Strong and radiative decays of the doubly charmed baryons

Li-Ye Xiao1,2,*, Kai-Lei Wang3, Qi-Fang Lü3,4, Xian-Hui Zhong3,4,†, and Shi-Lin Zhu1,2,5,‡
1) School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China
2) Center of High Energy Physics, Peking University, Beijing 100871, China
3) Department of Physics, Hunan Normal University, and Key Laboratory of Low-Dimensional Quantum Structures and Quantum Control of Ministry of Education, Changsha 410081, China
4) Synergetic Innovation Center for Quantum Effects and Applications (SICQEA), Hunan Normal University, Changsha 410081, China
5) Collaborative Innovation Center of Quantum Matter, Beijing 100871, China

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 $\Xi_{cc}^+(3519)$ and $\Omega_{cc}^+(3770)$ with $J^P = 3/2^+$ have a fairly large decay rate into the $\Xi_c^+\gamma$ and $\Omega_c^+\gamma$ channels with a width ~ 15 and ~ 7 keV, respectively. (ii) The lowest lying excited doubly charmed baryons are dominated by the $1P\rho$ 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 $A$ mode (1P 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 $O(10^{-3})$.

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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 $3621.40 \pm 0.72$ (stat) $\pm 0.27$ (syst) MeV. The newly observed $\Xi_{cc}^+ (3621)^{++}$ has attracted a great deal of attention from the hadron physics community [5,13].

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 [14–20]. The semi-leptonic 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 [13,34,41]. In this work, we shall perform a systematic 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 [42], which was quite successful in the description of the hadronic decays of the heavy-light mesons and baryons [43,51] 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 $cc$ and $bb$ systems [72,73] and the newly observed $\Omega_c$ 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 [42]

$$H_m = \sum_j f_m \bar{\psi}_j \gamma_\mu \gamma_5 \psi_\mu \phi_m,$$

where $\psi_j$ stands for the $j$-th quark field in a baryon. $f_\mu$ is the pseudoscalar meson decay constant and $\phi_m$ is the pseudoscalar meson octet

$$\phi_m = \left( \begin{array}{c} \frac{1}{\sqrt{2}} \pi^0 + \frac{1}{\sqrt{6}} \eta \\ \pi^- \\ \frac{1}{\sqrt{2}} \pi^0 + \frac{1}{\sqrt{6}} \eta \\ K^+ \\ K^0 \\ K^- \\ \bar{K^0} \\ \sqrt{2}\eta \end{array} \right).$$

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

$$H_r = -\sum_j e \bar{\psi}_j \gamma_\mu A^\mu (\mathbf{k}, \mathbf{r}_j) \psi_j,$$

where $\mathbf{k}$ stands for the three-momentum of the photon with the field $A^\mu$. $\mathbf{r}_j$ and $e_j$ represent the coordinate and charge of the $j$-th constituent quark, respectively. This model was successfully applied to discuss the radiative decay of doubly heavy mesons [72,73].
TABLE I: Masses and possible two body decay channels of the 1P doubly charmed baryons (denoted by $|N^{2S+1}L_Jm^J_i\rangle$), where $|N^{2S+1}L_Jm^J_i\rangle = \sum_{L_S,J} (LL, S, J)J_i^{\pi} \Psi_{LL, J_S}^n \phi$ [43]. The masses (MeV) are taken from the relativistic quark model [13].

