2m_Q}{3m_q}} > 1. \tag{14}$$

Since the bottom and charm quark masses are much larger than the light quark mass ($m_Q > m_q$), the excitation energy of the λ-mode is larger than that of the ρ-mode, $\omega_\lambda > \omega_\rho$ (see Fig. 2). Thus, the ρ-excitation modes are lighter than the λ-excitation modes for the $1P$ doubly charmed baryons. The realistic potential is much more complicated than the simple harmonic oscillator potential. However, the general feature of the level ordering of the $1P$ doubly charmed baryons should be similar.

III. CALCULATIONS AND RESULTS

Since the predicted mass of the lowest doubly charmed baryon $\Xi_{cc}(3621)^{++}$ in relativistic quark model [19] agrees with the recent experimental measurement by the LHCb collaboration, we adopt the masses of the doubly charmed states from Ref. [19] (see Table I) in our calculation.

A. The ground doubly charmed states with $J^P = 3/2^+$

The ground-state $|\Xi_{cc}{}^4S\frac{3}{2}^+\rangle$ has a mass near $M \sim 3727$ MeV [19], which is below the $\Xi_{cc}\pi$ threshold. Thus, the two-body strong decays are forbidden. This state should mainly decay into $\Xi_{cc}\gamma$. We plot the radiative decay widths of $|\Xi_{ccu}{}^4S\frac{3}{2}^+\rangle$ and $|\Xi_{ccd}{}^4S\frac{3}{2}^+\rangle$ (denoted with Ξ_{cc}^{*++} and Ξ_{cc}^{*+}, respectively) as a function of their masses in Figs. 3 and 4. The radiative decay widths are sensitive to the parent baryon masses. With $M = 3727$ MeV, the radiative partial decay widths of Ξ_{cc}^{*++} and Ξ_{cc}^{*+} are

$$\Gamma[\Xi_{cc}^{*++} \to \Xi_{cc}^{++}\gamma] \simeq 16.7\ \text{keV}, \tag{15}$$

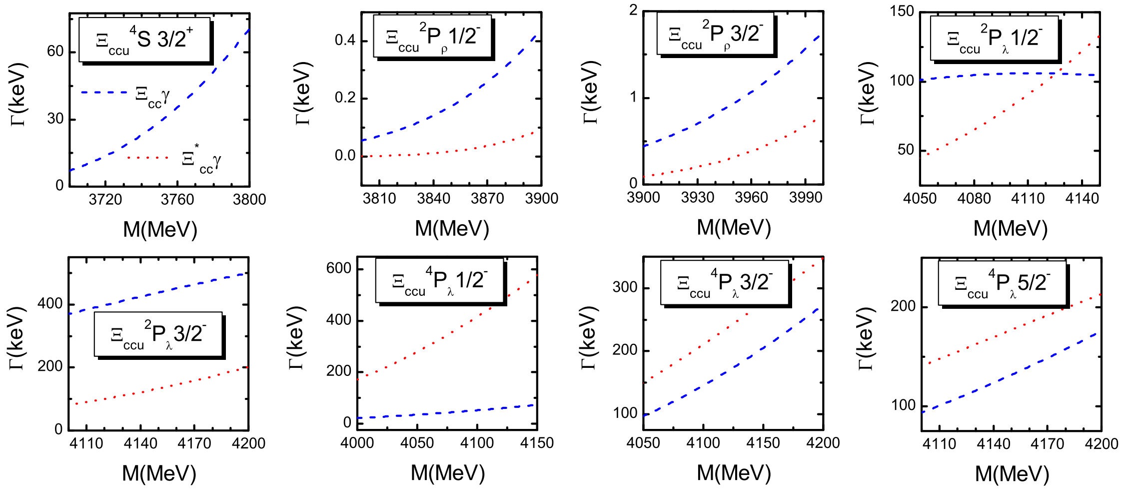

FIG. 3. The radiative decay widths of the low-lying S- and P-wave Ξ_{ccu} states as a function of the mass. In the figure, Ξ_{cc} and Ξ_{cc}^* stand for the $|\Xi_{ccu}{}^2S\frac{1}{2}^+\rangle$ and $|\Xi_{ccu}{}^4S\frac{3}{2}^+\rangle$ states. Their masses are 3621 MeV and 3727 MeV, respectively.

$$\Gamma[\Xi_{cc}^{*+} \to \Xi_{cc}^{+}\gamma] \simeq 14.6 \text{ keV}, \qquad (16)$$

respectively, which are comparable with the predictions in Refs. [13,40] (see Table II). The fairly large radiative partial decay widths indicate the missing $J^P = 3/2^+$ ground states Ξ_{cc}^{*++} (Ξ_{cc}^{*+}) might be observed in the $\Xi_{cc}^{++}\gamma$ ($\Xi_{cc}^{+}\gamma$) channel.

The predicted mass of ground-state $|\Omega_{cc}{}^4S\frac{3}{2}^+\rangle$ (denoted with Ω_{cc}^*) is around 3.87 GeV [19], which is obviously below the $\Xi_{cc}K$ threshold. This state mainly decays through the EM transition. From Fig. 5, the Ω_{cc}^* has a quite narrow radiative decay width of $\Gamma \simeq (0-2)$ keV if the mass of Ω_{cc}^* is less than 3.84 GeV. With $M = 3872$ MeV, we obtain

$$\Gamma(\Omega_{cc}^* \to \Omega_{cc}\gamma) \simeq 6.93 \text{ keV}, \qquad (17)$$

which is compatible with the results in Refs. [13,40].

B. The *P*-wave doubly charmed states

1. *ρ*-mode excitations

As emphasized in Sec. II, the ρ-mode orbitally excited state has relatively smaller mass than a λ-mode orbitally excited state for the doubly heavy baryon system. The masses of the $1P_\rho$ states of Ξ_{cc} and Ω_{cc} are above the threshold of $\Xi_{cc}\pi$ and $\Xi_{cc}K$, respectively. However, their strong decays are forbidden due to the orthogonality of spatial wave functions if we adopt the simple harmonic oscillator wave functions for the $1P$ and $1S$ states. In present work we focus on their radiative decays.

