

Lifetime of doubly charmed baryons

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Abstract

In this work, we evaluate the lifetimes of the doubly charmed baryons Ξ_{cc}^+ , Ξ_{cc}^{++} and Ω_{cc}^+ . We carefully calculate the non-spectator contributions at the quark level where the Cabibbo-suppressed diagrams are also included. The hadronic matrix elements are evaluated in the simple non-relativistic harmonic oscillator model. Our numerical results are generally consistent with that obtained by other authors who used the diquark model. However, all the theoretical predictions on the lifetimes are one order larger than the upper limit set by the recent SELEX measurement. This discrepancy would be clarified by the future experiment, if more accurate experiment still confirms the value of the SELEX collaboration, there must be some unknown mechanism to be explored.

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I. INTRODUCTION

The quite large difference of the lifetimes between D^\pm and D^0 and the lifetimes close to each other for B^\pm and B^0 are well explained by taking into account the non-spectator effects[1]. This success implies that the mechanism which governs the reactions at quark level is well understood. When we apply the mechanism to the heavy baryon case, some problems emerge. The famous puzzle in the heavy-flavor field that the lifetime of Λ_b is remarkably shorter than that of B meson is much alleviated recently when the operators of higher dimensions are taken into account[2, 3]. The more recent experimental value of the ratio $\tau(\Lambda_b)/\tau(B^0) = 1.041 \pm 0.057$ [4] is close to the theoretical evaluation[3]. However, in the theoretical works, one can notice that the evaluation of hadronic matrix elements is still very rough and based on some approximations. The possible errors brought up by the uncertainties in the hadronic matrix elements are still uncontrollable. In our recent work[5], we find that the short-distance contributions to the branching ratio of $\Lambda_b \rightarrow \Lambda \gamma$ which is evaluated in the PQCD approach, are much smaller than that from long-distance effects. Therefore, even though one has a full reason to believe that the low-energy QCD should solve the discrepancy if it exists, he must find a proper way to deal with the hadronic matrix elements.

The observation of doubly charmed baryon Ξ_{cc}^+ by the SELEX Collaboration at FERMILAB[6] provides an opportunity to investigate the hidden problems. Hopefully the study may shed some lights on the unknown non-perturbative QCD effects which result in obvious difference between baryons and mesons. Because Ξ_{cc}^+ contains two heavy quarks, by the heavy quark effective theory (HQET) the situation may become relatively simple and clear compared to the case of Λ_b or Λ_c which possesses only one heavy quark. Thus a careful study on the Ξ_{cc}^+ is necessary and interesting. Several groups already investigated the two-heavy-flavor baryons a long time ago[7, 8]. In their work, the evaluation of the hadronic matrix elements is based on the quark-diquark structure of the baryons. This is definitely reasonable, it is believed that two heavy quarks can constitute a more stable and compact color-anti-triplet diquark[9]. However, since charm quark, even b-quark, is not so heavy that the degree of freedom of the light flavor can be ignored, the diquark scenario may bring up certain errors, especially when evaluating lifetimes of baryons, because only inclusive processes are concerned. In this work, we do not use the diquark picture, but

instead, adopt a simpler non-relativistic model for the baryon and re-evaluate the hadronic matrix elements. As a by-product, one can compare the results by the diquark picture with that by the three valence-quark picture. It may help us to better understand the diquark picture and its application range.

The advantage is obvious, that we only concern the inclusive processes in terms of the optical theorem when calculating the lifetime. Therefore, we do not need to deal with the hadronization to light hadrons. The only non-perturbative effects come from the wave function of the heavy baryon. Moreover, since there are two heavy quarks in the baryon, the relativistic effects are not so significant and the framework of non-relativistic harmonic oscillator model might lead to a reasonable result.

Moreover, at the quark level, we carry out similar calculations as that in the literature, but we keep some new operators which are CKM suppressed and contribute to the lifetime. They appear at the non-spectator scattering at order of $\frac{1}{m_c^3}$ in heavy quark expansion(HQE). Later, our numerical results show that their contributions are indeed very tiny to make any substantial contributions.

All the concerned parameters in the model are obtained by fitting data, therefore we avoid some theoretical uncertainties and obtain reasonable results. Comparing these results with data, we may gain information about the the whole picture.

Our paper is organized as follows. In Section.II we derive the formulation for the lifetimes of Ξ_{cc}^+ , Ξ_{cc}^{++} and Ω_{cc}^+ which include the non-spectator effects. In Section.III, we use a simple model, i.e. the harmonic oscillator, to estimate the hadronic matrix elements. In Section.IV we present our numerical results along with the values of all the input parameters. The last section is devoted to our conclusion and discussion.

II. FORMULATION FOR LIFETIMES OF Ξ_{cc}^+ , Ξ_{cc}^{++} , Ω_{cc}^+

A. Spectator Contribution to Lifetimes of Ξ_{cc}^+ , Ξ_{cc}^{++} , Ω_{cc}^+

The lifetime is determined by the inclusive decays. Thus one can use the optical theorem to obtain the total width (lifetime) of the heavy hadron by calculating the absorptive part of the forward-scattering amplitude.

