Strong decays of the low-lying $1P$- and $1D$-wave Σ_c baryons

Yu-Hui Zhou,[1] Wen-Jia Wang,[1] Li-Ye Xiao,[1,*] and Xian-Hui Zhong[2,3,†]

[1]*Institute of Theoretical Physics, University of Science and Technology Beijing, Beijing 100083, China*
[2]*Department of Physics, Hunan Normal University, and Key Laboratory of Low-Dimensional Quantum Structures and Quantum Control of Ministry of Education, Changsha 410081, China*
[3]*Synergetic Innovation Center for Quantum Effects and Applications (SICQEA), Hunan Normal University, Changsha 410081, China*

(Received 29 March 2023; accepted 29 June 2023; published 17 July 2023)

In this work, we systematically study the Okubo-Zweig-Iizuka-allowed two-body strong decay properties of $1P$- and $1D$-wave Σ_c baryons within the j-j coupling scheme in the framework of the quark pair creation model. For a comparison, we also give the predictions of the chiral quark model. Some model dependencies can be found in the predictions of two models. The calculations indicate that: (i) The $1P$-wave λ-mode Σ_c states most likely to be relatively narrow states with a width of $\Gamma < 80$ MeV. Their main decay channels are $\Lambda_c\pi$, or $\Sigma_c\pi$, or $\Sigma_c^*\pi$. The $1P$-wave ρ-mode states most might be broad states with a width of $\Gamma \sim 100$–200 MeV. They dominantly decay into $\Sigma_c\pi$ and $\Sigma_c^*\pi$ channels. Some evidences of these $1P$-wave states are most likely to be observed in the $\Lambda_c\pi$ and $\Lambda_c\pi\pi$ invariant mass spectra around the energy range of 2.75–2.95 GeV. (ii) The $1D$-wave λ-mode Σ_c excitations may be moderate states with a width of about dozens of MeV. The $1D$-wave λ-mode states mainly decay into the $1P$-wave charmed baryon via the pionic decay processes. Meanwhile, several $1D$-wave λ-mode states have significant decay rates into DN or D^*N. Hence, the DN and D^*N are likely to be interesting channels for experimental exploration. (iii) Furthermore, the two $1D$-wave ρ-mode excitations $\Sigma_c|J^P = 5/2^+, 3\rangle_{\rho\rho}$ and $|J^P = 7/2^+, 3\rangle_{\rho\rho}$ are most likely to be fairly narrow state with a width of dozens of MeV, and they mainly decay into $\Lambda_c\pi$. Some evidences of them might be observed in the $\Lambda_c\pi$ invariant mass spectra around the energy range of 3.1–3.2 GeV.

DOI: 10.1103/PhysRevD.108.014019

I. INTRODUCTION

In the past five years, great progress has been achieved on the observation of singly heavy baryons in experiment. For the baryons containing single bottom quark, there are almost twelve new structures recently observed by LHCb and CMS. In 2018, $\Sigma_b(6097)^\pm$ [1] was reported by LHCb Collaboration in the $\Lambda_b^0\pi^\pm$ systems. At the same year, the LHCb Collaboration again found another resonance, $\Xi_b(6227)^-$, both in the $\Lambda_b^0K^-$ and $\Xi_b^0\pi^-$ channels [2]. In 2019, two almost degenerate narrow states $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ were observed by LHCb in the $\Lambda_b\pi^+\pi^-$ invariant mass distribution [3]. Especially in 2020, the LHCb Collaboration reported four narrow peaks, $\Omega_b(6316)^-$, $\Omega_b(6330)^-$, $\Omega_b(6340)^-$, and $\Omega_b(6350)^-$ in the $\Xi_b^0K^-$ channel [4]. Moreover, in 2021, the CMS Collaboration observed a narrow resonance $\Xi_b(6100)^-$ in the $\Xi_b^-\pi^+\pi^-$ invariant mass spectrum [5]. Very recently, the LHCb Collaboration reported two new excited Ξ_b^0 states $\Xi_b(6327)^0$ and $\Xi_b(6333)^0$ in the $\Lambda_b^0K^-\pi^+$ mass spectrum [6]. On other hand, for the singly charmed baryons, the progress in experiment is also surprising. In 2017, the LHCb Collaboration observed five new narrow Ω_c^0 states [7]: $\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3066)^0$, $\Omega_c(3090)^0$, and $\Omega_c(3119)^0$, of which all decay strongly to the final state $\Xi_c^+K^-$. The first four of them were confirmed by Belle experiments subsequently [8]. In addition, at the same year the LHCb Collaboration investigated a near-threshold enhancement in the D^0p amplitude and found a new Λ_c^+ resonance, denoted the $\Lambda_c(2860)^+$ [9]. This new state has been predicted as well by some references before [10–12]. Later, the LHCb Collaboration reported three new Ξ_c^0 states, $\Xi_c(2923)^0$, $\Xi_c(2939)^0$, and $\Xi_c(2965)^0$ in $\Lambda_c^+K^-$ decay mode [13] with no-determined spin-parity. Not long ago the Belle collaboration found possibly an excited Λ_c^+ state, $\Lambda_c(2910)^+$, via studying $\bar{B}^0 \to \Sigma_c(2455)^{0,++}\pi^\pm\bar{p}$