| State $|N^{2S+1}L_Jm^J_i\rangle$ | Wave function $\Psi_{LL, J_S}^n \phi$ | Mass $m$ [19] | Decay channel $\Xi(3621)$ [44] | Observed state | Mass $m$ [19] | Decay channel | Observed state |
|-----------------------------|-----------------------------------|--------------|-------------------|------------|--------------|----------------|----------------|
| $|0^+S^0\rangle$             | $|0^+_p \rangle \chi_{K^0}$         | 3620         | $\Xi$            | $\Xi(3621)$ | 3778         | $\Omega_c\gamma$ | ?              |
| $|0^+S^0\rangle$             | $|0^+_p \rangle \chi_{K^0}$         | 3727         | $\Xi_c \gamma$   | ?           | 3872         | $\Omega_c\gamma$ | ?              |
| $|1^+P^+\rangle$             | $|1^+_p \rangle \chi_{K^+}$         | 3838         | $\Xi_c \gamma$   | ?           | 4002         | $\Omega_c\gamma$ | ?              |
| $|1^+P^+\rangle$             | $|1^+_p \rangle \chi_{K^+}$         | 3959         | $\Xi_c \gamma$   | ?           | 4102         | $\Omega_c\gamma$ | ?              |
| $|2^+P^+\rangle$             | $|2^+_p \rangle \chi_{K^0}$         | 4136         | $\Xi_c \pi, \Xi_c \pi$, $\Xi_c \gamma$, $\Xi_c \gamma$ | ?           | 4271         | $\Xi_c K$, $\Xi_c K$, $\Omega_c\gamma$, $\Omega_c\gamma$ | ?              |
| $|2^+P^+\rangle$             | $|2^+_p \rangle \chi_{K^0}$         | 4196         | $\Xi_c \pi, \Xi_c \pi$, $\Xi_c \gamma$, $\Xi_c \gamma$ | ?           | 4325         | $\Xi_c K$, $\Xi_c K$, $\Omega_c\gamma$, $\Omega_c\gamma$ | ?              |
| $|1^+P^+\rangle$             | $|1^+_p \rangle \chi_{K^0}$         | 4053         | $\Xi_c \pi, \Xi_c \pi$, $\Xi_c \gamma$, $\Xi_c \gamma$ | ?           | 4208         | $\Xi_c K$, $\Xi_c K$, $\Omega_c\gamma$, $\Omega_c\gamma$ | ?              |
| $|1^+P^+\rangle$             | $|1^+_p \rangle \chi_{K^0}$         | 4101         | $\Xi_c \pi, \Xi_c \pi$, $\Xi_c \gamma$, $\Xi_c \gamma$ | ?           | 4252         | $\Xi_c K$, $\Xi_c K$, $\Omega_c\gamma$, $\Omega_c\gamma$ | ?              |
| $|1^+P^+\rangle$             | $|1^+_p \rangle \chi_{K^0}$         | 4155         | $\Xi_c \pi, \Xi_c \pi$, $\Xi_c \gamma$, $\Xi_c \gamma$ | ?           | 4303         | $\Xi_c K$, $\Xi_c K$, $\Omega_c\gamma$, $\Omega_c\gamma$ | ?              |

To match the nonrelativistic harmonic oscillator spatial wave function $N \Psi_{LL}$ 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]

$$H_{em}^m = \sum_j \left\{ \frac{\omega_m}{E_j + M_f} \sigma_j \cdot P_f + \frac{\omega_m}{E_j + M_f} \sigma_j \cdot P_f - \sigma_j \cdot q + \frac{\omega_m}{2\mu_f} \sigma_j \cdot P_f \right\} I_j \phi_m,$$

where the $\sigma_j$ and $\mu_f$ stands for the Pauli spin vector and the reduced mass of the $j$-th 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. $P_f = P_j - (m_j/M)P_{cm}$ is the internal momentum of the $j$-th quark in the baryon rest frame. $\omega_m$ and $q$ are the energy and three-vector momentum of the meson, respectively. $I_j$ is the isospin operator associated with the pseudoscalar meson

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

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

$$H_{em}^m = \sum_j \left[ e_j r_j \cdot e - \frac{e_j}{2m} \sigma_j \cdot (e \times \mathbf{k}) \right] e^{-i \mathbf{k} \cdot \mathbf{r}_j},$$

where the $e$ is the polarization vector of the photon.

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

$$\Gamma_m = \frac{\delta^2_j \langle E_f + M_j \rangle |q|^2}{4\pi M_f} \frac{1}{2I_j + 1} \sum_{J_i} |M_{J_i,J_f}|^2,$$

where $M_{J_i,J_f}$ is the transition amplitude, $J_i$ and $J_f$ 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, $\delta$ is a global parameter which has been determined in previous study of the strong decays of the charmed baryons and heavy-light mesons [43, 44]. Here, we fix its value the same as that in Refs. [43, 44], i.e., $\delta = 0.557$.