The total width is then written as

$$\Gamma(H_Q \rightarrow X) = \frac{1}{m_{H_Q}} \text{Im} \int d^4x \langle H_Q | \hat{T} | H_Q \rangle = \frac{1}{2m_{H_Q}} \langle H_Q | \hat{\Gamma} | H_Q \rangle, \quad (1)$$

where

$$\hat{T} = T\{\mathcal{L}_{eff}(x), \mathcal{L}_{eff}(0)\} \quad (2)$$

and \mathcal{L}_{eff} is the relevant effective Lagrangian. $1/m_Q$ is the expansion parameter, and the non-local operator \hat{T} is expanded as a sum of local operators and the corresponding Wilson coefficients include terms with increasing powers of $1/m_Q$. Definitely, the lowest dimensional term dominates in the limit $m_Q \rightarrow \infty$ and it is the dimension-three operator $\bar{c}c$. The total width of a charmed hadron H_c is determined by $\text{Im}\langle H_c | \hat{T} | H_c \rangle$ [10] with a proper normalization [11].

$$\begin{aligned} \Gamma(H_c \rightarrow f) = & \frac{G_F^2 m_c^5}{192\pi^3} |V_{CKM}|^2 \{c_3(f) \langle H_c | \bar{c}c | H_c \rangle \\ & + c_5(f) \frac{\langle H_c | \bar{c}i\sigma_{\mu\nu} G^{\mu\nu} c | H_c \rangle}{m_c^2} + \\ & \sum_i c_6^{(i)}(f) \frac{\langle H_c | (\bar{c}\Gamma_i q)(\bar{q}\Gamma_i c) | H_c \rangle}{m_c^3} + \mathcal{O}(\frac{1}{m_c^4})\}, \end{aligned} \quad (3)$$

where the coefficients $c_i(f)$ depend on the masses of the internal quarks in the loop. The coefficient $c_3(f)$ has been calculated to one-loop order [12, 13, 14] whereas the coefficient $c_5(f)$ is evaluated at the tree level [15, 16]. V_{CKM} is the Cabibbo-Kabayashi-Maskawa mixing matrix elements and $G_{\mu\nu}$ is the gluonic field strength tensor. Since the third term involves light quarks, it can be different for charmed hadrons with various light flavors. Thus, the difference appears at the $1/m_c^3$ order and in the hadronic matrix elements of four-quark operators. The contributions at orders higher than $1/m_c^3$ are neglected.

To the lowest order, the main contribution comes from the heavy quark(charm quark) decays, while the light flavors are treated as spectators. The contributions are due to the semileptonic and the nonleptonic decays as follows:

$$\Gamma(c \rightarrow s) = \sum_{l=e,\mu} \Gamma_{c \rightarrow s\bar{l}v} + \sum_{q(q')=u,d,s} \Gamma_{c \rightarrow s\bar{q}q'} \quad (4)$$

The semileptonic and nonleptonic decay rates of the c quark up to order $1/m_c^2$ has been evaluated by many authors [17], and here we would directly use their results.

B. Non-spectator Contributions to Inclusive Decays of Ξ_{cc}^+ , Ξ_{cc}^{++} , Ω_{cc}^+

The total width of hadrons which involve at least one charm quark c can be decomposed into two parts

$$\Gamma(H_Q \rightarrow f) = \Gamma^{spectator} + \Gamma^{non-spectator}. \quad (5)$$

For the spectator scenario, the contribution to the total width of the (ccd) -baryon ground state Ξ_{cc}^+ , the (ccu) -baryon ground state Ξ_{cc}^{++} and the (ccs) -baryon ground state Ω_{cc}^+ should be a sum of decays rates of two c -quarks individually namely

$$\Gamma_{ccq}^{spec} \simeq 2\Gamma_c^{spec}, \quad q = u, d, s. \quad (6)$$

To derive the non-spectator contributions for decays of Ξ_{cc}^+ , Ξ_{cc}^{++} and Ω_{cc}^+ , we need the relevant effective Lagrangian:[18]

$$\begin{aligned} \mathcal{L}_{eff}^{(\Delta c=1)}(\mu = m_c) = & -\frac{4G_F}{\sqrt{2}} \{ V_{cs}V_{ud}^* [C_1(\mu)\bar{s}\gamma^\mu Lc\bar{u}\gamma_\mu Ld + C_2(\mu)\bar{u}\gamma^\mu Lc\bar{s}\gamma_\mu Ld] \\ & + V_{cd}V_{ud}^* [C_1(\mu)\bar{d}\gamma^\mu Lc\bar{u}\gamma_\mu Ld + C_2(\mu)\bar{u}\gamma^\mu Lc\bar{d}\gamma_\mu Ld] \\ & + V_{cs}V_{us}^* [C_1(\mu)\bar{s}\gamma^\mu Lc\bar{u}\gamma_\mu Ls + C_2(\mu)\bar{u}\gamma^\mu Lc\bar{s}\gamma_\mu Ls] \\ & + V_{cs} \sum_{l=e,\mu} \bar{s}\gamma_\mu Lc\bar{\nu}_l\gamma^\mu Ll \} + h.c. \end{aligned} \quad (7)$$

where L denotes $\frac{1-\gamma_5}{2}$.

