

Strong decays of charmed baryons

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There has been important experimental progress in the sector of heavy baryons in the past several years. We study the strong decays of the S-wave, P-wave, D-wave and radially excited charmed baryons using the 3P_0 model. After comparing the calculated decay pattern and total width with the available data, we discuss the possible internal structure and quantum numbers of those charmed baryons observed recently.

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I. INTRODUCTION

Babar and Belle collaborations observed several excited charmed baryons: $\Lambda_c(2880, 2940)^+$, $\Xi_c(2980, 3077)^{+,0}$ and $\Omega_c(2768)^0$ last year [1, 2, 3, 4, 5], which inspired several investigations of these states in literature [6, 7, 8, 9]. We collect the experimental information of these recently observed hadrons in Table I. Their quantum numbers have not been determined except $\Lambda_c(2880)^+$. In order to understand their structures using the present experimental information, we study the strong decay pattern of the excited charmed baryons systematically in this work. In the past decades, there has been some research work on heavy baryons

[8, 11, 12].

The quantum numbers and decay widths of S-wave and some P-wave charmed baryons are known [13]. We first systematically analyze their strong decays in the framework of the 3P_0 strong decay model. Accordingly one can extract the parameters and estimate the accuracy of the 3P_0 model when it's applied in the charmed baryon system. Then we go one step further and extend the same formalism to study the decay patterns of these new charmed baryons $\Lambda_c(2880, 2940)^+$, $\Xi(2980, 3077)^{+,0}$ under different assignments of their quantum numbers. After comparing the theoretical results with the available experimental data, we can learn their favorable quantum numbers and assignments in the quark model.

| State | Mass and Width (MeV) | Decay channels in experiments | Other information |
|---------------------|---|------------------------------------|--|
| $\Lambda_c(2880)^+$ | $2881.5 \pm 0.3, < 8$ [10] | $\Lambda_c \pi^+ \pi^-$ | J^P favors $\frac{5}{2}^+$ [2], $\frac{\Gamma(\Sigma_c^*(2520)\pi^\pm)}{\Gamma(\Sigma_c(2455)\pi^\pm)} = 0.225 \pm 0.062 \pm 0.025$ [2] |
| | $2881.9 \pm 0.1 \pm 0.5, 5.8 \pm 1.5 \pm 1.1$ [1] | $D^0 p$ | |
| | $2881.2 \pm 0.2^{+0.4}_{-0.3}, 5.5^{+0.7}_{-0.5} \pm 0.4$ [2] | $\Sigma_c^{*,0,++}(2520)\pi^{+,-}$ | |
| $\Lambda_c(2940)^+$ | $2939. \pm 1.3 \pm 1.0, 17.5 \pm 5.2 \pm 5.9$ [1] | $D^0 p$ | - |
| | $2937.9 \pm 1.0^{+1.8}_{-0.4}, 10 \pm 4 \pm 5$ [2] | $\Sigma_c(2455)^{0,++}\pi^{+,-}$ | |
| $\Xi_c(2980)^+$ | $2967.1 \pm 1.9 \pm 1.0, 23.6 \pm 2.8 \pm 1.3$ [3] | $\Lambda_c^+ K^- \pi^+$ | - |
| | $2978.5 \pm 2.1 \pm 2.0, 43.5 \pm 7.5 \pm 7.0$ [4] | $\Lambda_c^+ K^- \pi^+$ | |
| $\Xi_c(2980)^0$ | $2977.1 \pm 8.8 \pm 3.5, 43.5$ [4] | $\Lambda_c^+ K_S^0 \pi^-$ | - |
| $\Xi_c(3077)^+$ | $3076.4 \pm 0.7 \pm 0.3, 6.2 \pm 1.6 \pm 0.5$ [3] | $\Lambda_c^+ K^- \pi^+$ | - |
| | $3076.7 \pm 0.9 \pm 0.5, 6.2 \pm 1.2 \pm 0.8$ [4] | $\Lambda_c^+ K^- \pi^+$ | |
| $\Xi_c(3077)^0$ | $3082.8 \pm 1.8 \pm 1.5, 5.2 \pm 3.1 \pm 1.8$ [4] | $\Lambda_c^+ K_S^0 \pi^-$ | - |
| $\Omega_c(2768)^0$ | 2768.3 ± 3.0 [5] | $\Omega_c^0 \gamma$ | $J^P = \frac{3}{2}^+$ |

TABLE I: A summary of recently observed charmed baryons by Babar and Belle collaborations.

Very recently CDF collaboration reported four particles [14, 15], which are consistent with Σ_b^\pm and $\Sigma_b^{*\pm}$ predicted in the quark model [16]. Their masses are

$M_{\Sigma_b^+} = 5808_{-2.3}^{+2.0} \pm 1.7$ MeV, $M_{\Sigma_b^-} = 5816_{-1.0}^{+1.0} \pm 1.7$ MeV, $M_{\Sigma_b^{*+}} = 5829_{-1.8}^{+1.6} \pm 1.7$, $M_{\Sigma_b^{*-}} = 5837_{-1.9}^{+2.1} \pm 1.7$ MeV. The

mass splitting between Σ_b and Σ_b^* was discussed in Refs. [17, 18] while the strong decays of $\Sigma_b^{\pm(*)}$ were studied in Ref. [19]. As a byproduct, we also calculate the strong decays of $\Sigma_b^{(*)\pm}$ and other S-wave bottom baryons in this work.

This paper is organized as follows. We give a short theoretical review of S-wave, P-wave and D-wave charmed baryons and introduce our notations for them in Section II. Then we give a brief review of 3P_0 model in Section III. We present the strong decay amplitudes of charmed baryons in Section IV. Section V is the numerical results. The last section is our discussion and conclusion. Some lengthy formulae are collected in the Appendix.

II. THE NOTATIONS AND CONVENTIONS OF CHARMED BARYON

We first introduce our notations for the excited charmed baryons. Inside a charmed baryon there are one charm quark and two light quarks (u, d or s). It belongs to either the symmetric 6_F or antisymmetric $\bar{3}_F$ flavor representation (see Fig. 1). For the S-wave charmed baryons, the total color-flavor-spin wave function and color wave function must be symmetric and antisymmetric respectively. Hence the spin of the two light quarks is $S=1$ for 6_F or $S=0$ for $\bar{3}_F$. The angular momentum and parity of the S-wave charmed baryons are $J^P = \frac{1}{2}^+$ or $\frac{3}{2}^+$ for 6_F and $J^P = \frac{1}{2}^+$ for $\bar{3}_F$. The names of S-wave charmed baryons are listed in Fig. 1, where we use the star to denote $\frac{3}{2}^+$ baryons and the prime to denote the $J^P = \frac{1}{2}^+$ baryons in the 6_F representation.

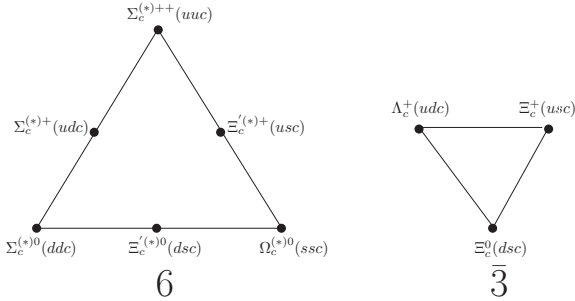


FIG. 1: The SU(3) flavor multiplets of charmed baryons

In Fig. 2 we introduce our notations and conventions for the P-wave charmed baryons. l_ρ is the orbital angular momentum between the two light quarks while l_λ denotes the orbital angular momentum between the charm quark and the two light quark system. We use the prime to label the Ξ_{cJ_l} baryons in the 6_F representation and the tilde to discriminate the baryons with $l_\rho = 1$ from that with $l_\lambda = 1$.

The notation for D-wave charmed baryons is more complicated (see Fig. 3). Besides the prime, l_ρ and l_λ

(a) $l_\rho = 0, l_\lambda = 1$

$$f_S(6): L = 1 \otimes S_{q_1 q_2} = 1 \begin{cases} J_l = 0: \Sigma_{c0}(\frac{1}{2}^-) & \Xi'_{c0}(\frac{1}{2}^-) \\ J_l = 1: \Sigma_{c1}(\frac{1}{2}^-, \frac{3}{2}^-) & \Xi'_{c1}(\frac{1}{2}^-, \frac{3}{2}^-) \\ J_l = 2: \Sigma_{c2}(\frac{3}{2}^-, \frac{5}{2}^-) & \Xi'_{c2}(\frac{3}{2}^-, \frac{5}{2}^-) \end{cases}$$

$$f_A(\bar{3}): L = 1 \otimes S_{q_1 q_2} = 0 \implies J_l = 1: \Lambda_{c1}(\frac{1}{2}^-, \frac{3}{2}^-) \quad \Xi_{c1}(\frac{1}{2}^-, \frac{3}{2}^-)$$

(b) $l_\rho = 1, l_\lambda = 0$

$$f_A(\bar{3}): L = 1 \otimes S_{q_1 q_2} = 1 \begin{cases} J_l = 0: \tilde{\Lambda}_{c0}(\frac{1}{2}^-) & \tilde{\Xi}_{c0}(\frac{1}{2}^-) \\ J_l = 1: \tilde{\Lambda}_{c1}(\frac{1}{2}^-, \frac{3}{2}^-) & \tilde{\Xi}_{c1}(\frac{1}{2}^-, \frac{3}{2}^-) \\ J_l = 2: \tilde{\Lambda}_{c2}(\frac{3}{2}^-, \frac{5}{2}^-) & \tilde{\Xi}_{c2}(\frac{3}{2}^-, \frac{5}{2}^-) \end{cases}$$

$$f_S(6): L = 1 \otimes S_{q_1 q_2} = 0 \implies J_l = 1: \tilde{\Sigma}_{c1}(\frac{1}{2}^-, \frac{3}{2}^-) \quad \tilde{\Xi}'_{c1}(\frac{1}{2}^-, \frac{3}{2}^-)$$

FIG. 2: The notations for P-wave charmed baryons. $f_S(6_F)$ and $f_A(\bar{3}_F)$ denote the SU(3) flavor representation. $S_{q_1 q_2}$ is the total spin of the two light quarks. L denotes the total orbital angular momentum of charmed baryon system.

defined above, we use the hat and check to denote the charmed baryons with $l_\rho = 2$ and $l_\rho = 1$ respectively. For the baryons with $l_\rho = 1$ and $l_\lambda = 1$, we use the superscript L to denote the different total angular momentum in $\tilde{\Lambda}_{cJ_l}^L, \tilde{\Sigma}_{cJ_l}^L$ and $\tilde{\Xi}_{cJ_l}^L$.

III. THE 3P_0 MODEL

The 3P_0 model was first proposed by Micu [20] and further developed by Yaouanc et al. later [21, 22, 23]. Now this model is widely used to study the strong decays of hadrons [24, 25, 26, 27, 28, 29, 30, 31].