FIG. 1: (Color online) The $\rho$- and $\lambda$-mode excitations of the $ccq$ system where $\rho$ and $\lambda$ are the Jacobi coordinates defined as $\rho = (r_1 - r_2)$ and $\lambda = (r_1 + r_2 - 2r_3)$, respectively. $Q_1$ and $Q_2$ stand for the charm quark, and $q_3$ stands for the light ($u, d, s$) quark.

FIG. 2: (Color online) Light-quark mass dependence of the excitation energy of the $\lambda$ mode (blue solid line) and the $\rho$ mode (red solid line) in Eq. (13).
Meanwhile, the partial radiative decay widths are
\[
\Gamma_{\gamma} = \frac{\left| k \right|^2}{2M_f} \frac{2}{2J_f + 1} \left( \sum_{J_i \in J_f} |A_{J_i} J_f| \right)^2, \tag{9}
\]
where \( A_{J_i} J_f \) stands for the EM transition amplitude.

In the calculation, the standard quark model parameters are adopted. Namely, we set \( m_u = m_d = 330 \text{ MeV}, m_s = 450 \text{ MeV}, \) and \( m_c = 1480 \text{ MeV} \) for the constituent quark masses. The decay constants for \( \pi \) and \( K \) mesons are taken as \( f_{\pi} = 132 \text{ MeV}, f_K = 160 \text{ MeV}, \) respectively. The masses of the resonances are then from the predictions with the relativistic quark model \([19]\). The mass of the ground-state \( |\Xi_{cc}^+ S_{1/2}^+ \rangle \) is adopted the experimental measurement, \( M = 3621 \text{ MeV} \).

The harmonic oscillator parameter \( \alpha_p \) in the spatial wave function of the \( \rho \)-mode excitation between the two charm quarks is taken as \( \alpha_p = 0.66 \text{ GeV} \) as in the charmonium system, which is significantly larger than that of the \( \rho \)-mode excitation between the two strange quarks \( \alpha_p = 0.44 \text{ GeV} \) adopted in \([51]\). Another harmonic oscillator parameter \( \alpha_\lambda \) is estimated with the relation:
\[
\alpha_\lambda = \left( \frac{3m_q}{2m_Q + m_q} \right)^{1/4} \alpha_p. \tag{10}
\]

In the simplified case of the harmonic oscillator potential, the \( \rho \) and \( \lambda \) degrees of freedom decouple,
\[
H = \frac{1}{2m_\rho} p_\rho^2 + \frac{1}{2m_\lambda} p_\lambda^2 + \frac{3}{2} K (\rho^2 + \lambda^2), \tag{11}
\]
where
\[
m_\rho = m_Q, \quad m_\lambda = \frac{3m_Q m_q}{2m_Q + m_q} \tag{12}
\]
and the oscillator frequencies \( \omega_\rho \) and \( \omega_\lambda \) are defined as
\[
\omega_\rho = (3K/m_\rho)^{1/2}, \quad \omega_\lambda = (3K/m_\lambda)^{1/2}. \tag{13}
\]
The ratio of the \( 1P \) \( \rho \) and \( \lambda \) excitation energies reads
\[
\frac{\omega_\rho}{\omega_\lambda} = \sqrt{\frac{1 + 2m_Q}{3m_Q}} > 1. \tag{14}
\]

Since the bottom and charm quark masses are much larger than the light quark mass \( (m_Q > m_q) \), the excitation energy of the \( \lambda \)-mode is larger than that of the \( \rho \)-mode, \( \omega_\lambda > \omega_\rho \) (see Fig. 3). Thus, the \( \rho \)-excitation modes are lighter than the \( \lambda \)-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.