*lyxiao@ustb.edu.cn
†zhongxh@hunnu.edu.cn

decays [14]. Recently, the LHCb collaboration observed two new excited states, $\Omega_c(3185)^0$ and $\Omega_c(3327)^0$ [15], in the $\Xi_c^+ K^-$ invariant-mass spectrum.

To decode the inner structures of those newly observed singly heavy baryons, there exist many theoretical calculations of the mass spectra and strong decays with various models in the literature [16–46]. The most popular explanation is interpreting those newly observed structures into traditional hadronic excited states, such as $1P$-wave [18–23,25–27,29–40], $2P$-wave [17], $1D$-wave [17], or $2S$-wave [16,17,24,41,42] excitations. Meanwhile, there are other unconventional interpretations, such as molecular states [42,43,47–49] or compact pentaquark states [45,46].

The Σ_c baryon spectrum is one of the important members of the singly heavy baryons. Meanwhile, there are very few signals of Σ_c baryons from experiments. Except for the well-established ground states, $\Sigma_c(2455)$ and $\Sigma_c(2520)$ [50], there is just one controversial candidate of excited Σ_c baryon, denoted as $\Sigma_c(2800)$ [51], of which the spin-parity are not determined. Fortunately, the upgrades of experimental technology of the LHC experiments have demonstrated a powerful capability in discovering the heavy baryons. Therefore, the missing $1P$- and $1D$-wave Σ_c excitations are likely to be discovered by forthcoming experiments. The mass spectrum of the Σ_c baryons were studied extensively in the literature [10,35,52–61]. It should be mentioned that for an excited singly heavy baryon, there are two kinds of excitations: λ-mode and ρ-mode excitations. The λ-mode excitation appears between the light diquark and the heavy quark, while the ρ-mode excitation occurs within the light diquark. According to the quark model predictions [20,52,57,62] the mass of the λ-mode resonances is about 70–150 MeV lower than that of ρ-mode resonances. We collect the mass predictions of the $1P$- and $1D$-wave Σ_c resonances in Table I. Except mass spectrum, the strong decay properties of the Σ_c baryons were also studied with various theoretical methods and models, such as the chiral quark model (ChQM) [63,64], the quark pair creation (QPC) model [65], lattice QCD [66], QCD sum rules [67], Eichten-Hill-Quigg (EHQ) formula [10], heavy hadron chiral perturbation theory [68] and nonrelativistic quark model [69,70], and so on.

For the low-lying $1P$-wave and $1D$-wave Σ_c baryons, their masses allow them decaying into the DN and D^*N (N denoting a nucleon) channels. However, only a few discussions exist in literature [53]. Meanwhile, the study on strong decay properties of ρ-mode excitations is rare. Based on those actuality, in the present work we carry out a

TABLE I. Predicted mass of Σ_c baryons($1P$-wave and $1D$-wave) in various quark models and possible decay channels within the QPC model.