In the quark model, there are two $1P_\rho$ states with $J^P = 1/2^-$ and $3/2^-$, respectively. In the doubly charmed baryon Ξ_{cc} family, the predicted mass of $|^2P_\rho\frac{1}{2}^-\rangle$ is about 3.84 GeV [19]. The mass of $|^2P_\rho\frac{3}{2}^-\rangle$ is about 3.96 GeV [19], which is $\sim$120 MeV heavier than that of $|^2P_\rho\frac{1}{2}^-\rangle$. Considering the

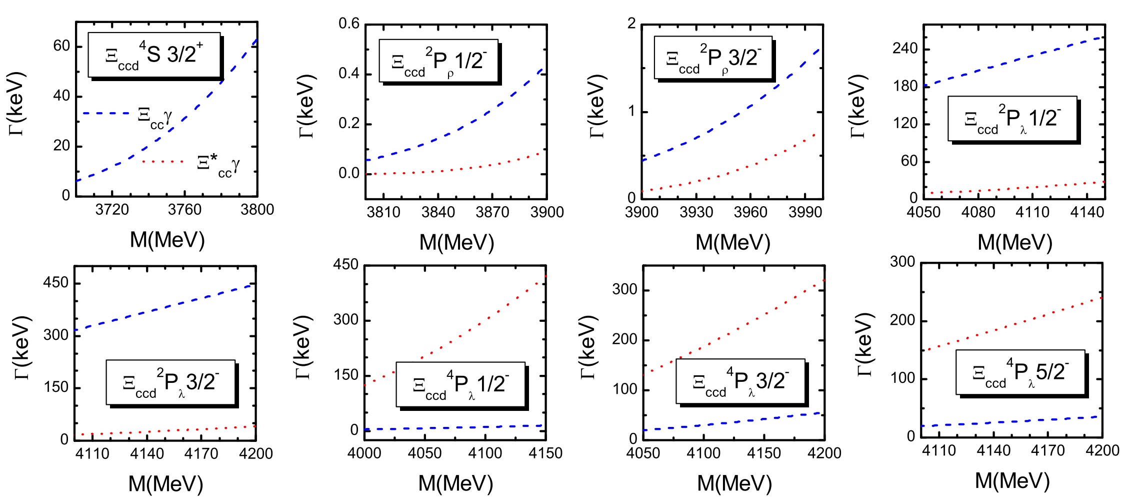

FIG. 4. The radiative decay widths of the low-lying S- and P-wave Ξ_{ccd} states as a function of the mass.

TABLE II. Radiative decay widths (keV) of the ground states with $J^P = 3/2^+$ compared with the three-quark model [40] and chiral perturbation theory [13].

Process	Our result	[40]	[13]
$\Xi_{cc}^{*++} \to \Xi_{cc}^{++}$	16.7	23.5	22.0
$\Xi_{cc}^{*+} \to \Xi_{cc}^{+}$	14.6	28.8	9.57
$\Omega_{cc}^{*} \to \Omega_{cc}$	6.93	2.11	9.45
$\Xi_{bb}^{*0} \to \Xi_{bb}^{0}$	1.19	0.31	…
$\Xi_{bb}^{*-} \to \Xi_{bb}^{-}$	0.24	0.06	…
$\Omega_{bb}^{*} \to \Omega_{bb}$	0.08	0.02	…

uncertainties of the predicted mass, we also plot the radiative decay width of $1P_\rho$ as a functions of the parent baryon mass in Figs. 3 and 4. It is interesting to note that the radiative decay widths of the ρ-mode orbitally excited states are isospin independent because the decay amplitude does not depend on the light quark. The $|^2P_{\rho}\frac{1}{2}^-\rangle$ should be a narrow state with a width of $\Gamma \leq 0.5$ keV. The state $|^2P_{\rho}\frac{3}{2}^-\rangle$ has a decay width of $\Gamma \leq 2$ keV. Since their strong decays are forbidden, the total decay widths are almost saturated by the total radiative decay widths. With the masses of $|^2P_{\rho}\frac{1}{2}^-\rangle$ and $|^2P_{\rho}\frac{3}{2}^-\rangle$ $M = 3838$ MeV and $M = 3959$ MeV, respectively, their total decay widths are

$$\Gamma^{\text{total}}_{|^2P_{\rho}\frac{1}{2}^-\rangle} \simeq 0.15 \text{ keV}, \qquad \Gamma^{\text{total}}_{|^2P_{\rho}\frac{3}{2}^-\rangle} \simeq 1.43 \text{ keV}. \tag{18}$$

In the Ω_{cc} family, the masses of $|^2P_{\rho}\frac{1}{2}^-\rangle$ and $|^2P_{\rho}\frac{3}{2}^-\rangle$ are about 4.00 and 4.10 GeV [19] respectively. From Fig. 5, the $|^2P_{\rho}\frac{1}{2}^-\rangle$ has a total decay width of $\Gamma \leq 0.5$ keV and $|^2P_{\rho}\frac{3}{2}^-\rangle$ has a total decay width of $\Gamma \leq 3.0$ keV, and their main decay channel is $\Omega_{cc}\gamma$.

2. λ-mode excitations

In the Ξ_{cc} family, the mass of the first orbital excitation of the λ-mode ($1P_\lambda$ states) is about 4.10 GeV [19]. The total decay width of $|\Xi_{cc}{}^2P_{\lambda}\frac{1}{2}^-\rangle$ is $\Gamma \simeq 50$ MeV. The main decay channels are $\Xi_{cc}\pi$ and $\Xi_{cc}^*\pi$. The partial width ratio between $\Xi_{cc}\pi$ and $\Xi_{cc}^*\pi$ is

$$\frac{\Gamma[|\Xi_{cc}{}^2P_{\lambda}\frac{1}{2}^-\rangle \to \Xi_{cc}\pi]}{\Gamma[|\Xi_{cc}{}^2P_{\lambda}\frac{1}{2}^-\rangle \to \Xi_{cc}^*\pi]} \simeq 0.46. \tag{19}$$

On the other hand, the radiative decay rate of $|\Xi_{cc}^{++}{}^2P_{\lambda}\frac{1}{2}^-\rangle$ into $\Xi_{cc}^{*++}\gamma$ is large, and the predicted branching fraction is

$$\mathcal{B}[|\Xi_{cc}^{++}{}^2P_{\lambda}1/2^-\rangle \to \Xi_{cc}^{*++}\gamma] \simeq 0.24\%. \tag{20}$$

The radiative decay rate of $|\Xi_{cc}^{+}{}^2P_{\lambda}\frac{1}{2}^-\rangle$ into $\Xi_{cc}^{+}\gamma$ is significant, and the predicted branching ratio is

$$\mathcal{B}[|\Xi_{cc}^{+}{}^2P_{\lambda}1/2^-\rangle \to \Xi_{cc}^{+}\gamma] \simeq 0.50\%. \tag{21}$$