| Process | Our result | \([40]\) | \([13]\) |
|---------|------------|---------|---------|
| \( \Xi_{cc}^{++} \rightarrow \Xi_{cc}^{++} \) | 16.7 | 23.5 | 22.0 |
| \( \Xi_{cc}^{++} \rightarrow \Xi_{cc}^{++} \) | 14.6 | 28.8 | 9.57 |
| \( \Omega_{cc}^{+} \rightarrow \Omega_{cc}^{+} \) | 6.93 | 2.11 | 9.45 |
| \( \Omega_{cc}^{0} \rightarrow \Omega_{cc}^{0} \) | 1.19 | 0.31 | \( \cdots \) |
| \( \Omega_{bb}^{+} \rightarrow \Omega_{bb}^{+} \) | 0.24 | 0.06 | \( \cdots \) |
| \( \Omega_{bb}^{0} \rightarrow \Omega_{bb}^{0} \) | 0.08 | 0.02 | \( \cdots \) |

#### A. The ground doubly charmed states with \( J^P = 3/2^+ \)

The ground-state \( |\Xi_{cc}^+ S_{1/2}^+ \rangle \) has a mass near \( M \sim 3727 \text{ MeV} \) \([19]\), which is below the \( \Xi_{cc}^{+} \) 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 \( |\Xi_{cc}^+ S_{1/2}^+ \rangle \) and \( |\Xi_{cc}^{+} S_{1/2}^+ \rangle \) (denoted with \( \Xi_{cc}^{++} \) and \( \Xi_{cc}^{+} \), respectively) as a function of their masses in Figs. 3 and 4.

The radiative decay widths are sensitive to the parent baryon masses. With \( M=3727 \text{ MeV} \), the radiative partial decay widths of \( \Xi_{cc}^{++} \) and \( \Xi_{cc}^{++} \) are
\[
\Gamma(\Xi_{cc}^{++} \rightarrow \Xi_{cc}^{++} \gamma) \approx 16.7 \text{ keV}, \tag{15}
\]
\[
\Gamma(\Xi_{cc}^{++} \rightarrow \Xi_{cc}^{++} \gamma) \approx 14.6 \text{ keV}, \tag{16}
\]
respectively, which are comparable with the predictions in Refs. \([40]\) and \([13]\) (see Tab. I). The fairly large radiative partial decay widths indicate the missing \( J^P = 3/2^+ \) ground states \( \Xi_{cc}^{++} \) might be observed in the \( \Xi_{cc}^{++} \gamma \) channel.

The predicted mass of ground-state \( |\Omega_{cc}^{-} S_{1/2}^+ \rangle \) (denoted with \( \Omega_{cc}^{-} \)) is around 3.87 GeV \([19]\), which is obviously below the \( \Xi_{cc}^{-} \) threshold. This state mainly decays through the EM transition. From Fig. 3, the \( \Omega_{cc}^{-} \) has a quite narrow radiative decay width of \( \Gamma \approx (0 - 2) \text{ keV} \) if the mass of \( \Omega_{cc}^{-} \) is less than 3.84 GeV. With \( M = 3872 \text{ MeV} \), we obtain
\[
\Gamma(\Omega_{cc}^{-} \rightarrow \Omega_{cc}^{-} \gamma) \approx 6.93 \text{ keV}, \tag{17}
\]
which is compatible with the results in Refs. \([40]\) and \([13]\).

#### B. The \( P \)-wave doubly charmed states

1. \( \rho \)-mode excitations

As emphasized in Sec. 3 the \( \rho \)-mode orbitally excited state has relatively smaller mass than a \( \lambda \)-mode orbitally excited state for the doubly heavy baryon system. The masses of the \( 1P_{\rho} \) states of \( \Xi_{cc} \) and \( \Omega_{cc} \) are above the threshold of \( \Xi_{cc}^{+} \) and \( \Xi_{cc}^{-} \), 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.
With the masses of light quark. The $\Omega_{ccu}$ states are isospin independent because the decay amplitude does not depend on the light quark. The $|\Gamma_{\Omega_{ccu}}\rangle$ should be a narrow state with a width of $\Gamma \leq 0.5$ keV. The state $|\Gamma_{\Omega_{ccu}}\rangle$ has a decay width of $\Gamma \leq 2$ keV. Since their strong decays are forbidden, the total decay widths are almost saturated by the radiative decay widths. With the masses of $|\Gamma_{\Omega_{ccu}}\rangle$ and $|\Gamma_{\Omega_{ccu}}\rangle M = 3838$ MeV and $M = 3959$ MeV, respectively, their total decay widths are