Notation	Quantum number						Mass						
$\Sigma_c\vert J^P, j\rangle_{\lambda(\rho)}$	l_λ	l_ρ	L	s_ρ	j	J^P	GIM [53]	RQM [54]	RQM [55]	NQM [10]	NQM [57]	QCD [61]	Decay channel
$\Sigma_c\vert J^P=\frac{1}{2}^-, 0\rangle_\lambda$	1	0	1	1	0	$\frac{1}{2}^-$	2823	2799	2805	2702	2802	2820	$\Sigma_c^{(*)}\pi, \Lambda_c\pi, DN$
$\Sigma_c\vert J^P=\frac{1}{2}^-, 1\rangle_\lambda$	1	0	1	1	1	$\frac{1}{2}^-$	2809	2713	2795	2765	2826	2790	
$\Sigma_c\vert J^P=\frac{3}{2}^-, 1\rangle_\lambda$	1	0	1	1	1	$\frac{3}{2}^-$	2829	2798	2799	2785	2807	2820	
$\Sigma_c\vert J^P=\frac{3}{2}^-, 2\rangle_\lambda$	1	0	1	1	2	$\frac{3}{2}^-$	2802	2773	2761	2798	2837	2800	
$\Sigma_c\vert J^P=\frac{5}{2}^-, 2\rangle_\lambda$	1	0	1	1	2	$\frac{5}{2}^-$	2835	2789	2790	2790	2839	2890	
$\Sigma_c\vert J^P=\frac{1}{2}^-, 1\rangle_\rho$	0	1	1	0	1	$\frac{1}{2}^-$					2909		$\Sigma_c^{(*)}\pi$
$\Sigma_c\vert J^P=\frac{3}{2}^-, 1\rangle_\rho$	0	1	1	0	1	$\frac{3}{2}^-$					2910		
$\Sigma_c\vert J^P=\frac{1}{2}^+, 1\rangle_{\lambda\lambda}$	2	0	2	1	1	$\frac{1}{2}^+$	3073	3041	3014	2949	3103		$\Sigma_c^{(*)}\pi, \Lambda_c\pi, D^{(*)}N, \Xi_c K,$
$\Sigma_c\vert J^P=\frac{3}{2}^+, 1\rangle_{\lambda\lambda}$	2	0	2	1	1	$\frac{3}{2}^+$	3084	3043	3005	2952	3065		$\Xi_c' K, \vert\Lambda_c(\Sigma_c)P_\lambda\rangle\pi$
$\Sigma_c\vert J^P=\frac{3}{2}^+, 2\rangle_{\lambda\lambda}$	2	0	2	1	2	$\frac{3}{2}^+$	3073	3040	3010	2964	3094		
$\Sigma_c\vert J^P=\frac{5}{2}^+, 2\rangle_{\lambda\lambda}$	2	0	2	1	2	$\frac{5}{2}^+$	3085	3038	3001	2942	3099		
$\Sigma_c\vert J^P=\frac{5}{2}^+, 3\rangle_{\lambda\lambda}$	2	0	2	1	3	$\frac{5}{2}^+$	3072	3023	2960	2962	3114		
$\Sigma_c\vert J^P=\frac{7}{2}^+, 3\rangle_{\lambda\lambda}$	2	0	2	1	3	$\frac{7}{2}^+$	3086	3013	3015	2943			
$\Sigma_c\vert J^P=\frac{1}{2}^+, 1\rangle_{\rho\rho}$	0	2	2	1	1	$\frac{1}{2}^+$							$\Sigma_c^{(*)}\pi, \Lambda_c\pi, \Xi_c K,$
$\Sigma_c\vert J^P=\frac{3}{2}^+, 1\rangle_{\rho\rho}$	0	2	2	1	1	$\frac{3}{2}^+$							$\Xi_c' K, \vert\Lambda_c(\Sigma_c)P_\lambda\rangle\pi$
$\Sigma_c\vert J^P=\frac{3}{2}^+, 2\rangle_{\rho\rho}$	0	2	2	1	2	$\frac{3}{2}^+$							
$\Sigma_c\vert J^P=\frac{5}{2}^+, 2\rangle_{\rho\rho}$	0	2	2	1	2	$\frac{5}{2}^+$							
$\Sigma_c\vert J^P=\frac{5}{2}^+, 3\rangle_{\rho\rho}$	0	2	2	1	3	$\frac{5}{2}^+$							
$\Sigma_c\vert J^P=\frac{7}{2}^+, 3\rangle_{\rho\rho}$	0	2	2	1	3	$\frac{7}{2}^+$							