(i) The inclusive decays of Ξ_{cc}^+ :

There are four diagrams which contribute to the the width of Ξ_{cc}^+ , as shown in Fig.1. Here we also include the Feynman diagrams which are CKM suppressed. Fig 1.(a),(c) are the W-exchange diagrams (WE), while Fig 1.(b),(d) are the pauli-interference diagrams (PI). Here Fig 1.(d) is arisen from the semi-leptonic decay of the charm quarks with the d -quark in Ξ_{cc}^+ . For the WE-type diagrams, we derive the contribution to the width as

$$\begin{aligned} \hat{\Gamma}_{WE}^{\Xi_{cc}^+} = & \frac{2G_F^2}{\pi} (|V_{cs}|^2|V_{ud}|^2 C(z_{s+}, z_{u+}) + |V_{cd}|^2|V_{ud}|^2 C(z_{u+}, z_{d+})) P_+^2 \\ & \{ [C_1^2(\mu) + C_2^2(\mu)] \bar{c}\gamma^\mu Lc\bar{d}\gamma_\mu Ld + 2C_1(\mu)C_2(\mu)\bar{c}\gamma^\mu Ldd\bar{d}\gamma_\mu Lc \}, \end{aligned} \quad (8)$$

where $P_+ = p_c + p_d$, $z_{q+} = \frac{m_q^2}{P_+^2}(q = u, d, s)$. The definition of the function $C(z_1, z_2)$ is

$$C(z_1, z_2) = -[-2(x_2^3 - x_1^3) - (x_2^2 - x_1^2)(3 + 2z_1 - 2z_2) + 4z_1(x_2 - x_1)], \quad (9)$$

where $x_{1,2} = \frac{(1+z_1-z_2) \mp \sqrt{(1+z_1-z_2)^2 - 4z_1}}{2}$. In the expressions q and \bar{q} are free field operators of quark and antiquark, and we will show in next section that all the non-perturbative QCD effects are included in the wavefunctions. Their explicit expressions are given as

$$q = \int \frac{d^3k}{(2\pi)^3} \frac{m_q}{E_q} \sum_{\alpha=1,2} (b_{q\alpha}(k) u_q^\alpha(k) e^{-ikx} + d_{q\alpha}^+(k) v_q^\alpha(k) e^{+ikx}) \quad (10)$$

$$\bar{q} = \int \frac{d^3k}{(2\pi)^3} \frac{m_q}{E_q} \sum_{\alpha=1,2} (b_{q\alpha}^+(k) \bar{u}_q^\alpha(k) e^{ikx} + d_{q\alpha}(k) \bar{v}_q^\alpha(k) e^{-ikx}). \quad (11)$$

For Ξ_{cc}^+ , $q=c, u$.

The contributions from the Pauli-interference(PI) non-spectator diagrams to the width of Ξ_{cc}^+ are:

$$\begin{aligned} \hat{\Gamma}_{PI}^{\Xi_{cc}^+} = & -\frac{2G_F^2}{3\pi} \{ |V_{ud}|^2 |V_{cd}|^2 F_{\mu\nu}(z_{u-}, z_{d-}) [NC_1^2(\mu) \bar{c} \gamma^\mu L d \bar{d} \gamma^\nu L c + C_2^2(\mu) \bar{c}^i \gamma^\mu L d^j \bar{d}^j \gamma^\nu L c^i \\ & + 2C_1(\mu) C_2(\mu) \bar{c} \gamma^\mu L d \bar{d} \gamma^\nu L c] + 2|V_{cd}|^2 F_{\mu\nu}(0, z_{l-}) \bar{c} \gamma^\mu L d \bar{d} \gamma^\nu L c \}, \end{aligned} \quad (12)$$

where $z_{q-} = \frac{m_q^2}{P_-^2}$ ($q = u, d, e, \mu$) and $P_- = p_c - p_d$. The definition of the function $F_{\mu\nu}(z_1, z_2)$ is

$$\begin{aligned} F_{\mu\nu}(z_1, z_2) = & -[2(x_2^3 - x_1^3) - \frac{3}{2}(2 + z_1 - z_2)(x_2^2 - x_1^2) + 3(x_2 - x_1)] P_-^2 g_{\mu\nu} \\ & + [2(x_2^3 - x_1^3) - 3(x_2^2 - x_1^2)] P_{-\mu} P_{-\nu}, \end{aligned} \quad (13)$$

where the definitions of z_1 and z_2 are the same as before.

(ii) The inclusive decays of Ξ_{cc}^{++} :

The non-spectator contribution to the width of Ξ_{cc}^{++} come from the diagrams shown in Fig.2. That is caused by an interference of the produced u -quark from decay of one of the charm quarks with the u -quark in Ξ_{cc}^{++} . Here we also include the CKM suppressed Feynman diagrams. The contribution is

$$\begin{aligned} \hat{\Gamma}_{PI}^{\Xi_{cc}^{++}} = & -\frac{2G_F^2}{3\pi} \{ |V_{cs}|^2 |V_{ud}|^2 F_{\mu\nu}(z_{s-}, z_{d-}) + |V_{cs}|^2 |V_{us}|^2 F_{\mu\nu}(z_{s-}, z_{s-}) \\ & + |V_{cd}|^2 |V_{ud}|^2 F_{\mu\nu}(z_{d-}, z_{d-}) \} \\ & \{ C_1^2(\mu) \bar{c}^i \gamma^\mu L u^j \bar{u}^j \gamma^\nu L c^i + NC_2^2(\mu) \bar{u} \gamma^\mu L c \bar{c} \gamma^\nu L u + 2C_1(\mu) C_2(\mu) \bar{u} \gamma^\mu L c \bar{c} L^\nu u \}, \end{aligned} \quad (14)$$

where $z_- = \frac{m_q^2}{P_-^2}$ ($q = s, d$), $P_- = p_c - p_u$.