$$\Gamma_{\text{total}} \approx 0.15 \text{ keV}, \quad \Gamma_{\text{total}} \approx 1.43 \text{ keV}.$$  

In the $\Omega_{ccu}$ family, the mass of $|\Gamma_{\Omega_{ccu}}\rangle$ and $|\Gamma_{\Omega_{ccu}}\rangle$ are about 4.0 and 4.10 GeV respectively. From Fig. 3 the $|\Gamma_{\Omega_{ccu}}\rangle$ has a total decay width of $\Gamma \leq 0.5$ keV and $|\Gamma_{\Omega_{ccu}}\rangle$ has a total decay width of $\Gamma \leq 3.0$ keV, and their main decay channel is $\Omega_{ccu}\gamma$.

2. $\lambda$-mode excitations

In the $\Xi_{cc}$ family, the mass of the first orbital excitation of the $\lambda$-mode ($1\lambda$ states) is about 4.10 GeV. The total decay width of $|\Xi_{ccu}\lambda_{\pm}\rangle$ is $\Gamma = 50$ MeV. The main decay channel is $\Xi_{ccu}\pi$. The partial width ratio between

FIG. 3: (Color online) The radiative decay widths of the low-lying $S$- and $P$-wave $\Xi_{ccu}$ states as a function of the mass. In the figure, $\Xi_{ccu}$ and $\Xi_{ccu}^*$ stand for the $|\Xi_{ccu}\rangle$ and $|\Xi_{ccu}^*\rangle$ states. Their masses are 3621 MeV and 3727 MeV, respectively.

FIG. 4: (Color online) The radiative decay widths of the low-lying $S$- and $P$-wave $\Xi_{cd}$ states as a function of the mass.
On the other hand, the radiative decay rate of $\Omega_{cc}^{+} S_{1/2}^+$ is

$$ \Gamma(\Omega_{cc}^{+} S_{1/2}^+ \rightarrow \pi^+ \pi^-) \approx 0.46. $$

The radiative decay rate of $|\Xi_{cc}^+ 2P_{1/2}^-\rangle$ into $\Xi_{cc}^{++}\gamma$ is large, and the predicted branching fraction is

$$ B \left( |\Xi_{cc}^+ 2P_{1/2}^-\rangle \rightarrow \Xi_{cc}^{++}\gamma \right) \approx 0.24\%. $$

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

$$ B \left( |\Xi_{cc}^+ 2P_{1/2}^-\rangle \rightarrow \Xi_{cc}^{++}\gamma \right) \approx 0.50\%. $$

The states $|\Xi_{cc}^+ 2P_{1/2}^-\rangle$ and $|\Xi_{cc}^+ 4P_{3/2}^-\rangle$ have a moderate width of $\Gamma \sim 100$ MeV, and dominantly decay into $\Xi_{cc}^{+}\pi$. The partial width of $\Gamma[|\Xi_{cc}^+ 2P_{1/2}^-\rangle \rightarrow \Xi_{cc}^{+}\pi]$ is sizable. The partial width ratio is

$$ \frac{\Gamma[|\Xi_{cc}^+ 2P_{1/2}^-\rangle \rightarrow \Xi_{cc}^{+}\pi]}{\Gamma[|\Xi_{cc}^+ 4P_{3/2}^-\rangle \rightarrow \Xi_{cc}^{+}\pi]} \approx 0.21, $$

which can be used to distinguish $|\Xi_{cc}^+ 2P_{1/2}^-\rangle$ from $|\Xi_{cc}^+ 4P_{3/2}^-\rangle$ in future experiments. The radiative partial widths of the $P$-wave $\Xi_{cc}^{++}$ states with $J^P = 3/2^-$ into $\Xi_{cc}^{++}\gamma$ and $\Xi_{cc}^{++}\gamma$ are around a few hundred keV. The radiative decays of $|\Xi_{cc}^+ 2P_{1/2}^-\rangle$ and $|\Xi_{cc}^+ 4P_{3/2}^-\rangle$ are dominated by $\Xi_{cc}^{+}\gamma$ and $\Xi_{cc}^{++}\gamma$, respectively.