According to this model, a pair of quarks with $J^{PC} = 0^{++}$ is created from the vacuum when a hadron decays, which is shown in Fig. 4 for the baryon decay process $A \rightarrow B + C$. The new $q\bar{q}$ pair created from the vacuum together with the qqq within the the initial baryon regroup into the outgoing meson and baryon via the quark rearrangement process. In the non-relativistic limit, the transition operator is written as

$$T = -3\gamma \sum_m \langle 1 m; 1 -m | 0 0 \rangle \int d^3\mathbf{k}_4 d^3\mathbf{k}_5 \delta^3(\mathbf{k}_4 + \mathbf{k}_5) \times \mathcal{Y}_1^m\left(\frac{\mathbf{k}_4 - \mathbf{k}_5}{2}\right) \chi_{1,-m}^{45} \varphi_0^{45} \omega_0^{45} b_{4i}^\dagger(\mathbf{k}_4) d_{5j}^\dagger(\mathbf{k}_5) \quad (1)$$

where i and j are the color indices of the created quark and anti-quark. $\varphi_0^{45} = (u\bar{u} + d\bar{d} + s\bar{s})/\sqrt{3}$ and $\omega_0^{45} = \delta_{ij}$ for the flavor and color singlet respectively. $\chi_{1,-m}^{45}$ is for

(a) $l_\rho = 0, l_\lambda = 2$

$$f_S(6): L = 2 \otimes S_{q_1 q_2} = 1 \begin{cases} J_l = 1: \Sigma_{c1}(\frac{1}{2}^+, \frac{3}{2}^+) & \Xi'_{c1}(\frac{1}{2}^+, \frac{3}{2}^+) \\ J_l = 2: \Sigma_{c2}(\frac{3}{2}^+, \frac{5}{2}^+) & \Xi'_{c2}(\frac{3}{2}^+, \frac{5}{2}^+) \\ J_l = 3: \Sigma_{c3}(\frac{5}{2}^+, \frac{7}{2}^+) & \Xi'_{c3}(\frac{5}{2}^+, \frac{7}{2}^+) \end{cases}$$

$$f_A(\bar{3}): L = 2 \otimes S_{q_1 q_2} = 0 \implies J_l = 2: \Lambda_{c2}(\frac{3}{2}^+, \frac{5}{2}^+) \quad \Xi_{c2}(\frac{3}{2}^+, \frac{5}{2}^+)$$

(b) $l_\rho = 2, l_\lambda = 0$

$$f_S(6): L = 2 \otimes S_{q_1 q_2} = 1 \begin{cases} J_l = 1: \hat{\Sigma}_{c1}(\frac{1}{2}^+, \frac{3}{2}^+) & \hat{\Xi}'_{c1}(\frac{1}{2}^+, \frac{3}{2}^+) \\ J_l = 2: \hat{\Sigma}_{c2}(\frac{3}{2}^+, \frac{5}{2}^+) & \hat{\Xi}'_{c2}(\frac{3}{2}^+, \frac{5}{2}^+) \\ J_l = 3: \hat{\Sigma}_{c3}(\frac{5}{2}^+, \frac{7}{2}^+) & \hat{\Xi}'_{c3}(\frac{5}{2}^+, \frac{7}{2}^+) \end{cases}$$

$$f_A(\bar{3}): L = 2 \otimes S_{q_1 q_2} = 0 \implies J_l = 2: \hat{\Lambda}_{c2}(\frac{3}{2}^+, \frac{5}{2}^+) \quad \hat{\Xi}_{c2}(\frac{3}{2}^+, \frac{5}{2}^+)$$

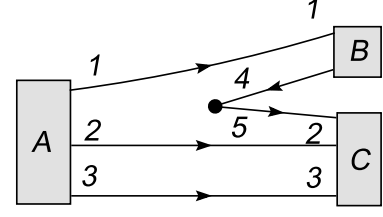
(c) $l_\rho = 1, l_\lambda = 1$

$$f_A(\bar{3}) \begin{cases} L = 1 \otimes S_{q_1 q_2} = 1 \begin{cases} J_l = 0: \tilde{\Lambda}_{c0}^1(\frac{1}{2}^+) & \tilde{\Xi}_{c0}^1(\frac{1}{2}^+) \\ J_l = 1: \tilde{\Lambda}_{c1}^1(\frac{1}{2}^+, \frac{3}{2}^+) & \tilde{\Xi}_{c1}^1(\frac{1}{2}^+, \frac{3}{2}^+) \\ J_l = 2: \tilde{\Lambda}_{c2}^1(\frac{3}{2}^+, \frac{5}{2}^+) & \tilde{\Xi}_{c2}^1(\frac{3}{2}^+, \frac{5}{2}^+) \end{cases} \\ L = 0 \otimes S_{q_1 q_2} = 1 \implies J_l = 1: \tilde{\Lambda}_{c1}^0(\frac{1}{2}^+, \frac{3}{2}^+) & \tilde{\Xi}_{c1}^0(\frac{1}{2}^+, \frac{3}{2}^+) \\ L = 2 \otimes S_{q_1 q_2} = 1 \begin{cases} J_l = 1: \tilde{\Lambda}_{c1}^2(\frac{1}{2}^+, \frac{3}{2}^+) & \tilde{\Xi}_{c1}^2(\frac{1}{2}^+, \frac{3}{2}^+) \\ J_l = 2: \tilde{\Lambda}_{c2}^2(\frac{3}{2}^+, \frac{5}{2}^+) & \tilde{\Xi}_{c2}^2(\frac{3}{2}^+, \frac{5}{2}^+) \\ J_l = 3: \tilde{\Lambda}_{c3}^2(\frac{5}{2}^+, \frac{7}{2}^+) & \tilde{\Xi}_{c3}^2(\frac{5}{2}^+, \frac{7}{2}^+) \end{cases} \end{cases}$$

$$f_S(6) \begin{cases} L = 0 \otimes S_{q_1 q_2} = 0 \implies J_l = 0: \tilde{\Sigma}_{c0}^0(\frac{1}{2}^+) & \tilde{\Xi}_{c0}^0(\frac{1}{2}^+) \\ L = 1 \otimes S_{q_1 q_2} = 0 \implies J_l = 1: \tilde{\Sigma}_{c1}^1(\frac{1}{2}^+, \frac{3}{2}^+) & \tilde{\Xi}_{c1}^1(\frac{1}{2}^+, \frac{3}{2}^+) \\ L = 2 \otimes S_{q_1 q_2} = 0 \implies J_l = 2: \tilde{\Sigma}_{c2}^2(\frac{3}{2}^+, \frac{5}{2}^+) & \tilde{\Xi}_{c2}^2(\frac{3}{2}^+, \frac{5}{2}^+) \end{cases}$$

FIG. 3: The notations for the D-wave charmed baryons.

the spin triplet state. $\mathcal{Y}_1^m(\mathbf{k}) \equiv |\mathbf{k}|Y_1^m(\theta_k, \phi_k)$ is a solid harmonic polynomial corresponding to the p-wave quark pair. γ is a dimensionless constant related to the strength of the quark pair creation from the vacuum, which was extracted by fitting to data. The hadron and meson state are defined as respectively according to the definition of

FIG. 4: The decay process of $A \rightarrow B + C$ in 3P_0 model.

mock state [32]

$$\begin{aligned} & |A(n_A {}^{2S_A+1} L_A J_A M_{J_A})(\mathbf{P}_A)\rangle \\ &= \sqrt{2E_A} \sum_{M_{L_A}, M_{S_A}} \langle L_A M_{L_A} S_A M_{S_A} | J_A M_{J_A} \rangle \\ &\quad \times \int d^3 \mathbf{k}_1 d^3 \mathbf{k}_2 d^3 \mathbf{k}_3 \delta^3(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3 - \mathbf{P}_A) \\ &\quad \times \psi_{n_A L_A M_{L_A}}(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3) \chi_{S_A M_{S_A}}^{123} \varphi_A^{123} \omega_A^{123} \\ &\quad \times |q_1(\mathbf{k}_1) q_2(\mathbf{k}_2) q_3(\mathbf{k}_3)\rangle, \end{aligned} \quad (2)$$

$$\begin{aligned} & |B(n_B {}^{2S_B+1} L_B J_B M_{J_B})(\mathbf{P}_B)\rangle \\ &= \sqrt{2E_B} \sum_{M_{L_B}, M_{S_B}} \langle L_B M_{L_B} S_B M_{S_B} | J_B M_{J_B} \rangle \\ &\quad \times \int d^3 \mathbf{k}_a d^3 \mathbf{k}_b \delta^3(\mathbf{k}_a + \mathbf{k}_b - \mathbf{P}_B) \psi_{n_B L_B M_{L_B}}(\mathbf{k}_a, \mathbf{k}_b) \\ &\quad \times \chi_{S_B M_{S_B}}^{ab} \varphi_B^{ab} \omega_B^{ab} |q_a(\mathbf{k}_a) \bar{q}_b(\mathbf{k}_b)\rangle \end{aligned} \quad (3)$$

and satisfy the normalization condition

$$\begin{aligned} \langle A(\mathbf{P}_A) | A(\mathbf{P}'_A) \rangle &= 2E_A \delta^3(\mathbf{P}_A - \mathbf{P}'_A), \\ \langle B(\mathbf{P}_B) | B(\mathbf{P}'_B) \rangle &= 2E_B \delta^3(\mathbf{P}_B - \mathbf{P}'_B). \end{aligned} \quad (4)$$

The subscripts 1, 2, 3 denote the quarks of parent hadron A. a and b refer to the quark and antiquark within the meson B respectively. $\mathbf{k}_i (i = 1, 2, 3)$ are the momentum of quarks in hadron A. \mathbf{k}_a and \mathbf{k}_b are the momentum of the quark and antiquark in meson B. $\mathbf{P}_{A(B)}$ represents the momentum of state A(B). $S_{A(B)}$ and $J_{A(B)}$ denote the total spin and the total angular momentum of state A(B).