(iii) For the inclusive decays of Ω_{cc}^+ :

The non-spectator contributions for Ω_{cc}^+ not only come from the Pauli interference of the

s -quark produced in the non-leptonic, but also from the semi-leptonic decay of the charm quarks with the s -quark in Ω_{cc}^+ , the later one is suggested by Voloshin et al.[19]. As above, here we include the CKM suppressed WE non-spectator diagrams. The WE non-spectator contribution to the width Ω_{cc}^+ is

$$\hat{\Gamma}_{WE}^{\Omega_{cc}^+} = \frac{2G_F^2}{\pi} |V_{us}|^2 |V_{cs}|^2 C(z_{u+}, z_{s+}) P_+^2 \{ [C_1^2(\mu) + C_2^2(\mu)] \bar{c} \gamma^\mu L c \bar{s} \gamma_\mu L s + 2C_1(\mu) C_2(\mu) \bar{c} \gamma^\mu L s \bar{s} \gamma_\mu L c \}, \quad (15)$$

where $z_{q+} = \frac{m_q^2}{P_+^2}$, $q = u, s$ and $P_+ = p_c + p_s$.

The PI non-spectator contribution to the width of Ω_{cc}^+ is

$$\begin{aligned} \hat{\Gamma}_{PI}^{\Omega_{cc}^+} = & -\frac{2G_F^2}{3\pi} \{ |V_{cs}|^2 |V_{ud}|^2 F_{\mu\nu}(z_{u-}, z_{d-}) + |V_{cs}|^2 |V_{us}|^2 F_{\mu\nu}(z_{u-}, z_{s-}) \} \\ & \{ NC_1^2(\mu) \bar{c} \gamma^\mu L s \bar{s} \gamma^\nu L c + C_2^2(\mu) \bar{c}^i \gamma^\mu L s^j \bar{s}^j \gamma^\nu L c^i + 2C_1(\mu) C_2(\mu) \bar{c} \gamma^\mu L s \bar{s} \gamma^\nu L c \} \\ & -2 \frac{2G_F^2}{3\pi} |V_{cs}|^2 F_{\mu\nu}(0, z_{l-}) \bar{c} \gamma^\mu L s \bar{s} \gamma^\nu L c, \end{aligned} \quad (16)$$

where $z_{q-} = \frac{m_q^2}{P_-^2}$, $q = u, d, s, e, \mu$ and $P_- = p_c - p_s$. Sandwiching the operators between initial and final Ξ_{cc}^+ , Ξ_{cc}^{++} , Ω_{cc}^+ states, we obtain the hadronic matrix elements:

$$\begin{aligned} \Gamma_{WE/PI}^{\Xi_{cc}^+} &= \langle \Xi_{cc}^+(\mathbf{P} = 0, s) | \hat{\Gamma}_{WE/PI}^{\Xi_{cc}^+} | \Xi_{cc}^+(\mathbf{P} = 0, s) \rangle \\ \Gamma_{PI}^{\Xi_{cc}^{++}} &= \langle \Xi_{cc}^{++}(\mathbf{P} = 0, s) | \hat{\Gamma}_{PI}^{\Xi_{cc}^{++}} | \Xi_{cc}^{++}(\mathbf{P} = 0, s) \rangle \\ \Gamma_{WE/PI}^{\Omega_{cc}^+} &= \langle \Omega_{cc}^+(\mathbf{P} = 0, s) | \hat{\Gamma}_{WE/PI}^{\Omega_{cc}^+} | \Omega_{cc}^+(\mathbf{P} = 0, s) \rangle. \end{aligned} \quad (17)$$

III. THE HADRONIC MATRIX ELEMENTS

Because the hadronic matrix elements are fully determined by the non-perturbative QCD effects which cannot be reliably evaluated at present yet, we need to invoke concrete phenomenological models to carry out the computations. In this work, we adopt a simple non-relativistic model, i.e. the harmonic oscillator[20]. This model has been widely employed in similar researches[21, 22, 23, 24, 25, 26]. In fact, an advantage of the calculations of the lifetimes of heavy hadrons is that one does not need to deal with the hadronization process of lighter products (quarks or even gluons) and the heavy hadrons can be well described by such simple non-relativistic models, and the results are relatively reliable than

for light hadron decays.

(i) The inclusive decays of Ξ_{cc}^+ :

In the harmonic oscillator model, the wavefunction of Ξ_{cc}^+ is expressed as $|\Xi_{cc}^+\rangle$ and

$$|\Xi_{cc}^+(\mathbf{P}, s)\rangle = A_B \sum_{color, spin} \chi_{spin, flavor} \varphi_{color} \int d^3 p_\rho d^3 p_\lambda \Psi_{\Xi_{cc}^+}(\mathbf{p}_\rho, \mathbf{p}_\lambda) |c_i(\mathbf{p}_{q_1}, s_{q_1}), c_j(\mathbf{p}_{q_2}, s_{q_2}), d_k(\mathbf{p}_{q_3}, s_{q_3})\rangle. \quad (18)$$