### Table III: The partial widths of strong and radiative decays for the $1P_{1/2}$ states. $\Gamma_{\text{total}}$ stands for the total decay width.

| State           | Mass(MeV) | $\Gamma[|\Xi_{cc}^+\pi\rangle](\text{MeV})$ | $\Gamma[|\Xi_{cc}^+\gamma\rangle](\text{MeV})$ | $\Gamma_{\text{total}}$(MeV) |
|-----------------|-----------|---------------------------------------------|---------------------------------------------|-----------------------------|
| $|\Xi_{cc}^+ 2P_{1/2}^-\rangle$ | 4136      | 15.6                                        | 33.9                                        | 49.7                        |
| $|\Xi_{cc}^+ 2P_{1/2}^-\rangle$ | 4196      | 21.6                                        | 101                                         | 123                         |
| $|\Xi_{cc}^+ 4P_{3/2}^-\rangle$ | 4053      | 133                                         | 1.22                                        | 134                         |
| $|\Xi_{cc}^+ 4P_{3/2}^-\rangle$ | 4101      | 7.63                                        | 84.6                                        | 92.6                        |
| $|\Xi_{cc}^+ 4P_{3/2}^-\rangle$ | 4155      | 75.3                                        | 22.8                                        | 98.4                        |

$\Xi_{cc}^{+}\pi$ and $\Xi_{cc}^{+}\pi$ is

$$ \frac{\Gamma[|\Xi_{cc}^+ 2P_{1/2}^-\rangle \rightarrow \Xi_{cc}^{+}\pi]}{\Gamma[|\Xi_{cc}^+ 4P_{3/2}^-\rangle \rightarrow \Xi_{cc}^{+}\pi]} \approx 0.46. $$

The states $|\Xi_{cc}^+ 2P_{1/2}^-\rangle$ and $|\Xi_{cc}^+ 4P_{3/2}^-\rangle$ have a moderate width of $\Gamma \sim 100$ MeV, and dominantly decay into $\Xi_{cc}^{+}\pi$. The partial width of $\Gamma[|\Xi_{cc}^+ 2P_{1/2}^-\rangle \rightarrow \Xi_{cc}^{+}\pi]$ is sizable. The partial width ratio is

$$ \frac{\Gamma[|\Xi_{cc}^+ 2P_{1/2}^-\rangle \rightarrow \Xi_{cc}^{+}\pi]}{\Gamma[|\Xi_{cc}^+ 4P_{3/2}^-\rangle \rightarrow \Xi_{cc}^{+}\pi]} \approx 0.21, $$

which can be used to distinguish $|\Xi_{cc}^+ 2P_{1/2}^-\rangle$ from $|\Xi_{cc}^+ 4P_{3/2}^-\rangle$ in future experiments. The radiative partial widths of the $P$-wave $\Xi_{cc}^{++}$ states with $J^P = 3/2^-$ into $\Xi_{cc}^{++}\gamma$ and $\Xi_{cc}^{++}\gamma$ are around a few hundred keV. The radiative decays of $|\Xi_{cc}^+ 2P_{1/2}^-\rangle$ and $|\Xi_{cc}^+ 4P_{3/2}^-\rangle$ 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 radiative processes may be measured in future experiments due to their sizeable branching fractions, \(O(10^{-3})\).