The S-matrix is defined as

$$\langle f | S | i \rangle = I - i 2\pi \delta(E_f - E_i) \mathcal{M}^{M_{J_A} M_{J_B} M_{J_C}}. \quad (5)$$

The helicity amplitude of the process $A \rightarrow B + C$ in the

center of mass frame of meson A is

$$\begin{aligned}
& \mathcal{M}^{M_{J_A} M_{J_B} M_{J_C}}(A \rightarrow BC) \\
&= \sqrt{8E_A E_B E_C} \gamma \sum_{\substack{M_{L_A}, M_{S_A}, \\ M_{L_B}, M_{S_B}, \\ M_{L_C}, M_{S_C}, m}} \langle L_A M_{L_A} S_A M_{S_A} | J_A M_{J_A} \rangle \\
& \times \langle L_B M_{L_B} S_B M_{S_B} | J_B M_{J_B} \rangle \langle L_C M_{L_C} S_C M_{S_C} | J_C M_{J_C} \rangle \\
& \times \langle 1 m; 1 - m | 0 0 \rangle \langle \chi_{S_C M_{S_C}}^{235} \chi_{S_B M_{S_B}}^{14} | \chi_{S_A M_{S_A}}^{123} \chi_{1-m}^{45} \rangle \\
& \times \langle \varphi_C^{235} \varphi_B^{14} | \varphi_A^{123} \varphi_0^{45} \rangle I_{M_{L_B}, M_{L_C}}^{M_{L_A}, m}(\mathbf{p}) \quad (6)
\end{aligned}$$

where the spatial integral $I_{M_{L_B}, M_{L_C}}^{M_{L_A}, m}(\mathbf{p})$ is defined as

$$\begin{aligned}
& I_{M_{L_B}, M_{L_C}}^{M_{L_A}, m}(\mathbf{p}) \\
&= \int d^3 \mathbf{k}_1 d^3 \mathbf{k}_2 d^3 \mathbf{k}_3 d^3 \mathbf{k}_4 d^3 \mathbf{k}_5 \delta^3(\mathbf{k}_4 + \mathbf{k}_5) \\
& \times \delta^3(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3 - \mathbf{P}_A) \delta^3(\mathbf{k}_1 + \mathbf{k}_4 - \mathbf{P}_B) \\
& \times \delta^3(\mathbf{k}_2 + \mathbf{k}_3 + \mathbf{k}_5 - \mathbf{P}_C) \\
& \times \psi_{n_B L_B M_{L_B}}^*(\mathbf{k}_1, \mathbf{k}_4) \psi_{n_C L_C M_{L_C}}^*(\mathbf{k}_2, \mathbf{k}_3, \mathbf{k}_5) \\
& \times \psi_{n_A L_A M_{L_A}}(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3) \mathcal{Y}_1^m\left(\frac{\mathbf{k}_4 - \mathbf{k}_5}{2}\right). \quad (7)
\end{aligned}$$

$\langle \chi_{S_C M_{S_C}}^{235} \chi_{S_B M_{S_B}}^{14} | \chi_{S_A M_{S_A}}^{123} \chi_{1-m}^{45} \rangle$ and $\langle \varphi_C^{235} \varphi_B^{14} | \varphi_A^{123} \varphi_0^{45} \rangle$ denote the spin and flavor matrix element respectively.

The decay width of the process $A \rightarrow B + C$ is

$$\Gamma = \pi^2 \frac{|\mathbf{p}|}{M_A^2 2J_A + 1} \sum_{M_{J_A}, M_{J_B}, M_{J_C}} |\mathcal{M}^{M_{J_A} M_{J_B} M_{J_C}}|^2,$$

where $|\mathbf{p}|$ is the momentum of the daughter baryon in the parent's center of mass frame. $s = 1/(1 + \delta_{BC})$ is a statistical factor which is needed if B and C are identical particles.

IV. THE STRONG DECAYS OF CHARMED BARYON

According to the 3P_0 model, the decay occurs through the recombination of the five quarks from the initial charmed baryon and the created quark pair. So there are three ways of regrouping:

$$\mathcal{A}(q_1, q_2, c_3) + \mathcal{P}(q_4, \bar{q}_5) \rightarrow \mathcal{B}(q_2, q_4, c_3) + \mathcal{C}(q_1, \bar{q}_5), \quad (8)$$

$$\mathcal{A}(q_1, q_2, c_3) + \mathcal{P}(q_4, \bar{q}_5) \rightarrow \mathcal{B}(q_1, q_4, c_3) + \mathcal{C}(q_2, \bar{q}_5), \quad (9)$$

$$\mathcal{A}(q_1, q_2, c_3) + \mathcal{P}(q_4, \bar{q}_5) \rightarrow \mathcal{B}(q_1, q_2, q_4) + \mathcal{C}(c_3, \bar{q}_5) \quad (10)$$

where q_i and c_3 denote the light quark and charm quark respectively.

When the excited charmed baryon decays into a charmed baryon plus a light meson as shown in Eq. (8) and (9), the total decay amplitude reads

$$\begin{aligned}
& M^{M_{J_A} M_{J_B} M_{J_C}} \\
&= -2\gamma \sqrt{8E_A E_B E_C} \sum_{M_{\rho_A}} \sum_{M_{L_A}} \sum_{M_{\rho_B}} \sum_{M_{L_B}} \sum_{m_1, m_3, m_4, m} \\
& \times \langle J_{12} M_{12}; s_3 m_3 | J_A M_{J_A} \rangle \langle l_{\rho_A} m_{\rho_A}; l_{\lambda_A} m_{\lambda_A} | L_A M_{L_A} \rangle \langle L_A M_{L_A}; S_{12} m_{12} | J_{12} M_{12} \rangle \\
& \times \langle s_1 m_1; s_2 m_2 | S_{12} m_{12} \rangle \langle J_{14} M_{14}; s_3 m_3 | J_B M_{J_B} \rangle \langle l_{\rho_B} m_{\rho_B}; l_{\lambda_B} m_{\lambda_B} | L_B M_{L_B} \rangle \\
& \times \langle L_B M_{L_B}; S_{14} m_{14} | J_{14} M_{14} \rangle \langle s_1 m_1; s_4 m_4 | S_{14} m_{14} \rangle \langle 1 m; 1 - m | 00 \rangle \langle s_4 m_4; s_5 m_5 | 1 - m \rangle \\
& \times \langle L_C M_{L_C}; S_C M_C | J_C M_{J_C} \rangle \langle s_2 m_2; s_5 m_5 | S_C M_C \rangle \times \langle \phi_B^{1,4,3} \phi_C^{2,5} | \phi_0^{4,5} \phi_A^{1,2,3} \rangle \times I_{M_{L_B}, M_{L_C}}^{M_{L_A}, m}(\mathbf{p}), \quad (11)
\end{aligned}$$

where the pre-factor 2 in front of γ arises from the fact that the amplitude from the Eq. (8) is the same as that from Eq. (9).

The overlap integral in the momentum space is

$$\begin{aligned}
& I_{M_{L_B}, M_{L_C}}^{M_{L_A}, m}(\mathbf{p}) \\
&= \delta^3(\mathbf{P}_B - \mathbf{P}_C) \int d^3 \mathbf{p}_1 d^3 \mathbf{p}_2 \psi_B^*(l_{\rho_B}, m_{\rho_B}, l_{\lambda_B}, m_{\lambda_B}) \\
& \times \psi_C^*(L_C M_{L_C}) \mathcal{Y}_1^m\left(\frac{\mathbf{P}_4 - \mathbf{P}_5}{2}\right) \psi_A(l_{\rho_A}, m_{\rho_A}, l_{\lambda_A}, m_{\lambda_A}). \quad (12)
\end{aligned}$$

Since all hadrons in the final states are S-wave in this work, eq. (12) can be further expressed as

$$\begin{aligned}
& I_{M_{L_B}, M_{L_C}}^{M_{L_A}, m}(\mathbf{p}) \\
&= \delta^3(\mathbf{P}_B - \mathbf{P}_C) \Pi(l_{\rho_A}, m_{\rho_A}, l_{\lambda_A}, m_{\lambda_A}, m), \quad (13)
\end{aligned}$$

where we have used the harmonic oscillator wave functions for both the meson and baryon. The expressions of $\Pi(l_{\rho_A}, m_{\rho_A}, l_{\lambda_A}, m_{\lambda_A}, m)$ for the decays of S-wave, P-wave and D-wave charmed baryons are collected in the Appendix. We also move the lengthy expressions of mo-

momentum space integration of S-wave, P-wave and D-wave charmed baryons to the Appendix.

V. NUMERICAL RESULTS

The decay widths of charmed baryons from the 3P_0 model involve several parameters: the strength of quark pair creation from vacuum γ , the R value in the harmonic oscillator wave function of meson and the $\alpha_{\rho,\lambda}$ in the baryon wave functions. We follow the convention of Ref. [34] and take $\gamma = 13.4$, which is considered as a universal parameter in the 3P_0 model. The R value of π and K mesons is 2.1 GeV^{-1} [34] while it's $R = 2.3 \text{ GeV}^{-1}$ for the D meson [35]. $\alpha_{\rho} = \alpha_{\lambda} = 0.5 \text{ GeV}$ for the proton and Λ [31]. For S-wave charmed baryons, the parameters α_{ρ} and α_{λ} in the harmonic oscillator wave functions can be fixed to reproduce the mass splitting through the contact term in the potential model [33]. Their values are $\alpha_{\rho} = 0.6 \text{ GeV}$ and $\alpha_{\lambda} = 0.6 \text{ GeV}$. For P-wave and D-wave charmed baryons, α_{ρ} and α_{λ} are expected to lie in the range $0.5 \sim 0.7 \text{ GeV}$. In the following, our numerical results are obtained with the typical values $\alpha_{\rho} = \alpha_{\lambda} = 0.6 \text{ GeV}$.

The strong decay widths of the S-wave charmed baryons $\Sigma_c^{++,+0}(2455)$, $\Sigma_c^{*++,+0}(2520)$ and $\Xi_c^{*+,0}(2645)$ are listed in Table II. Accordingly the decay widths of S-wave bottomed baryons are presented in Table III. Because Ξ_b , Ξ'_b and Ξ_b^* have not been observed so far, their masses are taken from the theoretical estimate in Ref. [36], which are $m_{\Xi_b} = 5805.7 \text{ MeV}$, $m_{\Xi'_b} = 5950 \text{ MeV}$ and $m_{\Xi_b^*} = 5966.1 \text{ MeV}$.

The quantum number and internal structure of the following P-wave charmed baryons $\Lambda_c^+(2593)$, $\Lambda_c^+(2625)$, $\Xi_c^{+,0}(2790)$ and $\Xi_c^{+,0}(2815)$ are relatively known experimentally [13]. Their strong decay modes and widths from the 3P_0 model are collected in Table IV. The quantum number of $\Sigma_c^{++}(2800)$ is still unknown [13]. Thus under different P-wave assignments of $\Sigma_c^{++}(2800)$, we present the strong decay widths of its possible decay modes in Table V. In the heavy quark limit, the process $\Sigma_c^{++}(2800) \rightarrow \Lambda_c^+ \pi^+$ is forbidden if $\Sigma_c^{++}(2800)$ is assigned as $\Sigma_{c1}(\frac{1}{2}^-)$, $\Sigma_{c1}(\frac{3}{2}^-)$, $\tilde{\Sigma}_{c1}(\frac{1}{2}^-)$ and $\tilde{\Sigma}_{c1}(\frac{3}{2}^-)$, which is observed in our calculation as can be seen from Table V.

$\Lambda_c(2880)^+$ and $\Lambda_c(2940)^+$ are observed in the invariant mass spectrum of $D^0 p$ [1]. The first radial excitation of Λ_c does not decay into $D^0 p$ from the 3P_0 model. Hence the possibility of $\Lambda_c(2880)^+$ and $\Lambda_c(2940)^+$ being a radial excitation is excluded. We calculate their strong decays assuming they are D-wave charmed baryons. The results are shown in Table VI and VII.