systematic analysis of the 1P- and 1D-wave Σ_c states for both ρ- and λ-mode excitations with the QPC model. For a comparison, we also give the predictions within the chiral quark model. The quark model classification and Okubo-Zweig-Iizuka (OZI) allowed two-body decay channels are summarized in Table I as well. It should be mentioned that the $D^{(*)}N$ decay channels for the ρ-mode excitations are forbidden. Because of the ρ-mode excitation occurring within the light diquark, when ρ-mode excitations decay into $D^{(*)}N$, the light diquark more like an outsider goes straight to the final baryon. Hence, the strong decays are forbidden due to the orthogonality of spatial wave functions. Thus, for the ρ-mode excitations, we only focus on the decay channels containing light π and K mesons.

This paper is structured as follows. In Sec. II, we briefly introduce the QPC model, chiral quark model and the relationship of states in different coupling schemes. Then we present our numerical results and discussions in Sec. III. A summary is given in Sec. IV.

II. THEORETICAL FRAMEWORK

A. QPC model

The QPC model, also famous as the $^3P_0$ model, was first proposed by Micu [71], Car-litz and Kislinger [72], and further developed by the Orsay group [73–75]. The main idea of this model is that strong decay takes place via the creation of quark-antiquark pair from the vacuum with quantum number 0^{++}. This model has been extensively applied to study the OZI-allowed strong transitions of hadron systems [36,76–80].

For a baryon decay process, one quark of the initial baryon state $|A\rangle$ regroups with the created antiquark to form a meson $|C\rangle$, and the other two quarks regroup with the created quark to form a daughter baryon $|B\rangle$. Considering the Σ_c^+ baryons being composed of two light quarks (u and d) and a heavy quark c, thus, according to the quark rearrangement process, any of the three quarks in the initial baryon can go into the final meson. Hence, there are three possible decay ways, as shown in Fig. 1.

In the QPC model, the transition operator for the OZI-allowed two-body decay process $A \to BC$ is given by

$$T = -3\gamma\sum_m \langle 1m; 1-m|00\rangle \int d^3\mathbf{p}_4 d^3\mathbf{p}_5 \delta^3(\mathbf{p}_4+\mathbf{p}_5) \times \mathcal{Y}_1^m\left(\frac{\mathbf{p}_4-\mathbf{p}_5}{2}\right)\chi^{45}_{1-m}\phi^{45}_0\omega^{45}_0 a^\dagger_{4i}(\mathbf{p}_4) b^\dagger_{5j}(\mathbf{p}_5), \tag{1}$$

where γ is a dimensionless parameter and accounts for the vacuum pair-production strength. $\mathbf{p}_4$ and $\mathbf{p}_5$ are the three-vector momenta of the created quark pair. $\omega_0^{45} = \delta_{ij}$, $\phi_0^{45} = (\mathrm{u}\bar{\mathrm{u}} + \mathrm{d}\bar{\mathrm{d}} + \mathrm{s}\bar{\mathrm{s}})/\sqrt{3}$ and χ^{45}_{1-m} denote the color singlet, flavor function and spin triplet of the quark pair, respectively. The solid harmonic polynomial $\mathcal{Y}_1^m = |\mathbf{p}|\mathbf{Y}_1^m(\theta_p\phi_p)$ reflects the

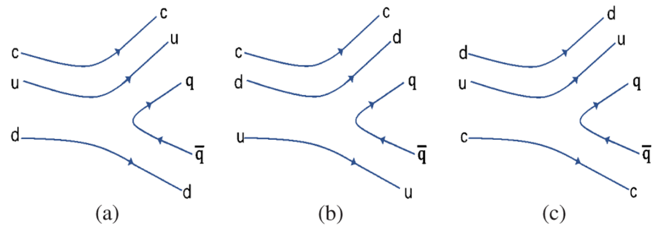

FIG. 1. Decay process of an excited Σ_c baryon in the QPC model.

momentum-space distribution. The creation operator $a^\dagger_{4i} d^\dagger_{5j}$ denotes the quark pair-creation in the vacuum.