From the Table III the decay widths of \(|\Xi_{cc}^{4}P_{\frac{1}{2}}^+\rangle\) and \(|\Xi_{cc}^{4}P_{\frac{3}{2}}^-\rangle\) are about \(\Gamma \sim 100\) MeV. The dominant decay mode of \(|\Xi_{cc}^{4}P_{\frac{1}{2}}^-\rangle\) is \(\Xi_{\gamma}\pi\), while \(|\Xi_{cc}^{4}P_{\frac{3}{2}}^-\rangle\) mainly decays into \(\Xi_{\gamma}\pi\) and \(\Xi_{\gamma}\rho\) channels with the partial decay ratio

\[
\frac{\Gamma(|\Xi_{cc}^{4}P_{\frac{1}{2}}^-\rangle \rightarrow \Xi_{\gamma}\pi|}{\Gamma(|\Xi_{cc}^{4}P_{\frac{3}{2}}^-\rangle \rightarrow \Xi_{\gamma}\pi|)} \approx 0.30. \quad (23)
\]

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

We analyze the decay properties of the \(P_{\frac{1}{2}}\) states in the \(\Omega_{cc}\) family and collect their partial strong and radiative decay widths in Table III. The states \(|\Xi_{cc}^{2}P_{\frac{3}{2}}^-\rangle\) and \(|\Xi_{cc}^{4}P_{\frac{3}{2}}^-\rangle\) are most likely to be the narrow states with a width of \(\Gamma \sim 40\) MeV, and the \(\Xi_{cc}\) decay channel almost saturates their total decay widths. The dominant radiative decay modes of these two states are \(\Omega_{cc}\gamma\) and \(\Omega_{cc}^\star\gamma\), respectively. The branching ratios are

\[
\mathcal{B}[^2P_{1/2}^+ \rightarrow \Omega_{cc}\gamma] \approx 0.81\% , \quad (24)
\]

\[
\mathcal{B}[^4P_{1/2}^- \rightarrow \Omega_{cc}^\star\gamma] \approx 0.48\% , \quad (25)
\]

which can be tested in future experiments.

The state \(|\Omega_{cc}^{4}P_{\frac{3}{2}}^-\rangle\) has a broad width of \(\Gamma \approx 320\) MeV, and mainly decays into \(\Xi_{cc}\). The states \(|\Omega_{cc}^{4}P_{\frac{1}{2}}^-\rangle\) and \(|\Omega_{cc}^{4}P_{\frac{3}{2}}^-\rangle\) may lie below the threshold of \(\Xi_{cc}\). If so, they mainly decay into \(\Xi_{cc}\) 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

\[
\mathcal{B}[^2P_{3/2}^- \rightarrow \Omega_{cc}\gamma] \approx 3.77\% , \quad (26)
\]

\[
\mathcal{B}[^4P_{3/2}^- \rightarrow \Omega_{cc}^\star\gamma] \approx 6.49\% . \quad (27)
\]
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 \( \Gamma \sim 185 \text{ MeV} \) and \( \Gamma \sim 140 \text{ MeV} \).

Considering the uncertainty of the mass predictions of the \( 1P_1 \) 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 \( \alpha_\rho \)

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 \( \alpha_\rho = 660 \text{ MeV} \). However, the harmonic oscillator parameter \( \alpha_\rho \) 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 \( \alpha_\rho \). The results are listed in Table IV.

It’s important to note that the effects on radiative decay widths from the parameter \( \alpha_\rho \) 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 \( \alpha_\rho \). 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 \( \alpha_\rho \).

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 \( \alpha_\rho \) of the \( \rho \)-mode excitation between the two bottom quarks \( \alpha_\rho = 0.70 \text{ GeV} \), which is slightly larger than that of the \( \rho \)-mode excitation between the two charm quarks \( \alpha_\rho = 0.66 \text{ GeV} \).

We collect the theoretical predictions for the doubly bottom baryons in Tables IV 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. [20]. On the other hand, the total decay widths of the \( 1P_1 \) 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...

FIG. 6: (Color online) The strong decay partial widths of the \( 1P_1 \)-wave \( \Xi_{cc} \) states as a function of the mass.