With positive parity, $\Xi(2980)^{+,0}$ and $\Xi(3077)^{+,0}$ can be either the first radially excited charmed baryons or the D-wave charmed baryons. With different assumptions of their quantum numbers we present their strong decay widths in Table VIII, IX and Fig. 8.

The numerical results depend on the parameters α_{ρ}

and α_{λ} in the harmonic oscillator wave functions of the charmed baryons. We illustrate such a dependence in Figs. 5, 6 and 7 using several typical decay channels: $\Sigma_c^{++}(2455) \rightarrow \Lambda_c^+ \pi^+$, $\Lambda_c^+(2593) \rightarrow \Sigma_c^{++}(2455) \pi^-$ and $\Lambda_c^+(2880) \rightarrow \Sigma_c^{*++}(2520) \pi^-$, where $\Sigma_c^{++}(2455)$, $\Lambda_c^+(2593)$ and $\Lambda_c^+(2880)$ are S-wave, P-wave and D-wave baryons respectively.

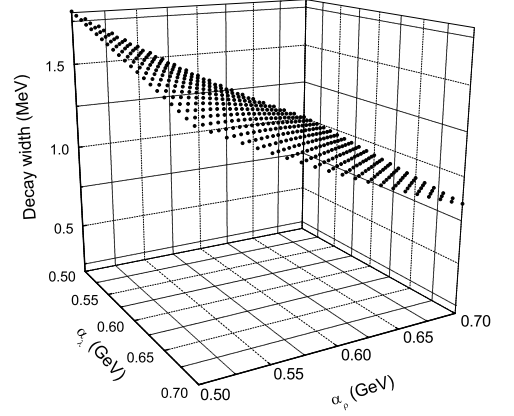


FIG. 5: The variation of the decay width of $\Sigma_c^{++}(2455) \rightarrow \Lambda_c^+ \pi^+$ with α_{ρ} and α_{λ} .

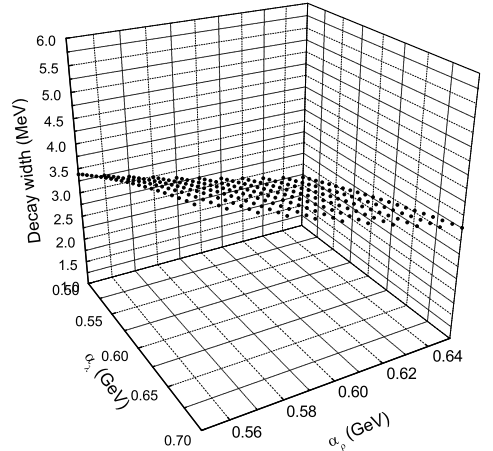


FIG. 6: The variation of decay width of $\Lambda_c^+(2593) \rightarrow \Sigma_c^{++}(2455) \pi^-$ with α_{ρ} and α_{λ} . Here $\Lambda_c^+(2593)$ is assigned as $\Lambda_{c1}(\frac{1}{2}^-)$.

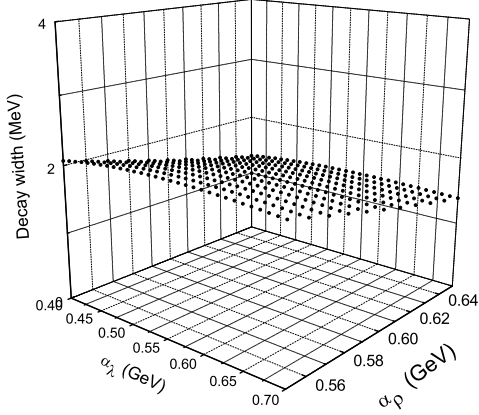


FIG. 7: The variation of decay width of $\Lambda_c^+(2880) \rightarrow \Sigma_c^{*++}(2520)\pi^-$ with α_ρ and α_λ . Here $\Lambda_c^+(2880)$ is assigned as $\Lambda_{c2}(\frac{5}{2}^+)$.

TABLE II: The strong decay widths of S-wave charmed baryons $\Sigma_c^{*++}(2455)$, $\Sigma_c^{*++}(2520)$ and $\Xi_c^{*+}(2645)$. Here all results are in units of MeV.

| | J^P | Channel | Width | Total width (Exp) [13] |
|------------------------|-----------------|--------------------|-------|------------------------|
| $\Sigma_c^{*++}(2455)$ | $\frac{1}{2}^+$ | $\Lambda_c^+\pi^+$ | 1.24 | 2.23 ± 0.30 |
| $\Sigma_c^+(2455)$ | $\frac{1}{2}^+$ | $\Lambda_c^+\pi^0$ | 1.40 | < 4.6 |
| $\Sigma_c^0(2455)$ | $\frac{1}{2}^+$ | $\Lambda_c^+\pi^-$ | 1.24 | 2.2 ± 0.40 |
| $\Sigma_c^{*++}(2520)$ | $\frac{3}{2}^+$ | $\Lambda_c^+\pi^+$ | 11.9 | 14.9 ± 1.9 |
| $\Sigma_c^{*+}(2520)$ | $\frac{3}{2}^+$ | $\Lambda_c^+\pi^0$ | 12.1 | < 17 |
| $\Sigma_c^{*0}(2520)$ | $\frac{3}{2}^+$ | $\Lambda_c^+\pi^-$ | 11.9 | 16.1 ± 2.1 |
| $\Xi_c^{*+}(2645)$ | $\frac{3}{2}^+$ | $\Xi_c^+\pi^0$ | 0.64 | < 3.1 |
| $\Xi_c^{*+}(2645)$ | $\frac{3}{2}^+$ | $\Xi_c^0\pi^+$ | 0.49 | |
| $\Xi_c^{*0}(2645)$ | $\frac{3}{2}^+$ | $\Xi_c^+\pi^-$ | 0.54 | < 5.5 |
| $\Xi_c^{*0}(2645)$ | $\frac{3}{2}^+$ | $\Xi_c^0\pi^0$ | 0.54 | |

VI. DISCUSSION AND CONCLUSION

At present it is still too difficult to calculate the strong decay widths of hadrons from the first principles of QCD. For this purpose, some phenomenological strong decay models were proposed such as the 3P_0 model, flux tube model, QCD sum rule, lattice QCD etc, among which only the first two approaches can be applied to the strong decays of excited hadrons. To a large extent, the predictions from the 3P_0 and flux tube models roughly agree with each other.

TABLE III: The strong decay widths of S-wave bottom baryons Σ_b , Σ_b^* , Ξ_b^* and Ξ_b^* . Here all results are in units of MeV.

| | J^P | Channel | Width | Experimental results [14] |
|-----------------|-----------------|--------------------|-------|---------------------------|
| Σ_b^+ | $\frac{1}{2}^+$ | $\Lambda_b^0\pi^+$ | 3.5 | ~ 8 |
| Σ_b^- | $\frac{1}{2}^+$ | $\Lambda_b^0\pi^-$ | 4.7 | |
| Σ_b^{*+} | $\frac{3}{2}^+$ | $\Lambda_b^0\pi^+$ | 7.5 | ~ 15 |
| Σ_b^{*-} | $\frac{3}{2}^+$ | $\Lambda_b^0\pi^-$ | 9.2 | |
| $\Xi_b^{'}$ | $\frac{1}{2}^+$ | $\Xi_b\pi$ | 0.10 | - |
| Ξ_b^* | $\frac{3}{2}^+$ | $\Xi_b\pi$ | 0.85 | - |

TABLE IV: The decay widths of P-wave charmed baryons $\Lambda_c^+(2593, 2625)$ and $\Xi_c^{*+}(2790, 2815)$ with the fixed structure and quantum number assignments. Here all results are in units of MeV.

| | Assignment | Channel | Γ | Γ_{Exp} [13] |
|---------------------|-------------------------------|-------------------------|----------------------|---------------------|
| $\Lambda_c^+(2593)$ | $\Lambda_{c1}(\frac{1}{2}^-)$ | $\Sigma_c^{*+}\pi^-$ | 3.4 | $3.6^{+2.0}_{-1.3}$ |
| | | $\Sigma_c^+\pi^0$ | 6.4 | |
| | | $\Sigma_c^0\pi^+$ | 3.4 | |
| $\Lambda_c^+(2625)$ | $\Lambda_{c1}(\frac{3}{2}^-)$ | $\Sigma_c^{*+}\pi^-$ | 1.9×10^{-3} | < 0.10 |
| | | $\Sigma_c^+\pi^0$ | 2.6×10^{-3} | < 1.9 |
| | | $\Sigma_c^0\pi^+$ | 1.9×10^{-3} | < 0.10 |
| $\Xi_c^+(2790)$ | $\Xi_{c1}(\frac{1}{2}^-)$ | $\Xi_c^{*+}\pi^0$ | 5.0 | < 15 |
| | | $\Xi_c^{\prime 0}\pi^+$ | 4.9 | |
| $\Xi_c^0(2790)$ | $\Xi_{c1}(\frac{1}{2}^-)$ | $\Xi_c^{*+}\pi^-$ | 5.2 | < 12 |
| | | $\Xi_c^{\prime 0}\pi^0$ | 5.1 | |
| $\Xi_c^+(2815)$ | $\Xi_{c1}(\frac{3}{2}^-)$ | $\Xi_c^{*+}\pi^0$ | 2.7 | < 3.5 |
| | | $\Xi_c^{*0}\pi^+$ | 2.6 | |
| $\Xi_c^0(2815)$ | $\Xi_{c1}(\frac{3}{2}^-)$ | $\Xi_c^{*+}\pi^-$ | 2.7 | < 6.5 |
| | | $\Xi_c^{*0}\pi^0$ | 2.8 | |

The 3P_0 model possesses inherent uncertainties [21, 29, 34]. In certain cases, the result from the 3P_0 model may be a factor of $2 \sim 3$ off the experimental width. The uncertainty source of the 3P_0 model arises from the strength of the quark pair creation from the vacuum γ , the approximation of non-relativity, and assuming the simple harmonic oscillator radial wave functions for the hadrons. Even with the above uncertainty, the 3P_0 model is still the most systematic, effective and widely used framework to study the hadron strong decays.

In this work, we have calculated the strong decay widths of charmed baryons using the 3P_0 model. Our numerical results do not strongly depend on the parameters α_ρ and α_λ as shown in Figs. 5, 6 and 7. Thus the following qualitative features and conclusions remain essentially unchanged with reasonable variations of α_ρ and α_λ .

Our results for the S-wave charmed baryons $\Sigma_c^{*++}(2455)$, $\Sigma_c^{*++}(2520)$ and $\Xi_c^{*+}(2645)$ are roughly consistent with experimental data within the inherent uncertainty of the 3P_0 model. As a byproduct, we have also calculated the strong decays of Σ_b^\pm and $\Sigma_b^{\pm\pm}$.