According to the definition of the mock state in the constituent quark model [81], the wave functions of the baryon states $|A\rangle$ and $|B\rangle$ and meson state $|C\rangle$ can be easily obtained. For example for the initial baryon state $|A\rangle$, the wave function is given by

$$\begin{aligned} &|A(N_A^{2S_A+1}L_A J_A M_{J_A})(\mathbf{P}_A)\rangle \\ &= \sqrt{2E_A}\varphi_A^{123}\omega_A^{123}\sum_{M_{L_A},M_{S_A}}\langle L_A M_{L_A}; S_A M_{S_A}|J_A, M_{J_A}\rangle \\ &\times \int d^3\mathbf{p}_1 d^3\mathbf{p}_2 d^3\mathbf{p}_3 \delta^3(\mathbf{p}_1+\mathbf{p}_2+\mathbf{p}_3-\mathbf{P}_A) \\ &\times \Psi_{N_A L_A M_{L_A}(\mathbf{p}_1\mathbf{p}_2\mathbf{p}_3)}\chi^{123}_{S_A M_{S_A}}|q_1(\mathbf{p}_1)q_2(\mathbf{p}_2)q_3(\mathbf{p}_3)\rangle, \end{aligned} \tag{2}$$

and the wave function of the final meson state $|C\rangle$ is

$$\begin{aligned} &|C(N_C^{2S_C+1}L_C J_C M_{J_C})(\mathbf{P}_C)\rangle \\ &= \sqrt{2E_C}\varphi_C^{ab}\omega_C^{ab}\sum_{M_{L_C}M_{S_C}}\langle L_C M_{L_C}; S_C M_{S_C}|J_C M_{J_C}\rangle \\ &\times \int d^3\mathbf{p}_a d^3\mathbf{p}_b \delta^3(\mathbf{p}_a+\mathbf{p}_b-\mathbf{P}_C) \\ &\times \Psi_{N_C L_C M_{L_C}(\mathbf{p}_a\mathbf{p}_b)}\chi^{ab}_{S_C M_{S_C}}|q_a(\mathbf{p}_a)q_b(\mathbf{p}_b)\rangle. \end{aligned} \tag{3}$$

The $\mathbf{p}_i$ ($i = 1$, 2, 3 and a, b) stands for the momentum of quarks in hadron $|A\rangle$ and $|C\rangle$. $\mathbf{P}_A$ and $\mathbf{P}_C$ denotes the momentum of initial baryon $|A\rangle$ and final meson $|C\rangle$, respectively. The spatial wave functions of baryons and mesons are described with simple harmonic oscillator wave functions. Thus, the spatial wave function of baryon $|A\rangle$ or $|B\rangle$ without the radial excitation reads

$$\begin{aligned} &\psi(l_\rho, m_\rho, l_\lambda, m_\lambda) \\ &= 3^{\frac{3}{4}}(-i)^{l_\rho}\left[\frac{2^{l_\rho+2}}{\sqrt{\pi}(2l_\rho+1)!!}\right]^{\frac{1}{2}}\left(\frac{1}{\alpha}\right)^{l_\rho+\frac{3}{2}}\exp\left(-\frac{\mathbf{p}_\rho^2}{2\alpha_\rho^2}\right)\mathcal{Y}_{l_\rho}^{m_\rho}(\mathbf{p}_\rho) \\ &\times(-i)^{l_\lambda}\left[\frac{2^{l_\lambda+2}}{\sqrt{\pi}(2l_\lambda+1)!!}\right]^{\frac{1}{2}}\left(\frac{1}{\alpha}\right)^{l_\lambda+\frac{3}{2}}\exp\left(-\frac{\mathbf{p}_\lambda^2}{2\alpha_\lambda^2}\right)\mathcal{Y}_{l_\lambda}^{m_\lambda}(\mathbf{p}_\lambda), \end{aligned} \tag{4}$$