The normalization condition for $|\Xi_{cc}^+(\mathbf{P}, s)\rangle$ is

$$\langle \Xi_{cc}^+(\mathbf{P}, s) | \Xi_{cc}^+(\mathbf{P}', s') \rangle = (2\pi)^3 \frac{M_{\Xi_{cc}}}{\omega_P} \delta^3(\mathbf{P} - \mathbf{P}') \delta_{s, s'}, \quad (19)$$

where $\chi_{spin, flavor} \varphi_{color}$ are the spin-flavor and color wavefunctions respectively. Their explicit expressions are

$$\chi_{s=\frac{1}{2}, flavor} = \frac{1}{\sqrt{6}} (2|c_\uparrow c_\uparrow d_\downarrow\rangle - |c_\uparrow c_\downarrow d_\uparrow\rangle - |c_\downarrow c_\uparrow d_\uparrow\rangle) \quad (20)$$

$$\varphi_{color} = \frac{1}{\sqrt{6}} \epsilon_{ijk}. \quad (21)$$

A_B is the normalization constant. The spatial wavefunction $\Psi_{\Xi_{cc}^+}$ is a three-body harmonic oscillator wavefunction and expressed as

$$\Psi_{\Xi_{cc}^+} = \exp\left(-\frac{\mathbf{p}_\rho^2}{2a_\rho^2} - \frac{\mathbf{p}_\lambda^2}{2a_\lambda^2}\right). \quad (22)$$

Here a_ρ and a_λ parameters reflecting the non-perturbative effects. In the above expressions, the Jacobi transformations of $\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3$ which are the momenta of the three valence quarks ccd , and variables $\mathbf{p}_\rho, \mathbf{p}_\lambda, \mathbf{P}$ are

$$\mathbf{p}_\rho = \frac{\mathbf{p}_1 - \mathbf{p}_2}{\sqrt{2}}, \mathbf{p}_\lambda = \frac{\mathbf{p}_1 + \mathbf{p}_2 - \frac{2m_c}{m_d} \mathbf{p}_3}{\sqrt{2\frac{2m_c + m_d}{m_d}}}, \mathbf{P} = \mathbf{p}_1 + \mathbf{p}_2 + \mathbf{p}_3. \quad (23)$$

We choose the center-of-mass frame of Ξ_{cc}^+ , i.e. ($\mathbf{P}=0$) to calculate the hadronic matrix elements. Substituting the four-quark operators into the expressions, we obtain the non-

spectator WE contributions to the width of Ξ_{cc}^+ as

$$\begin{aligned}\Gamma_{WE}^{\Xi_{cc}^+} = & 64\pi^2 G_F^2 P_+^2 (|V_{cs}|^2 |V_{ud}|^2 C(z_{s+}, z_{u+}) + |V_{cd}|^2 |V_{ud}|^2 C(z_{u+}, z_{d+})) (C_1(\mu) - C_2(\mu))^2 \\ & |A_B|^2 [2(1 + \frac{2m_c}{m_d})]^{3/2} \sum_{spin} \int d^3\mathbf{p}_\rho d^3\mathbf{p}_\lambda d^3\mathbf{p}'_\rho \\ & \exp[-\frac{\mathbf{p}_\rho^2}{2a_\rho^2} - \frac{\mathbf{p}_\lambda^2}{2a_\lambda^2}] \exp[-\frac{\mathbf{p}_\rho^2}{2a_\rho^2} - \frac{(\mathbf{p}_\lambda + \sqrt{1 + \frac{2m_c}{m_d}}(\mathbf{p}_\rho - \mathbf{p}'_\rho))^2}{2a_\lambda^2}] \bar{u}_c \gamma_\mu L u_c \bar{u}_d \gamma^\mu L u_d,\end{aligned}\quad (24)$$

and the PI contribution is

$$\begin{aligned}\Gamma_{PI}^{\Xi_{cc}^+} = & -\frac{64}{3}\pi^2 G_F^2 \{|V_{cd}|^2 |V_{ud}|^2 F_{\mu\nu}(z_{u-}, z_{d-}) [-NC_1^2(\mu) + C_2^2(\mu) - 2C_1(\mu)C_2(\mu)] \\ & - 2|V_{cd}|^2 F_{\mu\nu}(0, z_{l-})\} |A_B|^2 [2(1 + \frac{2m_c}{m_d})]^{3/2} \sum_{spin} \int d^3\mathbf{p}_\rho d^3\mathbf{p}_\lambda d^3\mathbf{p}'_\rho \\ & \exp[-\frac{\mathbf{p}_\rho^2}{2a_\rho^2} - \frac{\mathbf{p}_\lambda^2}{2a_\lambda^2}] \exp[-\frac{\mathbf{p}_\rho^2}{2a_\rho^2} - \frac{(\mathbf{p}_\lambda + \sqrt{1 + \frac{2m_c}{m_d}}(\mathbf{p}_\rho - \mathbf{p}'_\rho))^2}{2a_\lambda^2}] \bar{u}_c \gamma^\mu L u_d \bar{u}_d \gamma^\nu L u_c,\end{aligned}\quad (25)$$

where the sum over spin means a sum over the polarizations of the three valence quarks of Ξ_{cc}^+ with their corresponding C-G coefficients in the spin-flavor wavefunction. u_q , \bar{u}_q denote the Dirac spinors of free quarks q and the expression is

$$u_q = \sqrt{\frac{E_q + m_q}{2m_q}} \begin{pmatrix} 1 \\ \frac{\boldsymbol{\sigma} \cdot \mathbf{p}}{E_q + m_q} \end{pmatrix} \chi \quad (26)$$

$$\bar{u}_q = \sqrt{\frac{E_q + m_q}{2m_q}} \chi^\dagger \left(1 - \frac{\boldsymbol{\sigma} \cdot \mathbf{p}}{E_q + m_q} \right) \quad (27)$$

in our case q denotes c and d quarks.