TABLE V: The decay widths of $\Sigma_c^{++}(2800)$ in different P-wave charmed baryons assignments. $\mathcal{R} = \Sigma_c^{+,++}\pi^{+,0}/\Sigma_c^{*,++}\pi^{+,0}$. The total width of $\Sigma_c^{++}(2800)$ is 75_{-17}^{+22} MeV [13]. Here all results are in units of MeV.

| Assignment | $\Lambda_c^+\pi^+$ | $\Sigma_c^{+,++}\pi^{+,0}$ | $\Sigma_c^{*,++}\pi^{+,0}$ | \mathcal{R} |
|--------------------------------------|--------------------|----------------------------|----------------------------|--------------------|
| $\Sigma_{c0}(\frac{1}{2}^-)$ | 307 | 0.0 | 0.0 | - |
| $\Sigma_{c1}(\frac{1}{2}^-)$ | 0.0 | 296 | 0.4 | 740 |
| $\Sigma_{c1}(\frac{3}{2}^-)$ | 0.0 | 0.7 | 220 | 3×10^{-3} |
| $\Sigma_{c2}(\frac{3}{2}^-)$ | 8.1 | 1.3 | 0.3 | 4.3 |
| $\Sigma_{c2}(\frac{5}{2}^-)$ | 8.1 | 0.6 | 0.5 | 1.2 |
| $\tilde{\Sigma}_{c1}(\frac{1}{2}^-)$ | 0.0 | 75 | 69 | 1.1 |
| $\tilde{\Sigma}_{c1}(\frac{3}{2}^-)$ | 0.0 | 75 | 69 | 1.1 |

observed by CDF Collaboration recently. The numerical results are consistent with the experimental values too.

The decay width of P-wave baryon $\Lambda_c^+(2593)$ is three times larger than the experimental value. With the large experimental uncertainty and the inherent theoretical uncertainty of the 3P_0 model, such a deviation is still acceptable. The decay widths of $\Lambda_c^+(2625)$ and $\Xi_c^{+,0}(2790, 2815)$ are compatible with the experimental upper bound. By comparing our results with the experimental total width, we tend to exclude the $\Sigma_{c0}(\frac{1}{2}^-)$ assignment for $\Sigma_c^{++}(2800)$. Since the $\Sigma_c^{++}(2800)$ is observed in $\Lambda_c^+\pi^+$ channel [37], there are only two assignments left for $\Sigma_c^{++}(2800)$, i.e. $\Sigma_{c2}(\frac{3}{2}^-)$ or $\Sigma_{c2}(\frac{5}{2}^-)$. More experimental information such as the ratio $\frac{\Gamma[\Sigma_c^{++}(2800) \rightarrow \Sigma_c^{+,++}\pi^{+,0}]}{\Gamma[\Sigma_c^{++}(2800) \rightarrow \Sigma_c^{*,++}\pi^{+,0}]}$ will be helpful in the determination of the quantum number of $\Sigma_c^{++}(2800)$.

We have also calculated the strong decay widths of newly observed $\Lambda_c(2880, 2940)^+$, $\Xi(2980, 3077)^{+,0}$ assuming they are candidates of D-wave charmed baryons. We find that the only possible assignment of $\Lambda_c(2880)^+$ is $\tilde{\Lambda}_{c3}^2(\frac{5}{2}^+)$ after considering both its total decay width and the ratio $\Gamma(\Sigma_c^*\pi^\pm)/\Gamma(\Sigma_c\pi^\pm)$, which agrees very well with the indication from Belle experiment that $\Lambda_c(2880)^+$ favors $J^P = \frac{5}{2}^+$ by the analysis of the angular distribution [2].

Unfortunately the experiment information about the $\Lambda_c(2940)^+$, $\Xi(2980, 3077)^{+,0}$ is scarce at present. From their calculated decay widths, we can only exclude some assignments which are marked with crosses in Tables VII, VIII and IX. The decay width ratios of $\Lambda_c(2940)^+$, $\Xi(2980, 3077)^{+,0}$ from the 3P_0 model will be useful in the identification of their quantum numbers in the future since the inherent uncertainty cancels largely.

We have also discussed the strong decays of $\Xi(2980, 3077)^{+,0}$ assuming they are radial excitations. Unfortunately the numerical results in Fig. 8 depend quite strongly on the node of the spatial wave function which is related to the parameters of the harmonic oscillator wave functions as shown in Fig. 8. We are unable to make strong conclusions here.

Appendix

A. The harmonic oscillator wave functions used in our calculation

For the S-wave charmed baryon,

$$\psi(0, 0, 0) = 3^{3/4} \left(\frac{1}{\pi\alpha_\rho^2}\right)^{3/4} \left(\frac{1}{\pi\alpha_\lambda^2}\right)^{3/4} \exp\left[-\frac{\mathbf{p}_\rho^2}{2\alpha_\rho^2} - \frac{\mathbf{p}_\lambda^2}{2\alpha_\lambda^2}\right]. \quad (14)$$

For the P-wave charmed baryon,

$$\begin{aligned} \psi(1, m, 0) = & -i 3^{3/4} \left(\frac{8}{3\sqrt{\pi}}\right)^{1/2} \left(1/\alpha_\rho^2\right)^{5/4} \mathcal{Y}_1^m(\mathbf{p}_\rho) \\ & \times \left(\frac{1}{\pi\alpha_\lambda^2}\right)^{3/4} \exp\left[-\frac{\mathbf{p}_\rho^2}{2\alpha_\rho^2} - \frac{\mathbf{p}_\lambda^2}{2\alpha_\lambda^2}\right], \end{aligned} \quad (15)$$

$$\begin{aligned} \psi(0, 0, 1, m) = & -i 3^{3/4} \left(\frac{8}{3\sqrt{\pi}}\right)^{1/2} \left(\frac{1}{\alpha_\lambda^2}\right)^{5/4} \mathcal{Y}_1^m(\mathbf{p}_\lambda) \\ & \times \left(\frac{1}{\pi\alpha_\rho^2}\right)^{3/4} \exp\left[-\frac{\mathbf{p}_\rho^2}{2\alpha_\rho^2} - \frac{\mathbf{p}_\lambda^2}{2\alpha_\lambda^2}\right]. \end{aligned} \quad (16)$$

For the D-wave charmed baryon,

$$\begin{aligned} \psi(2, m, 0, 0) = & 3^{3/4} \left(\frac{16}{15\sqrt{\pi}}\right)^{1/2} \left(\frac{1}{\alpha_\rho^2}\right)^{7/4} \mathcal{Y}_2^m(\mathbf{p}_\rho) \\ & \times \left(\frac{1}{\pi\alpha_\lambda^2}\right)^{3/4} \exp\left[-\frac{\mathbf{p}_\rho^2}{2\alpha_\rho^2} - \frac{\mathbf{p}_\lambda^2}{2\alpha_\lambda^2}\right], \end{aligned} \quad (17)$$

$$\begin{aligned} \psi(0, 0, 2, m) = & 3^{3/4} \left(\frac{16}{15\sqrt{\pi}}\right)^{1/2} \left(\frac{1}{\alpha_\lambda^2}\right)^{7/4} \mathcal{Y}_2^m(\mathbf{p}_\lambda) \\ & \times \left(\frac{1}{\pi\alpha_\rho^2}\right)^{3/4} \exp\left[-\frac{\mathbf{p}_\rho^2}{2\alpha_\rho^2} - \frac{\mathbf{p}_\lambda^2}{2\alpha_\lambda^2}\right], \end{aligned} \quad (18)$$

$$\begin{aligned} \psi(1, m, 1, m') = & -3^{3/4} \left(\frac{8}{3\sqrt{\pi}}\right)^{1/2} \left(\frac{1}{\alpha_\rho^2}\right)^{5/4} \mathcal{Y}_1^m(\mathbf{p}_\rho) \\ & \times \left(\frac{8}{3\sqrt{\pi}}\right)^{1/2} \left(\frac{1}{\alpha_\lambda^2}\right)^{5/4} \mathcal{Y}_1^{m'}(\mathbf{p}_\lambda) \\ & \times \exp\left[-\frac{\mathbf{p}_\rho^2}{2\alpha_\rho^2} - \frac{\mathbf{p}_\lambda^2}{2\alpha_\lambda^2}\right]. \end{aligned} \quad (19)$$

Here $\mathcal{Y}_l^m(\mathbf{p})$ is the solid harmonic polynomial.

The ground state wave function of meson is

$$\psi(0, 0) = \left(\frac{R^2}{\pi}\right)^{3/4} \exp\left[-\frac{R^2(\mathbf{p}_2 - \mathbf{p}_5)^2}{8}\right]. \quad (20)$$

The the wave function of the first radially excited charmed baryon $\psi(n_\rho, n_\lambda)$ reads as

$$\begin{aligned} \psi(1, 0) &= 3^{3/4} \sqrt{\frac{2}{3}} \left(\frac{1}{\pi^2\alpha_\rho\alpha_\lambda}\right)^{3/2} \left[\frac{3}{2} - \frac{\mathbf{p}_\rho^2}{\alpha_\rho^2}\right] \exp\left[-\frac{\mathbf{p}_\rho^2}{2\alpha_\rho^2} - \frac{\mathbf{p}_\lambda^2}{2\alpha_\lambda^2}\right], \\ \psi(0, 1) &= 3^{3/4} \sqrt{\frac{2}{3}} \left(\frac{1}{\pi^2\alpha_\rho\alpha_\lambda}\right)^{3/2} \left[\frac{3}{2} - \frac{\mathbf{p}_\lambda^2}{\alpha_\lambda^2}\right] \exp\left[-\frac{\mathbf{p}_\rho^2}{2\alpha_\rho^2} - \frac{\mathbf{p}_\lambda^2}{2\alpha_\lambda^2}\right], \end{aligned}$$

where n_ρ and n_λ denote the radial quantum number between the two light quarks and between heavy quark and the two light quarks respectively. Here $\mathbf{p}_\rho = \sqrt{\frac{1}{2}}(\mathbf{p}_1 - \mathbf{p}_2)$ and $\mathbf{p}_\lambda = \sqrt{\frac{1}{6}}(\mathbf{p}_1 + \mathbf{p}_2 - 2\mathbf{p}_3)$ for the above expressions. All the above harmonic oscillator wave functions can be normalized as $\int d\mathbf{p}_1 d\mathbf{p}_2 d\mathbf{p}_3 |\psi|^2 = 1$.