The states $|\Xi_{cc}{}^2P_{\lambda}\frac{3}{2}^-\rangle$ and $|\Xi_{cc}{}^4P_{\lambda}\frac{3}{2}^-\rangle$ have a moderate width of $\Gamma \sim 100$ MeV, and dominantly decay into $\Xi_{cc}^*\pi$. The partial width of $\Gamma[|\Xi_{cc}{}^2P_{\lambda}\frac{3}{2}^-\rangle \to \Xi_{cc}\pi]$ is sizable. The partial width ratio is

$$\frac{\Gamma[|\Xi_{cc}{}^2P_{\lambda}3/2^-\rangle \to \Xi_{cc}\pi]}{\Gamma[|\Xi_{cc}{}^2P_{\lambda}3/2^-\rangle \to \Xi_{cc}^*\pi]} \simeq 0.21, \tag{22}$$

which can be used to distinguish $|\Xi_{cc}{}^2P_{\lambda}\frac{3}{2}^-\rangle$ from $|\Xi_{cc}{}^4P_{\lambda}\frac{3}{2}^-\rangle$ in future experiments. The radiative partial widths of the P-wave Ξ_{cc}^{++} states with $J^P = 3/2^-$ into $\Xi_{cc}^{++}\gamma$ and $\Xi_{cc}^{*++}\gamma$ are around a few hundred keV. The radiative decays of $|\Xi_{cc}^{+}{}^2P_{\lambda}\frac{3}{2}^-\rangle$ and $|\Xi_{cc}^{+}{}^4P_{\lambda}\frac{3}{2}^-\rangle$ are dominated by $\Xi_{cc}^{+}\gamma$ and $\Xi_{cc}^{*+}\gamma$, respectively. Their partial width can also reach up to several hundred keV as well. These

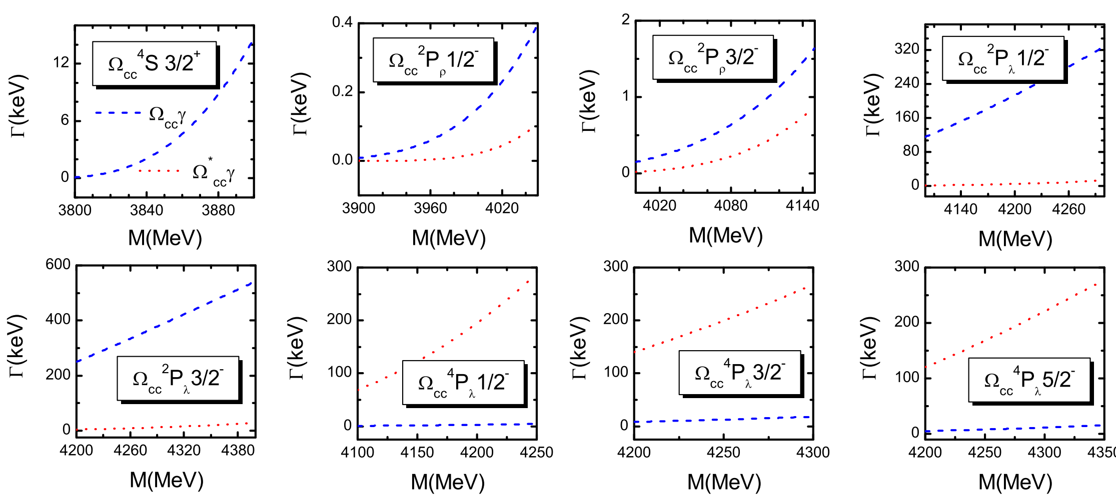

FIG. 5. The radiative decay widths of the low-lying S- and P-wave Ω_{cc} states as a function of the mass. In the figure, Ω_{cc} and Ω_{cc}^* stand for the $|\Omega_{cc}{}^2S\frac{1}{2}^+\rangle$ and $|\Omega_{cc}{}^4S\frac{3}{2}^+\rangle$ states. Their masses are 3778 MeV and 3872 MeV, respectively.

TABLE III. The partial widths of strong and radiative decays for the $1P_\lambda$ states. $\Gamma_{\rm total}$ stands for the total decay width.

State	Mass (MeV)	$\Gamma[\Xi_{cc}\pi]$ (MeV)	$\Gamma[\Xi_{cc}^*\pi]$ (MeV)	Types of light quark	$\Gamma[\Xi_{cc}\gamma]$ (keV)	$\Gamma[\Xi_{cc}^*\gamma]$ (keV)	$\Gamma_{\rm total}$ (MeV)
$\vert\Xi_{cc}{}^2P_{\lambda}\frac{1}{2}^-\rangle$	4136	15.6	33.9	u	105	117	49.7
				d	250	24.6	
$\vert\Xi_{cc}{}^2P_{\lambda}\frac{3}{2}^-\rangle$	4196	21.6	101	u	495	196	123
				d	442	40.7	
$\vert\Xi_{cc}{}^4P_{\lambda}\frac{1}{2}^-\rangle$	4053	133	1.22	u	35.7	287	134
				d	7.47	208	
$\vert\Xi_{cc}{}^4P_{\lambda}\frac{3}{2}^-\rangle$	4101	7.63	84.6	u	147	212	92.6
				d	30.5	189	
$\vert\Xi_{cc}{}^4P_{\lambda}\frac{5}{2}^-\rangle$	4155	75.3	22.8	u	136	181	98.4
				d	28.0	198	
State	Mass(MeV)	$\Gamma[\Xi_{cc}K]$ (MeV)	$\Gamma[\Xi_{cc}^*K]$ (MeV)		$\Gamma[\Omega_{cc}\gamma]$ (keV)	$\Gamma[\Omega_{cc}^*\gamma]$ (keV)	$\Gamma_{\rm total}$ (MeV)
$\vert\Omega_{cc}{}^2P_{\lambda}\frac{1}{2}^-\rangle$	4271	33.1	2.36	s	294	9.61	35.7
$\vert\Omega_{cc}{}^2P_{\lambda}\frac{3}{2}^-\rangle$	4325	11.4	174	s	430	157	185
$\vert\Omega_{cc}{}^4P_{\lambda}\frac{1}{2}^-\rangle$	4208	323	$\cdots$	s	3.19	209	323
$\vert\Omega_{cc}{}^4P_{\lambda}\frac{3}{2}^-\rangle$	4252	3.08	137	s	12.9	202	140
$\vert\Omega_{cc}{}^4P_{\lambda}\frac{5}{2}^-\rangle$	4303	41.5	4.38	s	12.0	225	45.9

radiative processes may be measured in future experiments due to their sizeable branching fractions, $\mathcal{O}(10^{-3})$.