(ii) The inclusive decays of Ξ_{cc}^{++} :

The contribution from the PI non-spectator diagrams to the width of Ξ_{cc}^{++} is

$$\begin{aligned}\Gamma_{PI}^{\Xi_{cc}^{++}} = & -\frac{64}{3}\pi^2 G_F^2 \{|V_{cs}|^2 |V_{ud}|^2 F_{\mu\nu}(z_{s-}, z_{d-}) + |V_{cs}|^2 |V_{us}|^2 F_{\mu\nu}(z_{s-}, z_{s-}) \\ & + |V_{cd}|^2 |V_{ud}|^2 F_{\mu\nu}(z_{d-}, z_{d-})\} (C_1^2(\mu) - NC_2^2(\mu) - 2C_1(\mu)C_2(\mu)) |A_B|^2 [2(1 + \frac{2m_c}{m_u})]^{3/2} \\ & \sum_{spin} \int d^3\mathbf{p}_\rho d^3\mathbf{p}_\lambda d^3\mathbf{p}'_\rho \exp[-\frac{\mathbf{p}_\rho^2}{2a_\rho^2} - \frac{\mathbf{p}_\lambda^2}{2a_\lambda^2}] \exp[-\frac{\mathbf{p}_\rho^2}{2a_\rho^2} - \frac{(\mathbf{p}_\lambda + \sqrt{1 + \frac{2m_c}{m_u}}(\mathbf{p}_\rho - \mathbf{p}'_\rho))^2}{2a_\lambda^2}] \\ & \bar{u}_c \gamma^\mu L u_u \bar{u}_u \gamma^\nu L u_c.\end{aligned}\quad (28)$$

Similar to the case of Ξ_{cc}^+ , the sum over spin means a sum of the polarizations of the three valence quarks of Ξ_{cc}^{++} with their C-G coefficients. One only needs to replace u by d in \mathbf{p}_ρ , \mathbf{p}_λ and other expressions are similar to that for Ξ_{cc}^+ .

(iii) The inclusive decays of Ω_{cc}^+ :

The contribution from the W-boson exchange(WE) non-spectator diagrams to the width of Ω_{cc}^+ is

$$\begin{aligned}\Gamma_{WE}^{\Omega_{cc}^+} = & 64\pi^2 G_F^2 P_+^2 |V_{us}|^2 |V_{cs}|^2 C(z_{u+}, z_{s+}) (C_1(\mu) - C_2(\mu))^2 \\ & |A_B|^2 [2(1 + \frac{2m_c}{m_s})]^{3/2} \sum_{spin} \int d^3\mathbf{p}_\rho d^3\mathbf{p}_\lambda d^3\mathbf{p}'_\rho \\ & \exp[-\frac{\mathbf{p}_\rho^2}{2a_\rho^2} - \frac{\mathbf{p}_\lambda^2}{2a_\lambda^2}] \exp[-\frac{\mathbf{p}_\rho^2}{2a_\rho^2} - \frac{(\mathbf{p}_\lambda + \sqrt{1 + \frac{2m_c}{m_s}}(\mathbf{p}_\rho - \mathbf{p}'_\rho))^2}{2a_\lambda^2}] \bar{u}_c \gamma_\mu L u_c \bar{u}_s \gamma^\mu L u_s,\end{aligned}\quad (29)$$

whereas that from the Pauli-interference(PI) non-spectator diagrams is

$$\begin{aligned}\Gamma_{PI}^{\Omega_{cc}^+} = & -\frac{64}{3}\pi^2 G_F^2 \{[|V_{cs}|^2 |V_{ud}|^2 F_{\mu\nu}(z_{u-}, z_{d-}) + |V_{cs}|^2 |V_{us}|^2 F_{\mu\nu}(z_{u-}, z_{s-})] \\ & [-NC_1^2(\mu) + C_2^2(\mu) - 2C_1(\mu)C_2(\mu)] - 2|V_{cs}|^2 F_{\mu\nu}(0, z_{l-})\} |A_B|^2 [2(1 + \frac{2m_c}{m_s})]^{3/2} \\ & \sum_{spin} \int d^3\mathbf{p}_\rho d^3\mathbf{p}_\lambda d^3\mathbf{p}'_\rho \exp[-\frac{\mathbf{p}_\rho^2}{2a_\rho^2} - \frac{\mathbf{p}_\lambda^2}{2a_\lambda^2}] \exp[-\frac{\mathbf{p}_\rho^2}{2a_\rho^2} - \frac{(\mathbf{p}_\lambda + \sqrt{1 + \frac{2m_c}{m_s}}(\mathbf{p}_\rho - \mathbf{p}'_\rho))^2}{2a_\lambda^2}] \\ & \bar{u}_c \gamma^\mu L u_s \bar{u}_s \gamma^\nu L u_c.\end{aligned}\quad (30)$$

The sum over polarizations is similar to that for Ξ_{cc}^+ and Ξ_{cc}^{++} .