B. The momentum space integration

The momentum space integration $\Pi(l_{\rho A}, m_{\rho A}, l_{\lambda A}, m_{\lambda A}, m)$ includes:

For the S-wave charmed baryon decay,

$$\Pi(0, 0, 0, 0, 0) = \beta |\mathbf{p}| \Delta_{0,0}. \quad (21)$$

For the P-wave charmed baryon decay,

$$\Pi(0, 0, 1, 0, 0) = \frac{1}{2f_1} [f_2 \beta |\mathbf{p}|^2 - \zeta] \Delta_{0,1},$$

$$\Pi(0, 0, 1, 1, -1) = \Pi(0, 0, 1, -1, 1) = \frac{\zeta}{2f_1} \Delta_{0,1},$$

$$\Pi(1, 0, 0, 0, 0) = \left[\beta \varpi |\mathbf{p}|^2 + \frac{1}{2\sqrt{2}\lambda_1} + \frac{\lambda_2 \zeta}{4\lambda_1 f_1} \right] \Delta_{1,0},$$

$$\Pi(1, 1, 0, 0, -1) = \Pi(1, -1, 0, 0, 1) = \beta \varpi |\mathbf{p}|^2 \Delta_{1,0}.$$

For the D-wave charmed baryon decay,

$$\Pi(0, 0, 2, 0, 0) = -\frac{f_2}{f_1^2} \left[\frac{f_2}{2} \beta |\mathbf{p}|^3 + \zeta |\mathbf{p}| \right] \times \Delta_{0,2},$$

$$\Pi(0, 0, 2, 1, -1) = \Pi(0, 0, 2, -1, 1) = \frac{\sqrt{3}\zeta f_2}{2f_1^2} |\mathbf{p}| \Delta_{0,2},$$

$$\Pi(2, 0, 0, 0, 0) = -2 \left[(\beta \varpi^2 |\mathbf{p}|^3 + \frac{1}{\sqrt{2}\lambda_1} \varpi |\mathbf{p}| + \frac{\lambda_2}{2\lambda_1 f_1} \zeta \varpi) \right] \Delta_{2,0},$$

$$\Pi(2, 1, 0, 0, -1) = \Pi(2, -1, 0, 0, 1) = \left[\left(\frac{1}{\sqrt{2}\lambda_1} + \frac{\lambda_2}{2\lambda_1 f_1} \zeta \right) \right] \Delta_{2,0},$$

$$\Pi(1, 0, 1, 0, 0) = \left[\frac{f_2}{2f_1} \beta \varpi |\mathbf{p}|^3 + \frac{1}{2f_1} \left(\frac{\lambda_2 \zeta}{2\lambda_1} \beta + \zeta \varpi + \frac{\lambda_2 f_2}{4\lambda_1 f_1} \right) |\mathbf{p}| + \frac{f_2}{4\sqrt{2}\lambda_1 f_1} |\mathbf{p}| \right] \Delta_{1,1},$$

$$\Pi(1, 1, 1, -1, 0) = \Pi(1, -1, 1, 1, 0) = \left[\frac{\lambda_2}{4\lambda_1 f_1} \beta |\mathbf{p}| \right] \Delta_{1,1},$$

$$\Pi(1, 0, 1, 1, -1) = \Pi(1, 0, 1, -1, 1) = \left[\frac{1}{2f_1} \varpi \zeta |\mathbf{p}| \right] \Delta_{1,1},$$

$$\Pi(1, 1, 1, 0, -1) = \Pi(1, -1, 1, 0, 1) = \left[\left(\frac{1}{2\sqrt{2}\lambda_1} + \frac{\lambda_2}{4\lambda_1 f_1} \zeta \right) \times \frac{f_2}{2f_1} |\mathbf{p}| \right] \Delta_{1,1}.$$

For the strong decay of the radial excitation, the mo-

mentum space integrals denoted as $\Pi(n_\rho, n_\lambda)$ are:

$$\Pi(0, 1) = \sqrt{\frac{2}{3}} \left[-\frac{\beta f_2^2}{4\alpha_\lambda^2 f_1^2} k^3 + \frac{3\beta}{2} k - \frac{3\beta}{2f_1 \alpha_\lambda^2} k + \frac{f_2 \zeta}{2f_1^2 \alpha_\lambda^2} k \right] \Delta_{0,0},$$

$$\Pi(1, 0) = \sqrt{\frac{2}{3}} \left[\frac{1}{\alpha_\rho^2} (\beta \varpi^2 k^3 - \frac{3\beta \alpha_\rho^2}{2} k + \frac{3\beta}{2\lambda_1} k - \frac{\sqrt{2}\varpi}{2\lambda_1} k - \frac{\lambda_2 \varpi \zeta}{3\lambda_1} k + \frac{\lambda_2^2}{4\lambda_1^2}) \right] \Delta_{0,0}.$$

where

$$\begin{aligned} \lambda_1 &= \frac{1}{\alpha_\rho^2} + \frac{1}{4} R^2, \quad \lambda_2 = -\frac{1}{2\sqrt{3}} R^2, \\ \lambda_3 &= \frac{1}{\alpha_\lambda^2} + \frac{1}{12} R^2, \quad \lambda_4 = \frac{1}{\sqrt{2}\alpha_\rho^2} + \frac{1}{2\sqrt{2}} R^2, \\ \lambda_5 &= -\left(\frac{1}{\sqrt{6}\alpha_\lambda^2} + \frac{1}{2\sqrt{6}} R^2 \right), \\ \lambda_6 &= \frac{1}{4\alpha_\rho^2} + \frac{1}{12\alpha_\lambda^2} + \frac{1}{8} R^2, \\ f_1 &= \lambda_3 - \frac{\lambda_2^2}{4\lambda_1}, \quad f_2 = \lambda_5 - \frac{2\lambda_2 \lambda_4}{4\lambda_1}, \\ f_3 &= \lambda_6 - \frac{\lambda_4^2}{4\lambda_1}, \quad \zeta = \frac{\lambda_2}{2\sqrt{2}\lambda_1} + \frac{1}{\sqrt{6}}, \\ \varpi &= \frac{\lambda_2 f_2}{4\lambda_1 f_1} - \frac{\lambda_4}{2\lambda_1}, \\ \beta &= \left(1 + \frac{\sqrt{3}\lambda_2 f_2 - 2\sqrt{3}\lambda_4 f_1 + 2\lambda_1 f_2}{4\sqrt{6}\lambda_1 f_1} \right), \end{aligned}$$

and

$$\begin{aligned} \Delta_{0,0} &= \left(\frac{1}{\pi \alpha_\rho^2} \right)^{\frac{3}{4}} \left(\frac{1}{\pi \alpha_\lambda^2} \right)^{\frac{3}{4}} \left(\frac{R^2}{\pi} \right)^{\frac{3}{4}} \left(\frac{\pi^2}{\lambda_1 f_1} \right)^{\frac{3}{2}} \\ &\times \exp \left[-\left(f_3 - \frac{f_2^2}{4f_1} \right) |\mathbf{p}|^2 \right] \\ &\times \left[-\sqrt{\frac{3}{4\pi}} \left(\frac{1}{\pi \alpha_\rho^2} \right)^{\frac{3}{4}} \left(\frac{1}{\pi \alpha_\lambda^2} \right)^{\frac{3}{4}} \right], \end{aligned}$$

$$\begin{aligned} \Delta_{0,1} &= \left(\frac{1}{\pi \alpha_\rho^2} \right)^{\frac{3}{4}} \left(\frac{1}{\pi \alpha_\lambda^2} \right)^{\frac{3}{4}} \left(\frac{R^2}{\pi} \right)^{\frac{3}{4}} \left(\frac{\pi^2}{\lambda_1 f_1} \right)^{\frac{3}{2}} \\ &\exp \left[-\left(f_3 - \frac{f_2^2}{4f_1} \right) |\mathbf{p}|^2 \right] \\ &\times \left[\frac{3i}{4\pi} \left(\frac{1}{\pi \alpha_\rho^2} \right)^{\frac{3}{4}} \left(\frac{8}{3\sqrt{\pi}} \right)^{\frac{1}{2}} \left(\frac{1}{\alpha_\lambda^2} \right)^{\frac{5}{4}} \right], \end{aligned}$$

$$\Delta_{1,0} = \left(\frac{1}{\pi\alpha_\rho^2}\right)^{\frac{3}{4}} \left(\frac{1}{\pi\alpha_\lambda^2}\right)^{\frac{3}{4}} \left(\frac{R^2}{\pi}\right)^{\frac{3}{4}} \left(\frac{\pi^2}{\lambda_1 f_1}\right)^{\frac{3}{2}} \\ \exp \left[- \left(f_3 - \frac{f_2^2}{4f_1}\right) |\mathbf{p}|^2 \right] \\ \times \left[\frac{3i}{4\pi} \left(\frac{8}{3\sqrt{\pi}}\right)^{\frac{1}{2}} \left(\frac{1}{\alpha_\rho^2}\right)^{\frac{5}{4}} \left(\frac{1}{\pi\alpha_\lambda^2}\right)^{\frac{3}{4}} \right],$$

$$\Delta_{0,2} = \left(\frac{1}{\pi\alpha_\rho^2}\right)^{\frac{3}{4}} \left(\frac{1}{\pi\alpha_\lambda^2}\right)^{\frac{3}{4}} \left(\frac{R^2}{\pi}\right)^{\frac{3}{4}} \left(\frac{\pi^2}{\lambda_1 f_1}\right)^{\frac{3}{2}} \\ \exp \left[- \left(f_3 - \frac{f_2^2}{4f_1}\right) |\mathbf{p}|^2 \right] \\ \times \left[\frac{\sqrt{15}}{8\pi} \left(\frac{1}{\pi\alpha_\rho^2}\right)^{\frac{3}{4}} \left(\frac{16}{15\sqrt{\pi}}\right)^{\frac{1}{2}} \left(\frac{1}{\alpha_\lambda^2}\right)^{\frac{7}{4}} \right],$$

$$\Delta_{2,0} = \left(\frac{1}{\pi\alpha_\rho^2}\right)^{\frac{3}{4}} \left(\frac{1}{\pi\alpha_\lambda^2}\right)^{\frac{3}{4}} \left(\frac{R^2}{\pi}\right)^{\frac{3}{4}} \left(\frac{\pi^2}{\lambda_1 f_1}\right)^{\frac{3}{2}} \\ \exp \left[- \left(f_3 - \frac{f_2^2}{4f_1}\right) |\mathbf{p}|^2 \right] \\ \times \left[\frac{\sqrt{15}}{8\pi} \left(\frac{16}{15\sqrt{\pi}}\right)^{\frac{1}{2}} \left(\frac{1}{\alpha_\rho^2}\right)^{\frac{7}{4}} \left(\frac{1}{\pi\alpha_\lambda^2}\right)^{\frac{3}{4}} \right],$$

$$\Delta_{1,1} = \left(\frac{1}{\pi\alpha_\rho^2}\right)^{\frac{3}{4}} \left(\frac{1}{\pi\alpha_\lambda^2}\right)^{\frac{3}{4}} \left(\frac{R^2}{\pi}\right)^{\frac{3}{4}} \left(\frac{\pi^2}{\lambda_1 f_1}\right)^{\frac{3}{2}} \\ \exp \left[- \left(f_3 - \frac{f_2^2}{4f_1}\right) |\mathbf{p}|^2 \right] \\ \times \left[- \left(\frac{3}{4\pi}\right)^{\frac{3}{2}} \frac{8}{3\sqrt{\pi}} \left(\frac{1}{\alpha_\lambda^2 \alpha_\rho^2}\right)^{\frac{5}{4}} \right].$$