From the Table III, the decay widths of $|\Xi_{cc}{}^4P_{\lambda}\frac{1}{2}^-\rangle$ and $|\Xi_{cc}{}^4P_{\lambda}\frac{5}{2}^-\rangle$ are about $\Gamma \sim 100$ MeV. The dominant decay mode of $|\Xi_{cc}{}^4P_{\lambda}\frac{1}{2}^-\rangle$ is $\Xi_{cc}\pi$, while $|\Xi_{cc}{}^4P_{\lambda}\frac{5}{2}^-\rangle$ mainly decays into $\Xi_{cc}\pi$ and $\Xi_{cc}^*\pi$ channels with the partial decay ratio

$$\frac{\Gamma[|\Xi_{cc}{}^4P_{\lambda}5/2^-\rangle \to \Xi_{cc}^*\pi]}{\Gamma[|\Xi_{cc}{}^4P_{\lambda}5/2^-\rangle \to \Xi_{cc}\pi]} \simeq 0.30. \quad (23)$$

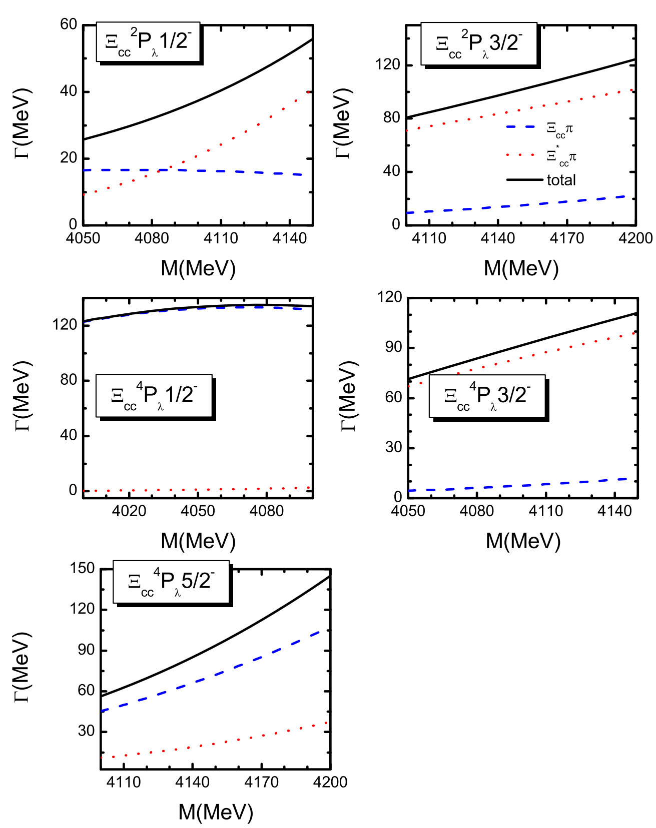

FIG. 6. The strong decay partial widths of the $1P_\lambda$-wave Ξ_{cc} states as a function of the mass.

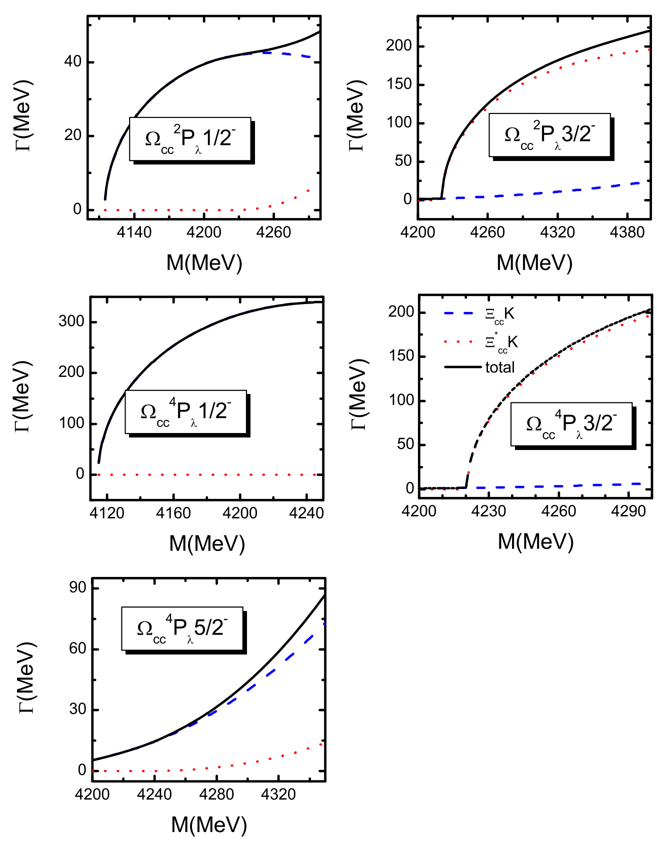

FIG. 7. The strong decay partial widths of the $1P_\lambda$-wave Ω_{cc} states as a function of the mass.

For the EM transitions, the $\Xi^{*}_{cc}\gamma$ channel is their dominant decay mode. The radiative decay partial widths into $\Xi^{*++,+}_{cc}\gamma$ are a few hundred keV. The branching fractions for these radiative decay processes are $\mathcal{O}(10^{-3})$. These sizeable branching fractions indicate that the radiative decays of $|\Xi_{cc}{}^4P_{\lambda}\frac{1}{2}^-\rangle$ and $|\Xi_{cc}{}^4P_{\lambda}\frac{5}{2}^-\rangle$ may be observed in future experiments.

We analyze the decay properties of the $1P_\lambda$ states in the Ω_{cc} family and collect their partial strong and radiative decay widths in Table III. The states $|\Omega_{cc}{}^2P_{\lambda}\frac{1}{2}^-\rangle$ and $|\Omega_{cc}{}^4P_{\lambda}\frac{5}{2}^-\rangle$ are most likely to be the narrow states with a width of $\Gamma\sim 40$ MeV, and the $\Xi_{cc}K$ decay channel almost saturates their total decay widths. The dominant radiative decay modes of these two states are $\Omega_{cc}\gamma$ and $\Omega^{*}_{cc}\gamma$, respectively. The branching ratios are

$$\mathcal{B}[{}^2P_\lambda 1/2^- \to \Omega_{cc}\gamma] \simeq 0.81\%, \tag{24}$$

$$\mathcal{B}[{}^4P_\lambda 5/2^- \to \Omega^{*}_{cc}\gamma] \simeq 0.48\%, \tag{25}$$

which can be tested in future experiments.

TABLE IV. The variation of the strong decay width of the $1P_\lambda$ states with the harmonic oscillator parameter α_ρ. $\Gamma_{\rm total}$ is the total decay width. The unit of the mass, width, and α_ρ is MeV.