IV. INPUT PARAMETERS AND NUMERICAL RESULTS

To obtain the decay amplitudes, we adopt the input parameters as follows[7, 27]: $G_F = 1.166 \times 10^{-5} \text{GeV}^{-2}$, $|V_{cs}| = 0.9737$, $|V_{ud}| = 0.9745$, $C_1(m_c) = 1.3$, $C_2(m_c) = -0.57$, $m_c = 1.60 \text{ GeV}$, $m_s = 0.45 \text{ GeV}$, $m_u = m_d = 0.3 \text{ GeV}$, $m_s^* = 0.2 \text{ GeV}$, $m_u^* = m_d^* = 0$, $M_{\Xi_{cc}^+} = M_{\Xi_{cc}^{++}} = 3.519 \text{ GeV}$, $M_{\Omega_{cc}^+} = 3.578 \text{ GeV}$, $M_{\Xi_{cc}^{+*}} - M_{\Xi_{cc}^+} = M_{\Xi_{cc}^{++*}} - M_{\Xi_{cc}^{++}} = M_{\Omega_{cc}^{+*}} - M_{\Omega_{cc}^+} = 0.132 \text{ GeV}$. Here m_{q^*} denotes the current quark mass of flavor q .

The non-perturbative parameters a_ρ , a_λ in the harmonic oscillator wavefunctions are selected as follows: for J/ψ , in ref.[20], $a_\rho^2 = 0.33 \text{ GeV}^2$, for D -mesons, $a_\rho^2 = 0.25 \text{ GeV}^2$. For

TABLE I: The numerical results about the contributions from the different components and the evaluated lifetime for the doubly charmed baryons. For a comparison, in the following table, we list the corresponding lifetimes predicted by the authors of ref.[7] where the diquark picture was employed. It is noted that in ref.[7], the authors used various input parameters and obtained slightly diverse results, we take average values of the numbers in the table. There is only one datum for the lifetimes on $\tau_{\Xi_{cc}^+}$ given by the SELEX collaboration which is also listed the table.

Ξ_{cc}^+	$\Gamma_{spec}(10^{-12}\text{GeV})$	$\Gamma_{non}^{WE}(10^{-13}\text{GeV})$	$\Gamma_{non}^{PI}(10^{-15}\text{GeV})$	$\tau_{\Xi_{cc}^+}(\text{ps})$	$\tau_{\Xi_{cc}^+}(\text{ps})$ in ref.[7]	exp(ps)
	2.01	6.43	-3.36	0.25	0.19	0.033
Ξ_{cc}^{++}	$\Gamma_{spec}(10^{-12}\text{GeV})$		$\Gamma_{non}^{PI}(10^{-12}\text{GeV})$	$\tau_{\Xi_{cc}^{++}}(\text{ps})$	$\tau_{\Xi_{cc}^{++}}(\text{ps})$ in ref.[7]	
	2.01		-1.02	0.67	0.52	—
Ω_{cc}^+	$\Gamma_{spec}(10^{-12}\text{GeV})$	$\Gamma_{non}^{WE}(10^{-14}\text{GeV})$	$\Gamma_{non}^{PI}(10^{-12}\text{GeV})$	$\tau_{\Omega_{cc}^+}(\text{ps})$	$\tau_{\Omega_{cc}^+}(\text{ps})$ in ref.[7]	
	2.01	4.25	1.10	0.21	0.22	—

the doubly charmed baryons, because a_ρ reflects the coupling between two charm quarks, we set it to be the same as that for J/ψ . a_λ reflects the coupling of the light quark with these two charm quark, thus we can reasonably set it to be the same as a_ρ in D-mesons.

With these parameters as input, the lifetimes of the doubly charmed baryons can be evaluated out (see TABLE.I), if the non-spectator effects are taken into account.

V. CONCLUSION AND DISCUSSION

In this work, we evaluate the lifetimes of doubly charmed baryons with the non-spectator effects being properly taken into account. As argued in the introduction, to evaluate the lifetimes (the total widths), only the inclusive processes are concerned, and then the non-perturbative effects are all from the wavefunctions of the doubly charmed baryons. Due to existence of the two heavy charm quarks, the non-relativistic harmonic oscillator model should apply in this case. Mainly, we carefully calculate the contribution of non-perturbative effects to the lifetimes in the model, which are closely related to the bound states of the baryons.

Our numerical results indicate that the non-spectator contributions to the lifetimes of

Ξ_{cc}^+ , Ξ_{cc}^{++} and Ω_{cc}^+ are substantial. The non-spectator contributions to the width of Ξ_{cc}^+ are mainly from the WE diagrams (the PI diagrams which contribute are CKM suppressed), since the WE contribution is constructive, therefore the lifetime of Ξ_{cc}^+ is much suppressed. By contraries, for Ξ_{cc}^{++} and Ω_{cc}^+ , the non-spectator contributions are mainly from the PI diagrams and the net effect is destructive. It is noted that for Ω_{cc}^+ there still are Cabibbo-suppressed WE diagrams, but for Ξ_{cc}^{++} there are only PI diagrams. Therefore the predicted lifetime of Ξ_{cc}^{++} is larger than that of other two baryons. We also employ other values for parameters a_ρ, a_λ and find that the resultant values can vary within 20% uncertainty.