FIG. 7: (Color online) The strong decay partial widths of the \( 1P_1 \)-wave \( \Omega_{cc} \) states as a function of the mass.
TABLE V: The partial widths of strong and radiative decays for the 1P states. \( \Gamma_{\text{total}} \) stands for the total decay width.

| State | \( \text{Mass(MeV)} \) | \( \Gamma[\Xi_{cc}\pi](\text{MeV}) \) | \( \Gamma[\Xi_{bb}\pi](\text{MeV}) \) | \( \Gamma[\Xi_{cc}\gamma](\text{keV}) \) | \( \Gamma[\Xi_{bb}\gamma](\text{keV}) \) | \( \Gamma_{\text{total}}(\text{MeV}) \) |
|-------|---------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| \( \Xi_{bb}^2P_{3/2}^- \) | 10368 | \ldots | \ldots | 1.15 | 1.11 | \( 1.87 \times 10^{-3} \) |
| \( \Xi_{bb}^4P_{1/2}^- \) | 10408 | \ldots | \ldots | 3.20 | 3.16 | \( 6.54 \times 10^{-5} \) |
| \( \Xi_{bb}^4P_{3/2}^- \) | 10675 | 1.59 | 80.0 | \ldots | \ldots | \( 9.56 \times 10^{-3} \) |
| \( \Xi_{bb}^4P_{5/2}^- \) | 10694 | 1.59 | 80.0 | 71.1 | 79.3 | \( 5.96 \times 10^{-5} \) |
| \( \Xi_{bb}^4P_{3/2}^+ \) | 10632 | 20.5 | 8.16 | \ldots | \ldots | \( 1.33 \times 10^{-3} \) |
| \( \Xi_{bb}^4P_{5/2}^+ \) | 10647 | 8.58 | 39.0 | 14.0 | 271 | \ldots |
| \( \Xi_{bb}^4P_{5/2}^+ \) | 10661 | 58.9 | 36.2 | 121 | 569 | \ldots |

\( J^P = 1/2^-, 3/2^-, 5/2^- \). Our main predictions are summarized as follows.

For the ground states with \( J^P = 3/2^+ \), their decay rates are dominated
by the radiative transitions. The radiative partial width of \( \Xi_{cc}^{++} (\Xi_{bb}^{++}) \) into \( \Xi_{cc}^{0} \gamma (\Xi_{bb}^{0} \gamma) \) is predicted to be several tens keV.
The \( \Xi_{cc}^{++} \) might be reconstructed in the \( \Xi_{cc}^{0} \gamma \) 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 \( \rho \)-mode 1P-wave components \( |\Xi_{cc}^{++} 2P_{3/2}^- \rangle \) and \( |\Xi_{cc}^{++} 2P_{1/2}^- \rangle \), 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 \( \rho \)-mode and the \( \lambda \)-mode excitations. Even with the mixing, the ratio of the radiative decays should be significant for the lowest lying excited doubly charmed baryons. The \( |\Xi_{cc}^{++} 2P_{3/2}^- \rangle \) and \( |\Xi_{cc}^{++} 2P_{1/2}^- \rangle \) may also be reconstructed in the \( \Xi_{cc}^{0} \gamma \) channel
with \( \Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+ \) at LHCb.

For the \( \lambda \)-mode 1P3 states in \( \Xi_{cc} \) family, their total strong decay widths are about \( \Gamma \sim 100 \text{ MeV} \). The \( |\Xi_{cc}^{++} 4P_{3/2}^\perp \rangle \) and \( |\Xi_{cc}^{++} 4P_{3/2}^- \rangle \) 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 \( |\Xi_{cc}^{++} 2P_{3/2}^- \rangle \) and \( |\Xi_{cc}^{++} 4P_{3/2}^- \rangle \) mainly decay into the \( \Xi_{cc}^{++} \pi^0 \) channel, which may be searched for by reconstructing \( \Xi_{cc}^{++} \) in the decay chain of \( \Xi_{cc}^{++} \to \Xi_{cc}^{++} \gamma \to \Lambda_c^+ K^- \pi^+ \pi^+ \) at LHCb.

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

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