State	Mass	Width	$\alpha_\rho=620$	$\alpha_\rho=580$	$\alpha_\rho=540$	$\alpha_\rho=500$	$\alpha_\rho=460$
$\lvert\Xi_{cc}{}^2P_{\lambda}\frac{1}{2}^-\rangle$	4136	$\Gamma[\Xi_{cc}\pi]$	9.80	5.39	2.34	0.58	0.02
		$\Gamma[\Xi^*_{cc}\pi]$	37.2	40.2	43.3	46.4	49.2
		$\Gamma_{\rm total}$	47.0	45.6	45.7	47.0	49.2
$\lvert\Xi_{cc}{}^2P_{\lambda}\frac{3}{2}^-\rangle$	4196	$\Gamma[\Xi_{cc}\pi]$	22.5	23.0	23.1	22.8	21.6
		$\Gamma[\Xi^*_{cc}\pi]$	81.8	66.8	55.8	48.6	44.8
		$\Gamma_{\rm total}$	104	89.8	78.9	71.3	66.3
$\lvert\Xi_{cc}{}^4P_{\lambda}\frac{1}{2}^-\rangle$	4053	$\Gamma[\Xi_{cc}\pi]$	94.6	62.7	37.2	18.4	6.26
		$\Gamma[\Xi^*_{cc}\pi]$	1.34	1.48	1.64	1.82	2.01
		$\Gamma_{\rm total}$	95.9	64.2	38.8	20.2	8.27
$\lvert\Xi_{cc}{}^4P_{\lambda}\frac{3}{2}^-\rangle$	4101	$\Gamma[\Xi_{cc}\pi]$	8.11	8.58	9.00	9.32	9.49
		$\Gamma[\Xi^*_{cc}\pi]$	67.0	51.7	39.0	29.0	22.5
		$\Gamma_{\rm total}$	75.1	60.3	48.0	38.2	31.0
$\lvert\Xi_{cc}{}^4P_{\lambda}\frac{5}{2}^-\rangle$	4155	$\Gamma[\Xi_{cc}\pi]$	78.9	81.9	83.9	84.5	82.7
		$\Gamma[\Xi^*_{cc}\pi]$	24.6	26.4	28.3	30.0	31.5
		$\Gamma_{\rm total}$	103	108	112	114	114
$\lvert\Omega_{cc}{}^2P_{\lambda}\frac{1}{2}^-\rangle$	4271	$\Gamma[\Xi_{cc}K]$	32.4	23.8	16.4	10.4	5.71
		$\Gamma[\Xi^*_{cc}K]$	2.64	2.98	3.37	3.84	4.41
		$\Gamma_{\rm total}$	35.1	26.8	19.8	14.2	10.1
$\lvert\Omega_{cc}{}^2P_{\lambda}\frac{3}{2}^-\rangle$	4325	$\Gamma[\Xi_{cc}K]$	12.2	13.0	13.8	14.4	14.8
		$\Gamma[\Xi^*_{cc}K]$	143	115	90.7	69.4	51.6
		$\Gamma_{\rm total}$	155	128	104	83.8	66.4
$\lvert\Omega_{cc}{}^4P_{\lambda}\frac{1}{2}^-\rangle$	4208	$\Gamma[\Xi_{cc}K]$	264	211	163	120	83.3
		$\Gamma[\Xi^*_{cc}K]$	…	…	…	…	…
		$\Gamma_{\rm total}$	264	211	163	120	83.3
$\lvert\Omega_{cc}{}^4P_{\lambda}\frac{3}{2}^-\rangle$	4252	$\Gamma[\Xi_{cc}K]$	3.36	3.68	4.02	4.38	4.75
		$\Gamma[\Xi^*_{cc}K]$	118	100	84.3	69.3	55.6
		$\Gamma_{\rm total}$	121	104	88.3	73.7	60.4
$\lvert\Omega_{cc}{}^4P_{\lambda}\frac{5}{2}^-\rangle$	4303	$\Gamma[\Xi_{cc}K]$	44.7	48.0	51.3	54.3	56.8
		$\Gamma[\Xi^*_{cc}K]$	4.86	5.41	6.05	6.79	7.63
		$\Gamma_{\rm total}$	49.6	53.4	57.3	61.1	64.4

The state $|\Omega_{cc}{}^4P_{\lambda}\frac{1}{2}^-\rangle$ has a broad width of $\Gamma \simeq 320$ MeV, and mainly decays into $\Xi_{cc}K$. The states $|\Omega_{cc}{}^2P_{\lambda}\frac{3}{2}^-\rangle$ and $|\Omega_{cc}{}^4P_{\lambda}\frac{3}{2}^-\rangle$ may lie below the threshold of $\Xi^*_{cc}K$. If so, they mainly decay into $\Xi_{cc}K$ channel with a fairly narrow width $\Gamma \sim 11$ MeV and $\Gamma \sim 3$ MeV, respectively. The branching ratios of the main radiative decay channels are

$$\mathcal{B}[^2P_{\lambda}3/2^- \to \Omega_{cc}\gamma] \simeq 3.77\%, \quad (26)$$

$$\mathcal{B}[^4P_{\lambda}3/2^- \to \Omega^*_{cc}\gamma] \simeq 6.49\%, \quad (27)$$

respectively, which are significant and can be searched for in experiment. However, if their masses are above the threshold of $\Xi^*_{cc}K$, their dominant decay modes should be $\Xi^*_{cc}K$ and their total decay widths may reach $\Gamma \sim 185$ MeV and $\Gamma \sim 140$ MeV.

Considering the uncertainty of the mass predictions of the $1P_{\lambda}$ states, we plot the radiative and strong decay widths as a function of the mass in Figs. 3–7, respectively. The sensitivities of the decay properties of the doubly charmed states to their masses can be clearly seen from these figures.

C. The effect of α_ρ

We have discussed the decay properties of the ground state with $J^P = 3/2^+$ and $1P$-wave states with $J^P = 1/2^-$, $3/2^-$, $5/2^-$ for the doubly charmed baryons. All of the theoretical predictions in the present work are obtained with the parameter $\alpha_\rho = 660$ MeV. However, the harmonic oscillator parameter α_ρ is not determined absolutely, which bares a large uncertainty. Fixing the mass values as in Ref. [19], we further consider the decay properties as a function of the parameter α_ρ. The results are listed in Table IV.

It's important to note that the effects on radiative decay widths from the parameter α_ρ are much smaller than that on strong decay widths, so we just list the hadronic decay width in table. From the table, only the decay properties of the doubly charmed states with $J^P = 1/2^-$ are sensitive to the harmonic oscillator parameter α_ρ. Fortunately, the decay properties of the other doubly charmed states with $J^P = 3/2^-$ and $J^P = 5/2^-$ states are less sensitivities to this parameter. Thus, our numerical results and main predictions in present work should hold in a reasonable range of the parameter α_ρ.

TABLE V. The partial widths of strong and radiative decays for the $1P$ states. $\Gamma_{\rm total}$ stands for the total decay width.

State	Mass (MeV)	$\Gamma[\Xi_{bb}\pi]$ (MeV)	$\Gamma[\Xi^*_{bb}\pi]$ (MeV)	Types of light quark	$\Gamma[\Xi_{bb}\gamma]$ (keV)	$\Gamma[\Xi^*_{bb}\gamma]$ (keV)	$\Gamma_{\rm total}$ (MeV)
$\lvert\Xi_{bb}{}^2P_{\rho}\frac{1}{2}^-\rangle$	10 368	⋯	⋯	$u(d)$	1.15	0.72	1.87×10^{-3}
$\lvert\Xi_{bb}{}^2P_{\rho}\frac{3}{2}^-\rangle$	10 408	⋯	⋯	$u(d)$	3.30	2.66	5.96×10^{-3}
$\lvert\Xi_{bb}{}^2P_{\lambda}\frac{1}{2}^-\rangle$	10 675	1.39	80.0	u	455	235	82.1
				d	71.1	59.3	
$\lvert\Xi_{bb}{}^2P_{\lambda}\frac{3}{2}^-\rangle$	10 694	16.3	55.4	u	984	265	72.9
				d	182	67.1	
$\lvert\Xi_{bb}{}^4P_{\lambda}\frac{1}{2}^-\rangle$	10632	20.5	6.16	u	555	1.33×10^3	28.5
				d	14.0	271	
$\lvert\Xi_{bb}{}^4P_{\lambda}\frac{3}{2}^-\rangle$	10 647	8.58	39.0	u	172	773	48.5
				d	43.5	149	
$\lvert\Xi_{bb}{}^4P_{\lambda}\frac{5}{2}^-\rangle$	10 661	58.9	36.2	u	121	569	95.6
				d	30.5	104	