In the above expressions, $|\mathbf{p}|$ reads as

$$|\mathbf{p}| = \frac{\sqrt{(m_A^2 - (m_B + m_C)^2)(m_A^2 - (m_B - m_C)^2)}}{2m_A}.$$

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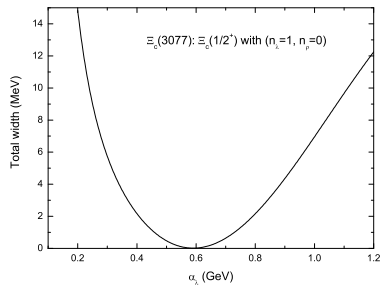
TABLE VI: The decay widths of $\Lambda_c^+(2880)$ with different D-wave assignments. All results are in units of MeV.

| Assignment | $\Sigma_c^{0,+,++}\pi^{+,0,-}$ | $\Sigma_c^{*0,+,++}\pi^{+,0,-}$ | $\frac{\Gamma(\Sigma_c^*\pi^\pm)}{\Gamma(\Sigma_c\pi^\pm)}$ | D^0p | Remark |
|---|--------------------------------|---------------------------------|---|--------|--------|
| $\Lambda_{c2}(\frac{3}{2}^+)$ | 7.8 | 0.9 | 0.11 | 0.0 | × |
| $\Lambda_{c2}(\frac{5}{2}^+)$ | 0.06 | 5.34 | 89 | 0.0 | × |
| $\tilde{\Lambda}_{c2}(\frac{3}{2}^+)$ | 78.3 | 59.1 | 0.75 | 0.0 | × |
| $\tilde{\Lambda}_{c2}(\frac{5}{2}^+)$ | 78.3 | 59.1 | 0.75 | 0.0 | × |
| $\tilde{\Lambda}_{c1}^0(\frac{1}{2}^+)$ | 0.9 | 2.3 | 2.6 | 2.3 | × |
| $\tilde{\Lambda}_{c1}^0(\frac{3}{2}^+)$ | 0.22 | 6.0 | 27 | 2.3 | × |
| $\tilde{\Lambda}_{c0}^1(\frac{1}{2}^+)$ | 132 | 144 | 1.1 | 0.0 | × |
| $\tilde{\Lambda}_{c1}^1(\frac{1}{2}^+)$ | 66.3 | 18.0 | 0.27 | 150 | × |
| $\tilde{\Lambda}_{c1}^1(\frac{3}{2}^+)$ | 16.5 | 45.0 | 2.7 | 150 | × |
| $\tilde{\Lambda}_{c2}^1(\frac{3}{2}^+)$ | 82.8 | 9.0 | 0.10 | 0.0 | × |
| $\tilde{\Lambda}_{c2}^1(\frac{5}{2}^+)$ | 0.0 | 54.1 | — | 0.0 | × |
| $\tilde{\Lambda}_{c1}^2(\frac{1}{2}^+)$ | 25.7 | 8.1 | 0.32 | 64 | × |
| $\tilde{\Lambda}_{c1}^2(\frac{3}{2}^+)$ | 6.5 | 20.4 | 3.1 | 64 | × |
| $\tilde{\Lambda}_{c2}^2(\frac{3}{2}^+)$ | 57.9 | 14.2 | 0.24 | 0.0 | × |
| $\tilde{\Lambda}_{c2}^2(\frac{5}{2}^+)$ | 9.4 | 47.1 | 5.0 | 0.0 | × |
| $\tilde{\Lambda}_{c3}^2(\frac{5}{2}^+)$ | 10.8 | 5.5 | 0.51 | 12 | × |
| $\tilde{\Lambda}_{c3}^2(\frac{7}{2}^+)$ | 6.1 | 7.4 | 1.2 | 12 | × |

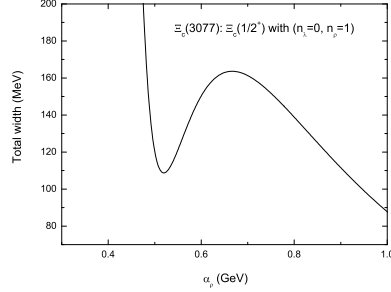
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TABLE VII: The decay widths of $\Lambda_c^+(2940)$ with different D-wave assignments. Here all results are in units of MeV.

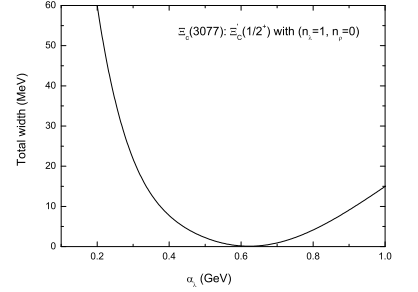
| Assignment | $\Sigma_c^{0,+,++}\pi^{+,0,-}$ | $\Sigma_c^{*0,+,++}\pi^{+,0,-}$ | $\frac{\Gamma(\Sigma_c^*\pi^\pm)}{\Gamma(\Sigma_c\pi^\pm)}$ | D^0p | Remark |
|---|--------------------------------|---------------------------------|---|--------|--------|
| $\Lambda_{c2}(\frac{3}{2}^+)$ | 11.7 | 9.1 | 0.77 | 0.0 | × |
| $\Lambda_{c2}(\frac{5}{2}^+)$ | 0.2 | 9.1 | 46 | 0.0 | × |
| $\tilde{\Lambda}_{c2}(\frac{3}{2}^+)$ | 170 | 150 | 0.88 | 0.0 | × |
| $\tilde{\Lambda}_{c2}(\frac{5}{2}^+)$ | 170 | 150 | 0.88 | 0.0 | × |
| $\tilde{\Lambda}_{c1}^0(\frac{1}{2}^+)$ | 2.2 | 0.5 | 0.23 | 11 | |
| $\tilde{\Lambda}_{c1}^0(\frac{3}{2}^+)$ | 0.6 | 1.4 | 2.3 | 11 | |
| $\tilde{\Lambda}_{c0}^1(\frac{1}{2}^+)$ | 212 | 259 | 1.2 | 0.0 | × |
| $\tilde{\Lambda}_{c1}^1(\frac{1}{2}^+)$ | 106 | 32.4 | 0.31 | 340 | × |
| $\tilde{\Lambda}_{c1}^1(\frac{3}{2}^+)$ | 26.5 | 81.0 | 3.1 | 340 | × |
| $\tilde{\Lambda}_{c2}^1(\frac{3}{2}^+)$ | 142 | 16.2 | 0.11 | 0.0 | × |
| $\tilde{\Lambda}_{c2}^1(\frac{5}{2}^+)$ | 0.0 | 97.0 | — | 0.0 | × |
| $\tilde{\Lambda}_{c1}^2(\frac{1}{2}^+)$ | 34.5 | 12.6 | 0.37 | 95 | × |
| $\tilde{\Lambda}_{c1}^2(\frac{3}{2}^+)$ | 8.6 | 31.7 | 3.7 | 95 | × |
| $\tilde{\Lambda}_{c2}^2(\frac{3}{2}^+)$ | 77.7 | 27.7 | 0.36 | 0.0 | × |
| $\tilde{\Lambda}_{c2}^2(\frac{5}{2}^+)$ | 19.5 | 75.6 | 3.9 | 0.0 | × |
| $\tilde{\Lambda}_{c3}^2(\frac{5}{2}^+)$ | 22.2 | 12.9 | 0.58 | 49 | × |
| $\tilde{\Lambda}_{c3}^2(\frac{7}{2}^+)$ | 12.4 | 17.5 | 1.4 | 49 | × |



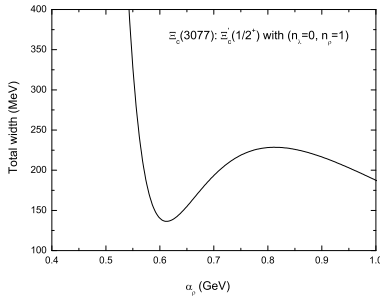
(a)



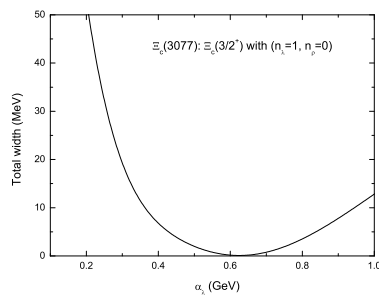
(b)



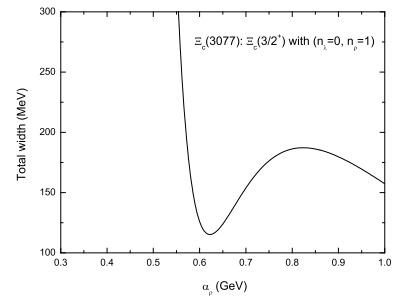
(c)



(d)



(e)



(f)

FIG. 8: The dependence of the total decay width of $\Xi_c(3077)$ on the parameter α_λ or α_ρ if $\Xi_c(3077)$ is a radial excitation. In these figures, we fix $\alpha_\rho = 0.6$ GeV for the case with $n_\lambda = 1$, and $\alpha_\lambda = 0.6$ GeV for $n_\rho = 1$. The situation of $\Xi_c(2980)$ as a radial excitation is very similar.