Our results are

$$\tau(\Xi_{cc}^+) = 0.25 \text{ ps} \quad \tau(\Xi_{cc}^{++}) = 0.67 \text{ ps} \quad \text{and} \quad \tau(\Omega_{cc}^+) = 0.21 \text{ ps}.$$

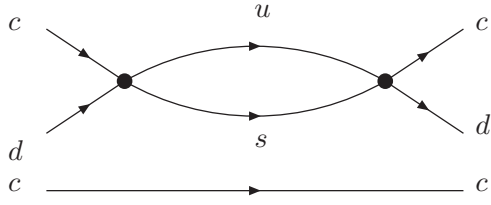
These are generally consistent with the results obtained by Kiselev et al.[7] and Guberina et al.[8], even though they used different models for calculating the hadronic matrix elements. Concretely, they used the diquark picture and attributed the non-perturbative effects into the wavefunction of the diquark at origin. Kiselev et al. gave $\tau(\Xi_{cc}^+) \sim 0.16 - 0.22 \text{ ps}$ $\tau(\Xi_{cc}^{++}) \sim 0.40 - 0.65 \text{ ps}$ and $\tau(\Omega_{cc}^+) \sim 0.24 - 0.28$.

Although all the theoretical predictions based on different models agree with each other, they are obviously one order larger than the upper limit of the measured value on the lifetime of Ξ_{cc}^+ (0.033 ps) by the SELEX collaboration[6]. This deviation, as suggested by some authors, may come from experiments[28]. So far the difference between theoretical predictions and experimental data may imply some unknown physics mechanisms which drastically change the value, if the future experiment, say at LHCb, confirms the measurement of the SELEX. Recently, several groups have studied the possibility of doubly heavy baryon production at hadron collider LHC and future linear collider ILC[29, 30] and the effective field theories for two heavy quarks system are also further investigated[31]. We are expecting the new data from more accurate experiments at LHC and ILC to improve our theoretical framework and determine if there are contributions from new physics beyond the standard model.

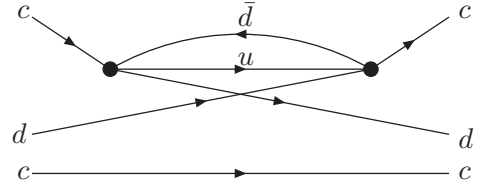
Acknowledgement: This work is supported by the National Natural Science Foundation of China.

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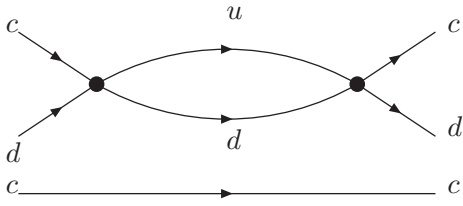
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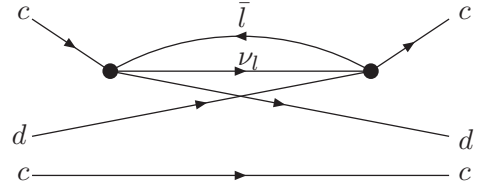
(a)



(b)

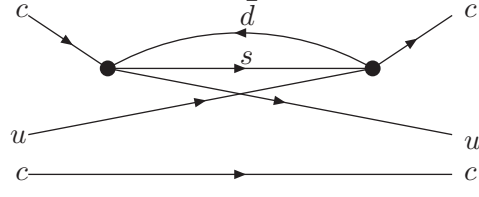


(c)

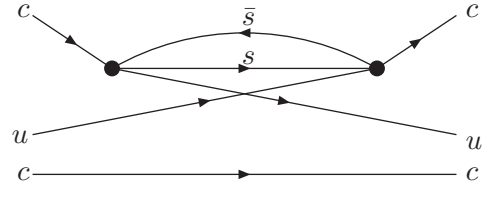


(d)

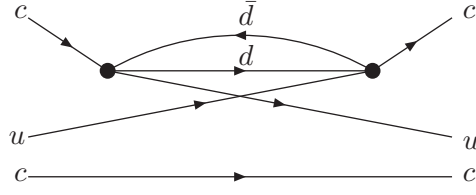
FIG. 1: non-spectator effects contribution to lifetime of Ξ_{cd}



(a)

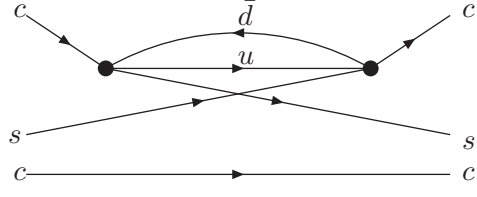


(b)

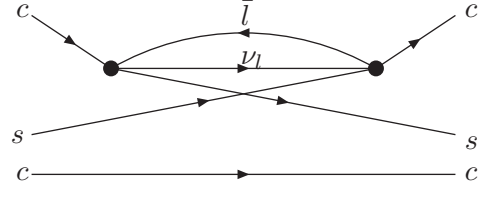


(c)

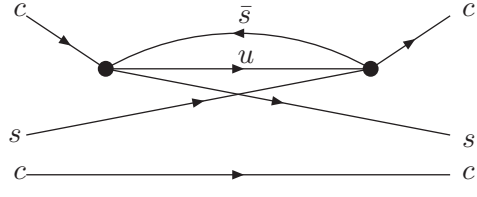
FIG. 2: non-spectator effects contribution to lifetime of Ξ_{ccu}



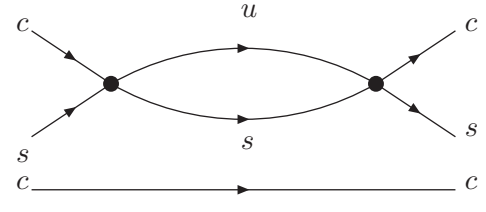
(a)



(b)



(c)



(d)

FIG. 3: non-spectator effects contribution to lifetime of Ω_{ccs}