State	Mass (MeV)	$\Gamma[\Xi_{bb}K]$ (MeV)	$\Gamma[\Xi^*_{bb}K]$ (MeV)		$\Gamma[\Omega_{bb}\gamma]$ (keV)	$\Gamma[\Omega^*_{bb}\gamma]$ (keV)	$\Gamma_{\rm total}$ (MeV)
$\lvert\Omega_{bb}{}^2P_{\rho}\frac{1}{2}^-\rangle$	10 532	⋯	⋯	s	1.41	1.11	2.52×10^{-3}
$\lvert\Omega_{bb}{}^2P_{\rho}\frac{3}{2}^-\rangle$	10 566	⋯	⋯	s	3.38	3.16	6.54×10^{-3}
$\lvert\Omega_{bb}{}^2P_{\lambda}\frac{1}{2}^-\rangle$	10 804	16.2	14.1	s	76.9	26.2	30.4
$\lvert\Omega_{bb}{}^2P_{\lambda}\frac{3}{2}^-\rangle$	10 821	6.40	82.7	s	151	30.0	89.3
$\lvert\Omega_{bb}{}^4P_{\lambda}\frac{1}{2}^-\rangle$	10 771	149	0.40	s	6.38	188	149.6
$\lvert\Omega_{bb}{}^4P_{\lambda}\frac{3}{2}^-\rangle$	10 785	2.28	96.9	s	20.0	117	99.3
$\lvert\Omega_{bb}{}^4P_{\lambda}\frac{5}{2}^-\rangle$	10 798	19.0	6.00	s	14.2	90.9	25.1

D. The doubly bottom states

As a byproduct, we also investigate the strong and radiative decay properties of the ground state with $J^P = 3/2^+$ and $1P$-wave states with $J^P = 1/2^-, 3/2^-, 5/2^-$ for the doubly bottom baryons. Now the harmonic oscillator parameter α_ρ of the ρ-mode excitation between the two bottom quarks $\alpha_\rho = 0.70$ GeV, which is slightly larger than that of the ρ-mode excitation between the two charm quarks $\alpha_\rho = 0.66$ GeV.

We collect the theoretical predictions for the doubly bottom baryons in Tables II and V. The radiative decay width of the ground states with $J^P = 3/2^+$ is quite narrow, which is similar to the predictions in Ref. [40]. On the other hand, the total decay widths of the $1P_\lambda$ states are about several tens MeV.

IV. SUMMARY

In the framework of the nonrelativistic constituent quark model, we have systematically studied the strong and radiative decay properties of the low-lying doubly charmed baryons, i.e., the ground state with $J^P = 3/2^+$ and $1P$-wave states with $J^P = 1/2^-$, $3/2^-$, $5/2^-$. Our main predictions are summarized as follows.

For the ground states with $J^P = 3/2^+$, their decays are dominated by the radiative transitions. The radiative partial width of Ξ_{cc}^{*++} (Ξ_{cc}^{*+}) into $\Xi_{cc}^{++}\gamma$ ($\Xi_{cc}^{+}\gamma$) is predicted to be several tens keV. The Ξ_{cc}^{*++} might be reconstructed in the $\Xi_{cc}^{++}\gamma$ channel with $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ at LHCb.

We want to emphasize that the lowest lying excited doubly charmed baryons should be dominated by the ρ-mode $1P$-wave components $|\Xi_{cc}^{++\,2}P_{\rho\frac{1}{2}^-}\rangle$ and $|\Xi_{cc}^{++\,2}P_{\rho\frac{3}{2}^-}\rangle$, which should be quite narrow states. Their decay widths are dominated by the one-photon radiative transitions into the ground state with $J^P = 1/2^+$ due to the absence of the strong decay modes. In the realistic case, there may exist mixing between the ρ-mode and the λ-mode excitations. Even with the mixing, the ratio of the radiative decays should be significant for the lowest lying excited doubly charmed baryons. The $|\Xi_{cc}^{++\,2}P_{\rho\frac{1}{2}^-}\rangle$ and $|\Xi_{cc}^{++\,2}P_{\rho\frac{3}{2}^-}\rangle$ may also be reconstructed in the $\Xi_{cc}^{++}\gamma$ channel with $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ at LHCb.

For the λ-mode $1P_\lambda$ states in Ξ_{cc} family, their total strong decay widths are about $\Gamma \sim 100$ MeV. The $|\Xi_{cc}^{++\,4}P_{\lambda\frac{1}{2}^-}\rangle$ and $|\Xi_{cc}^{++\,4}P_{\lambda\frac{5}{2}^-}\rangle$ mainly decay into the $\Xi_{cc}^{++}\pi^0$ channel, which may be reconstructed with $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ at LHCb. The $|\Xi_{cc}^{++\,2}P_{\lambda\frac{3}{2}^-}\rangle$ and $|\Xi_{cc}^{++\,4}P_{\lambda\frac{3}{2}^-}\rangle$ mainly decay into the $\Xi_{cc}^{*++}\pi^0$ channel, which may be searched for by reconstructing Ξ_{cc}^{*++} in the decay chain of $\Xi_{cc}^{*++} \to \Xi_{cc}^{++}\gamma \to \Lambda_c^+ K^- \pi^+ \pi^+ \gamma$ at LHCb.

We have also investigated the strong and radiative decay properties of the low-lying S- and P-wave Ω_{cc}, Ξ_{bb}, and Ω_{bb} states in this work. Hopefully our predictions should be useful in looking for the states in their corresponding family.