TABLE VIII: The decay widths of $\Xi_c^+(2980)$ with different D-wave assignments. Here all results are in units of MeV.

| Assignment | $\Xi_c^0 \pi^+$ | $\Xi_c'^0 \pi^+$ | $\Xi_c^{*0} \pi^+$ | $\Sigma_c^{++} k^-$ | $\Lambda_c^+ k^0$ | Remark |
|-------------------------------------|-----------------|-----------------------|-----------------------|-----------------------|-------------------|----------|
| $\Xi_{c2}(\frac{3}{2}^+)$ | 0.0 | 1.1 | 0.11 | 0.37 | 0.0 | \times |
| $\Xi_{c2}(\frac{5}{2}^+)$ | 0.0 | 0.12×10^{-2} | 0.67 | 0.11×10^{-3} | 0.0 | \times |
| $\Xi_{c1}'(\frac{1}{2}^+)$ | 4.4 | 0.72 | 0.18 | 0.25 | 5.3 | |
| $\Xi_{c1}'(\frac{3}{2}^+)$ | 4.4 | 0.18 | 0.46 | 0.062 | 5.3 | |
| $\Xi_{c2}'(\frac{3}{2}^+)$ | 0.0 | 0.16 | 0.17 | 0.56 | 0.0 | \times |
| $\Xi_{c2}'(\frac{5}{2}^+)$ | 0.0 | 0.47×10^{-2} | 1.0 | 0.71×10^{-4} | 0.0 | \times |
| $\Xi_{c3}'(\frac{5}{2}^+)$ | 0.054 | 0.53×10^{-2} | 0.14×10^{-2} | 0.82×10^{-4} | 0.053 | \times |
| $\Xi_{c3}'(\frac{7}{2}^+)$ | 0.054 | 0.30×10^{-2} | 0.19×10^{-2} | 0.46×10^{-4} | 0.053 | \times |
| $\Xi_{c2}^{\dagger}(\frac{3}{2}^+)$ | 0.0 | 9.5 | 6.1 | 0.61 | 0.0 | |
| $\Xi_{c2}^{\dagger}(\frac{5}{2}^+)$ | 0.0 | 9.5 | 6.1 | 0.61 | 0.0 | |
| $\Xi_{c1}^{\dagger}(\frac{1}{2}^+)$ | 74 | 6.3 | 1.0 | 0.40 | 78 | \times |
| $\Xi_{c1}^{\dagger}(\frac{3}{2}^+)$ | 74 | 1.6 | 2.5 | 0.10 | 78 | \times |
| $\Xi_{c2}^{\dagger}(\frac{3}{2}^+)$ | 0.0 | 14 | 4.5 | 0.91 | 0.0 | |
| $\Xi_{c2}^{\dagger}(\frac{5}{2}^+)$ | 0.0 | 6.3 | 7.1 | 0.40 | 0.0 | |
| $\Xi_{c3}^{\dagger}(\frac{5}{2}^+)$ | 48 | 7.2 | 2.9 | 0.46 | 50 | \times |
| $\Xi_{c3}^{\dagger}(\frac{7}{2}^+)$ | 48 | 4.1 | 3.9 | 0.26 | 50 | \times |
| $\Xi_{c0}^0(\frac{1}{2}^+)$ | 0.0 | 0.30 | 1.4 | 1.3 | 0.0 | \times |
| $\Xi_{c1}^0(\frac{1}{2}^+)$ | 1.0 | 0.40 | 0.46 | 1.7 | 0.46 | \times |
| $\Xi_{c1}^0(\frac{3}{2}^+)$ | 1.0 | 0.10 | 1.2 | 0.43 | 0.46 | \times |
| $\Xi_{c1}^{\kappa}(\frac{1}{2}^+)$ | 0.0 | 18 | 4.4 | 5.5 | 0.0 | |
| $\Xi_{c1}^{\kappa}(\frac{3}{2}^+)$ | 0.0 | 4.5 | 11 | 1.4 | 0.0 | |
| $\Xi_{c0}^1(\frac{1}{2}^+)$ | 0.0 | 18 | 18 | 5.5 | 0.0 | |
| $\Xi_{c1}^1(\frac{1}{2}^+)$ | 62 | 9.1 | 2.2 | 2.8 | 72 | \times |
| $\Xi_{c1}^1(\frac{3}{2}^+)$ | 62 | 2.3 | 5.5 | 0.69 | 72 | \times |
| $\Xi_{c2}^1(\frac{3}{2}^+)$ | 0.0 | 11 | 1.1 | 0.34 | 0.0 | \times |
| $\Xi_{c2}^1(\frac{5}{2}^+)$ | 0.0 | 0.0 | 6.6 | 0.0 | 0.0 | \times |
| $\Xi_{c2}^{\kappa}(\frac{3}{2}^+)$ | 0.0 | 5.6 | 1.8 | 2.4 | 0.0 | |
| $\Xi_{c2}^{\kappa}(\frac{5}{2}^+)$ | 0.0 | 1.7 | 4.32 | 0.24 | 0.0 | |
| $\Xi_{c1}^2(\frac{1}{2}^+)$ | 19 | 3.7 | 1.1 | 1.6 | 23 | |
| $\Xi_{c1}^2(\frac{3}{2}^+)$ | 19 | 0.93 | 2.6 | 0.40 | 23 | |
| $\Xi_{c2}^2(\frac{3}{2}^+)$ | 0.0 | 8.4 | 1.7 | 0.36 | 0.0 | |
| $\Xi_{c2}^2(\frac{5}{2}^+)$ | 0.0 | 1.2 | 6.0 | 0.16 | 0.0 | |
| $\Xi_{c3}^2(\frac{5}{2}^+)$ | 8.1 | 1.3 | 60 | 0.19 | 8.7 | \times |
| $\Xi_{c3}^2(\frac{7}{2}^+)$ | 8.1 | 0.75 | 0.81 | 0.10 | 8.7 | |

TABLE IX: The decay widths of $\Xi_c^+(3077)$ with different D-wave assignments. Here all results are in units of MeV.

| Assignment | $\Xi_c^0 \pi^+$ | $\Xi_c'^0 \pi^+$ | $\Xi_c^{*0} \pi^+$ | $\Sigma_c^{++} k^-$ | $\Sigma_c^{++} k^-$ | $\Lambda_c^+ k^0$ | $D^+ \Lambda$ | Remark |
|------------------------------------|-----------------|------------------------|--------------------|-----------------------|-----------------------|-------------------|-----------------------|--------|
| $\Xi_{c2}(\frac{3}{2}^+)$ | 0.0 | 2.1 | 0.30 | 0.73 | 0.054 | 0.0 | 0.0 | |
| $\Xi_{c2}(\frac{5}{2}^+)$ | 0.0 | 0.037 | 1.7 | 0.42×10^{-2} | 0.32 | 0.0 | 0.0 | |
| $\Xi_{c1}'(\frac{1}{2}^+)$ | 7.0 | 1.4 | 0.46 | 0.49 | 0.089 | 4.4 | 3.2 | |
| $\Xi_{c1}'(\frac{3}{2}^+)$ | 7.0 | 0.36 | 1.1 | 0.12 | 0.22 | 4.4 | 3.2 | |
| $\Xi_{c2}'(\frac{3}{2}^+)$ | 0.0 | 3.2 | 0.43 | 1.1 | 0.081 | 0.0 | 0.0 | |
| $\Xi_{c2}'(\frac{5}{2}^+)$ | 0.0 | 0.025×10^{-2} | 2.5 | 0.28×10^{-2} | 0.48 | 0.0 | 0.0 | × |
| $\Xi_{c3}'(\frac{5}{2}^+)$ | 0.19 | 0.029 | 0.012 | 0.32×10^{-2} | 0.32×10^{-3} | 0.12 | 0.026 | × |
| $\Xi_{c3}'(\frac{7}{2}^+)$ | 0.19 | 0.016×10^{-3} | 0.016 | 0.18×10^{-2} | 0.44×10^{-3} | 0.12 | 0.026 | × |
| $\Xi_{c2}^{\Delta}(\frac{3}{2}^+)$ | 0.0 | 34 | 29 | 6.0 | 2.0 | 0.0 | 0.0 | × |
| $\Xi_{c2}^{\Delta}(\frac{5}{2}^+)$ | 0.0 | 34 | 29 | 6.0 | 2.0 | 0.0 | 0.0 | × |
| $\Xi_{c1}^{\Delta}(\frac{1}{2}^+)$ | 201 | 23 | 4.8 | 4.0 | 0.33 | 130 | 38 | × |
| $\Xi_{c1}^{\Delta}(\frac{3}{2}^+)$ | 201 | 5.7 | 12 | 1.0 | 0.83 | 130 | 38 | × |
| $\Xi_{c2}^{\Delta}(\frac{3}{2}^+)$ | 0.0 | 51 | 22 | 8.9 | 1.5 | 0.0 | 0.0 | × |
| $\Xi_{c2}^{\Delta}(\frac{5}{2}^+)$ | 0.0 | 23 | 34 | 4.0 | 2.3 | 0.0 | 0.0 | × |
| $\Xi_{c3}^{\Delta}(\frac{5}{2}^+)$ | 129 | 26 | 14 | 4.5 | 0.94 | 84 | 25 | × |
| $\Xi_{c3}^{\Delta}(\frac{7}{2}^+)$ | 129 | 15 | 19 | 2.6 | 0.13 | 84 | 25 | × |
| $\Xi_{c0}^0(\frac{1}{2}^+)$ | 0.0 | 0.69 | 0.13 | 0.29 | 1.2 | 0.0 | 0.0 | |
| $\Xi_{c1}^0(\frac{1}{2}^+)$ | 15 | 0.92 | 0.044 | 0.39 | 0.38 | 11 | 0.64×10^{-3} | × |
| $\Xi_{c1}^0(\frac{3}{2}^+)$ | 15 | 0.23 | 0.11 | 0.096 | 0.96 | 11 | 0.64×10^{-3} | × |
| $\Xi_{c1}^{\kappa}(\frac{1}{2}^+)$ | 0.0 | 39 | 12 | 12 | 0.21 | 0.0 | 0.0 | × |
| $\Xi_{c1}^{\kappa}(\frac{3}{2}^+)$ | 0.0 | 9.9 | 30 | 3.0 | 5.2 | 0.0 | 0.0 | × |
| $\Xi_{c0}^1(\frac{1}{2}^+)$ | 0.0 | 39 | 47 | 12 | 8.3 | 0.0 | 0.0 | × |
| $\Xi_{c1}^1(\frac{1}{2}^+)$ | 110 | 20 | 5.9 | 6.1 | 1.0 | 69 | 42 | × |
| $\Xi_{c1}^1(\frac{3}{2}^+)$ | 110 | 5.0 | 15 | 1.5 | 2.6 | 69 | 42 | × |
| $\Xi_{c2}^1(\frac{3}{2}^+)$ | 0.0 | 25 | 3.0 | 7.6 | 0.52 | 0.0 | 0.0 | × |
| $\Xi_{c2}^1(\frac{5}{2}^+)$ | 0.0 | 0.0 | 18 | 0.0 | 3.1 | 0.0 | 0.0 | × |
| $\Xi_{c2}^{\kappa}(\frac{3}{2}^+)$ | 0.0 | 9.2 | 6.0 | 3.9 | 0.75 | 0.0 | 0.0 | |
| $\Xi_{c2}^{\kappa}(\frac{5}{2}^+)$ | 0.0 | 5.8 | 10 | 1.1 | 2.1 | 0.0 | 0.0 | |
| $\Xi_{c1}^2(\frac{1}{2}^+)$ | 22 | 6.1 | 2.3 | 2.6 | 0.54 | 14 | 15 | × |
| $\Xi_{c1}^2(\frac{3}{2}^+)$ | 22 | 1.5 | 5.6 | 0.64 | 1.3 | 14 | 15 | × |
| $\Xi_{c2}^2(\frac{3}{2}^+)$ | 0.0 | 14 | 5.2 | 5.8 | 0.77 | 0.0 | 0.0 | × |
| $\Xi_{c2}^2(\frac{5}{2}^+)$ | 0.0 | 3.9 | 14 | 0.74 | 3.0 | 0.0 | 0.0 | × |
| $\Xi_{c3}^2(\frac{5}{2}^+)$ | 21 | 4.4 | 2.5 | 0.85 | 0.23 | 14 | 4.3 | × |
| $\Xi_{c3}^2(\frac{7}{2}^+)$ | 21 | 2.5 | 3.4 | 0.48 | 0.31 | 14 | 4.3 | × |