where $\mathbf{p}_\rho$ denotes the relative momentum within the light diquark, and $\mathbf{p}_\lambda$ is the relative momentum between the light diquark and the heavy quark in the baryon. The ground state spatial wave function of meson $|C\rangle$ is

$$\psi_{0,0} = \left(\frac{R^2}{\pi}\right)^{\frac{3}{4}} \exp\left(-\frac{R^2 \mathbf{p}_{ab}^2}{2}\right). \tag{5}$$

$\mathbf{p}_{ab}$ stands for the relative momentum between the quark and antiquark in the meson. Then, the partial decay amplitude in the center of mass frame can be obtained by

$$\begin{aligned}&\mathcal{M}^{M_{J_A}M_{J_B}M_{J_C}}(A \to B + C)\\ &\quad= \gamma\sqrt{8E_A E_B E_C} \prod_{A,B,C} \langle \chi^{124}_{S_B M_{S_B}} \chi^{35}_{S_C M_{S_C}} | \chi^{123}_{S_A M_{S_A}} \chi^{45}_{1-m} \rangle \\ &\qquad \times \langle \varphi^{124}_B \varphi^{35}_C | \varphi^{123}_A \varphi^{45}_0 \rangle I^{M_{L_A},m}_{M_{L_B},M_{L_C}}(\mathbf{p}). \end{aligned} \tag{6}$$

Here, $I^{M_{L_A},m}_{M_{L_B},M_{L_C}}(\mathbf{p})$ denotes the spatial integration, and $\prod_{A,B,C}$ is the Clebsch-Gorden coefficients, which can be expanded as

$$\begin{aligned}&\sum \langle L_B M_{L_B}; S_B M_{S_B} | J_B, M_{J_B} \rangle \langle L_C M_{L_C}; S_C M_{S_C} | J_C, M_{J_C} \rangle \\ &\quad \times \langle L_A M_{L_A}; S_A M_{S_A} | J_A, M_{J_A} \rangle \langle 1m; 1-m | 00 \rangle. \end{aligned} \tag{7}$$

Finally, the decay width of initial state $|A\rangle$ decaying into final state $|BC\rangle$ can be calculated by the following formula,

$$\begin{aligned}&\Gamma(A \to BC)\\ &\quad = \pi^2 \frac{|\mathbf{p}|}{M_A^2} \frac{1}{2J_A + 1} \sum_{M_{J_A}, M_{J_B}, M_{J_C}} |\mathcal{M}^{M_{J_A}, M_{J_B}, M_{J_C}}|^2. \end{aligned} \tag{8}$$

Here, $\mathbf{p}$ is the momentum of the daughter baryon $|B\rangle$ in the center of mass frame of baryon $|A\rangle$, which can be obtained by

$$|\mathbf{p}| = \frac{\sqrt{[M_A^2 - (M_B - M_C)^2][M_A^2 - (M_B + M_C)^2]}}{2M_A}. \tag{9}$$

In our calculation, we adopt $m_u = m_d = 330$ MeV, $m_s = 450$ MeV, and $m_c = 1700$ MeV for the constituent quark mass. The harmonic oscillator strength R for light flavor mesons is taken to be $R = 2.5\ \mathrm{GeV}^{-1}$, and that for D meson is $R = 1.67\ \mathrm{GeV}^{-1}$ [82]. The parameter of the ρ-mode excitation between the two light quarks is taken as $\alpha_\rho = 0.4$ GeV. The other parameter α_λ is obtained by the relation [83]

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

The value of vacuum pair-production strength γ is fixed as $\gamma = 6.95$, which is the same as that in our previous work [84]. Additionally, the masses of final baryons and mesons are derived from the Particle Data Group [50].