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[1] C. Patrignani *et al.* (Particle Data Group), Review of particle physics, Chin. Phys. C **40**, 100001 (2016).
[2] M. Mattson *et al.* (SELEX Collaboration), First Observation of the Doubly Charmed Baryon Ξ_{cc}^{+}, Phys. Rev. Lett. **89**, 112001 (2002).
[3] M. A. Moinester *et al.* (SELEX Collaboration), First observation of doubly charmed baryons, Czech. J. Phys. **53**, B201 (2003).
[4] R. Aaij *et al.* (LHCb Collaboration), Observation of the Doubly Charmed Baryon Ξ_{cc}^{++}, Phys. Rev. Lett. **119**, 112001 (2017).
[5] H. X. Chen, Q. Mao, W. Chen, X. Liu, and S. L. Zhu, Establishing low-lying doubly charmed baryons, Phys. Rev. D **96**, 031501 (2017).
[6] H. S. Li, L. Meng, Z. W. Liu, and S. L. Zhu, Magnetic moments of the doubly charmed and bottomed baryons, Phys. Rev. D **96**, 076011 (2017).
[7] W. Wang, F. S. Yu, and Z. X. Zhao, Weak decays of doubly heavy baryons: the $1/2 \to 1/2$ case, arXiv:1707.02834.
[8] L. Meng, N. Li, and S. l. Zhu, Possible hadronic molecules composed of the doubly charmed baryon and nucleon, arXiv:1707.03598.
[9] W. Wang, Z. P. Xing, and J. Xu, Weak decays of doubly heavy baryons: SU(3) Analysis, arXiv:1707.06570.
[10] M. Karliner and J. L. Rosner, Discovery of doubly-charmed Xi_{cc} baryon implies a stable ($bb\bar{u}\,\bar{d}$) tetraquark, arXiv:1707.07666.
[11] E. J. Eichten and C. Quigg, Heavy-quark symmetry implies stable heavy tetraquark mesons $Q_i Q_j \bar{q}_k \bar{q}_l$, arXiv:1707.09575.
[12] T. Gutsche, M. A. Ivanov, J. G. Körner, and V. E. Lyubovitskij, Decay chain information on the newly discovered double charm baryon state Ξ_{cc}^{++}, Phys. Rev. D **96**, 054013 (2017).
[13] H.-S. Li, L. Meng, Z.-W. Liu, and S.-L. Zhu, Radiative decays of the doubly charmed baryons in chiral perturbation theory, arXiv:1708.03620.

[14] F.-S. Yu, H.-Y. Jiang, R.-H. Li, C.-D. L, W. Wang, and Z.-X. Zhao, Discovery potentials of doubly charmed baryons, arXiv:1703.09086.

[15] J. Hu and T. Mehen, Chiral Lagrangian with heavy quark-diquark symmetry, Phys. Rev. D **73**, 054003 (2006).

[16] R. Roncaglia, D. B. Lichtenberg, and E. Predazzi, Predicting the masses of baryons containing one or two heavy quarks, Phys. Rev. D **52**, 1722 (1995).

[17] S. S. Gershtein, V. V. Kiselev, A. K. Likhoded, and A. I. Onishchenko, Spectroscopy of doubly heavy baryons, Phys. Rev. D **62**, 054021 (2000).

[18] C. Itoh, T. Minamikawa, K. Miura, and T. Watanabe, Doubly charmed baryon masses and quark wave functions in baryons, Phys. Rev. D **61**, 057502 (2000).

[19] D. Ebert, R. N. Faustov, V. O. Galkin, and A. P. Martynenko, Mass spectra of doubly heavy baryons in the relativistic quark model, Phys. Rev. D **66**, 014008 (2002).

[20] W. Roberts and M. Pervin, Heavy baryons in a quark model, Int. J. Mod. Phys. A **23**, 2817 (2008).

[21] T. Yoshida, E. Hiyama, A. Hosaka, M. Oka, and K. Sadato, Spectrum of heavy baryons in the quark model, Phys. Rev. D **92**, 114029 (2015).

[22] Z. Shah, K. Thakkar, and A. K. Rai, Excited statemass spectra of doubly heavy baryons Ω_{cc}, Ω_{bb} and Ω_{bc}, Eur. Phys. J. C **76**, 530 (2016).

[23] S. S. Gershtein, V. V. Kiselev, A. K. Likhoded, and A. I. Onishchenko, Spectroscopy of doubly charmed baryons: Ξ_{cc}^{+} and Ξ_{cc}^{++}, Mod. Phys. Lett. A **14**, 135 (1999).

[24] J. R. Zhang and M. Q. Huang, Doubly heavy baryons in QCD sum rules, Phys. Rev. D **78**, 094007 (2008).

[25] Z. G. Wang, Analysis of the $\frac{1}{2}^{+}$ doubly heavy baryon states with QCD sum rules, Eur. Phys. J. A **45**, 267 (2010).

[26] Z. S. Brown, W. Detmold, S. Meinel, and K. Orginos, Charmed bottom baryon spectroscopy from lattice QCD, Phys. Rev. D **90**, 094507 (2014).

[27] A. Faessler, T. Gutsche, M. A. Ivanov, J. G. Korner, and V. E. Lyubovitskij, Semileptonic decays of double heavy baryons, Phys. Lett. B **518**, 55 (2001).

[28] C. Albertus, E. Hernandez, J. Nieves, and J. M. Verde-Velasco, Static properties and semileptonic decays of doubly heavy baryons in a nonrelativistic quark model, Eur. Phys. J. A **32**, 183 (2007); Erratum, Eur. Phys. J. A **36**, 119 (2008).

[29] W. Roberts and M. Pervin, Hyperfine mixing and the semileptonic decays of double-heavy baryons in a quark model, Int. J. Mod. Phys. A **24**, 2401 (2009).

[30] C. Albertus, E. Hernandez, and J. Nieves, Hyperfine mixing in $b \to c$ semileptonic decay of doubly heavy baryons, Phys. Lett. B **683**, 21 (2010).

[31] A. Faessler, T. Gutsche, M. A. Ivanov, J. G. Korner, and V. E. Lyubovitskij, Semileptonic decays of double heavy baryons in a relativistic constituent three-quark model, Phys. Rev. D **80**, 034025 (2009).

[32] A. I. Onishchenko, Exclusive decays of $\Xi_{QQ'}$ baryons in NRQCD sum rules, arXiv:hep-ph/0006271.

[33] V. V. Kiselev and A. K. Likhoded, Usp. Fiz. Nauk **172**, 497 (2002) [Baryons with two heavy quarks, Phys. Usp. **45**, 455 (2002)].

[34] M. J. White and M. J. Savage, Semileptonic decay of baryons with two heavy quarks, Phys. Lett. B **271**, 410 (1991).

[35] M. A. Sanchis-Lozano, Weak decays of doubly heavy hadrons, Nucl. Phys. **B440**, 251 (1995).

[36] E. Hernandez, J. Nieves, and J. M. Verde-Velasco, Heavy quark symmetry constraints on semileptonic form-factors and decay widths of doubly heavy baryons, Phys. Lett. B **663**, 234 (2008).

[37] X. H. Guo, H. Y. Jin, and X. Q. Li, Weak semileptonic decays of heavy baryons containing two heavy quarks, Phys. Rev. D **58**, 114007 (1998).

[38] D. Ebert, R. N. Faustov, V. O. Galkin, and A. P. Martynenko, Semileptonic decays of doubly heavy baryons in the relativistic quark model, Phys. Rev. D **70**, 014018 (2004); Erratum, Phys. Rev. D **77**, 079903 (2008).

[39] R. H. Hackman, N. G. Deshpande, D. A. Dicus, and V. L. Teplitz, M1 transitions in the MIT bag model, Phys. Rev. D **18**, 2537 (1978).

[40] T. Branz, A. Faessler, T. Gutsche, M. A. Ivanov, J. G. Korner, V. E. Lyubovitskij, and B. Oexl, Radiative decays of double heavy baryons in a relativistic constituent three–quark model including hyperfine mixing, Phys. Rev. D **81**, 114036 (2010).

[41] A. Bernotas and V. Šimonis, Radiative M1 transitions of heavy baryons in the bag model, Phys. Rev. D **87**, 074016 (2013).

[42] X. H. Zhong and Q. Zhao, Charmed baryon strong decays in a chiral quark model, Phys. Rev. D **77**, 074008 (2008).

[43] A. Manohar and H. Georgi, Chiral quarks and the non-relativistic quark model, Nucl. Phys. **B234**, 189 (1984).

[44] X. H. Zhong and Q. Zhao, Strong decays of heavy-light mesons in a chiral quark model, Phys. Rev. D **78**, 014029 (2008).

[45] X. H. Zhong and Q. Zhao, Strong decays of newly observed D_{sJ} states in a constituent quark model with effective Lagrangians, Phys. Rev. D **81**, 014031 (2010).

[46] X. H. Zhong, Strong decays of the newly observed $D(2550)$, $D(2600)$, $D(2750)$, and $D(2760)$, Phys. Rev. D **82**, 114014 (2010).

[47] L. Y. Xiao and X. H. Zhong, Strong decays of higher excited heavy-light mesons in a chiral quark model, Phys. Rev. D **90**, 074029 (2014).

[48] L. Y. Xiao and X. H. Zhong, Ξ baryon strong decays in a chiral quark model, Phys. Rev. D **87**, 094002 (2013).

[49] L. H. Liu, L. Y. Xiao, and X. H. Zhong, Charm-strange baryon strong decays in a chiral quark model, Phys. Rev. D **86**, 034024 (2012).

[50] H. Nagahiro, S. Yasui, A. Hosaka, M. Oka, and H. Noumi, Structure of charmed baryons studied by pionic decays, Phys. Rev. D **95**, 014023 (2017).

[51] K. L. Wang, L. Y. Xiao, X. H. Zhong, and Q. Zhao, Understanding the newly observed Ω_c states through their decays, Phys. Rev. D **95**, 116010 (2017).

[52] Z. P. Li, The Kaon photoproduction of nucleons in the chiral quark model, Phys. Rev. C **52**, 1648 (1995).

[53] Z. P. Li and B. Saghai, Study of the baryon resonances structure via eta photoproduction, Nucl. Phys. **A644**, 345 (1998).

[54] Z. P. Li, The Eta photoproduction of nucleons, and the structure of the resonance $S_{11}(1535)$ in the quark model, Phys. Rev. D **52**, 4961 (1995).

[55] Q. Zhao, J. S. Al-Khalili, Z. P. Li, and R. L. Workman, Pion photoproduction on the nucleon in the quark model, Phys. Rev. C **65**, 065204 (2002).

[56] Z. P. Li, The Threshold pion photoproduction of nucleons in the chiral quark model, Phys. Rev. D **50**, 5639 (1994).

[57] Z. P. Li, H. X. Ye, and M. H. Lu, An unified approach to pseudoscalar meson photoproductions off nucleons in the quark model, Phys. Rev. C **56**, 1099 (1997).

[58] B. Saghai and Z. P. Li, Quark model study of the eta photoproduction: Evidence for a new S_{11} resonance?, Eur. Phys. J. A **11**, 217 (2001).

[59] Q. Zhao, B. Saghai, and Z. P. Li, Quark model approach to the eta meson electroproduction on the proton, J. Phys. G **28**, 1293 (2002).

[60] J. He, B. Saghai, and Z. Li, Study of η photoproduction on the proton in a chiral constituent quark approach via one-gluon-exchange model, Phys. Rev. C **78**, 035204 (2008).

[61] J. He and B. Saghai, Combined study of $\gamma p \to \eta p$ and $\pi^- p \to \eta n$ in a chiral constituent quark approach, Phys. Rev. C **80**, 015207 (2009).

[62] X. H. Zhong, Q. Zhao, J. He, and B. Saghai, Study of $\pi^- p \to \eta n$ at low energies in a chiral constituent quark model, Phys. Rev. C **76**, 065205 (2007).

[63] X. H. Zhong and Q. Zhao, The $K^- p \to \Sigma^0 \pi^0$ reaction at low energies in a chiral quark model, Phys. Rev. C **79**, 045202 (2009).

[64] X. H. Zhong and Q. Zhao, Lambda resonances studied in $K^- p \to \Sigma^0 \pi^0$ in a chiral quark model, Chin. Phys. C **33**, 1377 (2009).

[65] X. H. Zhong and Q. Zhao, η photoproduction on the quasi-free nucleons in the chiral quark model, Phys. Rev. C **84**, 045207 (2011).

[66] X. H. Zhong and Q. Zhao, η' photoproduction on the nucleons in the quark model, Phys. Rev. C **84**, 065204 (2011).

[67] X. H. Zhong and Q. Zhao, Low energy reactions $K^- p \to \Sigma^0 \pi^0$, $\Lambda \pi^0$, $\bar{K}^0 n$ and the strangeness $S = -1$ hyperons, Phys. Rev. C **88**, 015208 (2013).

[68] L. Y. Xiao and X. H. Zhong, Low-energy $K^- p \to \Lambda \eta$ reaction and the negative parity Λ resonances, Phys. Rev. C **88**, 065201 (2013).

[69] L. Y. Xiao, X. Cao, and X. H. Zhong, Neutral pion photoproduction on the nucleon in a chiral quark model, Phys. Rev. C **92**, 035202 (2015).

[70] L. Y. Xiao, F. Ouyang, K. L. Wang, and X. H. Zhong, Combined analysis of the $\pi^- p \to K^0 \Lambda$, ηn reactions in a chiral quark model, Phys. Rev. C **94**, 035202 (2016).

[71] K. L. Wang, L. Y. Xiao, and X. H. Zhong, Quark model study of the $\pi N \to \pi N$ reactions up to the $N(1440)$ resonance region, Phys. Rev. C **95**, 055204 (2017).

[72] W. J. Deng, H. Liu, L. C. Gui, and X. H. Zhong, Charmonium spectrum and their electromagnetic transitions with higher multipole contributions, Phys. Rev. D **95**, 034026 (2017).

[73] W. J. Deng, H. Liu, L. C. Gui, and X. H. Zhong, Spectrum and electromagnetic transitions of bottomonium, Phys. Rev. D **95**, 074002 (2017).

[74] S. J. Brodsky and J. R. Primack, The electromagnetic interactions of composite aystems, Ann. Phys. (N.Y.) **52**, 315 (1969).