B. Chiral quark model

Within the chiral quark model (ChQM), the low energy effective quark-pseudoscalar-meson coupling at tree level in the SU(3) flavor basis reads [85]

$$H_m = \sum_j \frac{1}{f_m} \bar{\psi}_j \gamma^j_\mu \gamma^j_5 \psi_j \vec{\tau} \cdot \partial^\mu \vec{\phi}_m. \tag{11}$$

Here, f_m denotes the pseudoscalar meson decay constant and ψ_j represents the jth quark field in a baryon. ϕ_m is the pseudoscalar meson octet, which is

$$\phi_m = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & K^0 \\ K^- & \bar{K}^0 & -\sqrt{\frac{2}{3}\eta} \end{pmatrix}. \tag{12}$$

In this work, because of the harmonic oscillator spatial wave function of baryons being nonrelativistic form, the coupling is adopt the nonrelativistic form as well and is written as [86–88]

$$\begin{aligned} H_m^{nr} = \sum_j \bigg\{ &\frac{\omega_m}{E_f + M_f} \boldsymbol{\sigma}_j \cdot \mathbf{P}_f + \frac{\omega_m}{E_i + M_i} \boldsymbol{\sigma}_j \cdot \mathbf{P}_i \\ &- \boldsymbol{\sigma}_j \cdot \mathbf{q} + \frac{\omega_m}{2\mu_q} \boldsymbol{\sigma}_j \cdot \mathbf{p}'_j \bigg\} I_j \phi_m. \end{aligned} \tag{13}$$

In this equation, $\mathbf{q}$ and ω_m denote the three-vector momentum and energy of the meson, respectively; the $\boldsymbol{\sigma}_j$ represents the Pauli spin vector; $M_{i(f)}$, $E_{i(f)}$, and $\mathbf{P}_{i(f)}$ stand for the mass, energy, and three-vector momentum of the initial (final) baryon; μ_q is the reduced mass of the jth quark in the initial and final baryons. $\mathbf{p}'_j = \mathbf{p}_j - (m_j/M)\mathbf{P}_{\mathrm{c.m.}}$ stands for the internal momentum of the j-th quark in the baryon rest frame. I_j is the isospin operator associated with the pseudoscalar meson and $\varphi_m = e^{-i\mathbf{q}\cdot\mathbf{r}_j}$ is the plane wave for the emitting light pseudoscalar meson from a decay process.

Hence, the partial decay amplitudes $M_{J_{iz},J_{fz}}$ of a light pseudoscalar meson emission in a baryon's strong decays can be calculated. Then, the strong decay width can be worked out by

$$\Gamma = \left(\frac{\delta}{f_m}\right)^2 \frac{(E_f + M_f)|q|}{4\pi M_i} \frac{1}{2J_i + 1} \sum_{J_{iz} J_{fz}} |M_{J_{iz},J_{fz}}|^2, \tag{14}$$

where J_{iz} and J_{fz} denote the third components of the total angular momenta of the initial and final baryons, respectively. δ is a global parameter accounting for the strength of the quark-meson couplings. Here, we fix its value the same as that in Refs. [83,89], i.e., $\delta = 0.557$ MeV, which is determined by experimental data. The decay constants f_m for π and K mesons are taken as $f_\pi = 132$ MeV and $f_K = 160$ MeV, respectively. In addition, the constituent quark masses are the same as in that of the quark pair creation model.

C. Coupling scheme

It should be pointed out that due to the heavy quark symmetry, the physical states may be closer to the j-j coupling scheme. In the heavy quark symmetry limit, the states within the j-j coupling scheme are constructed by

$$|J^P, j\rangle = |\{[(l_\rho l_\lambda)_L s_\rho]_j s_Q\}_{J^P}\rangle. \tag{15}$$

In the expression, l_ρ and l_λ are the quantum numbers of the orbital angular momentum for ρ- and λ-mode excitations, respectively. The the quantum number of total orbital angular momentum $L = |l_\rho - l_\lambda|, \ldots, l_\rho + l_\lambda$. s_ρ is the spin quantum number of the light quark pair, and s_Q is the spin quantum number of the heavy quark.

The states within the j-j coupling scheme can be expressed as linear combinations of the states within the L-S coupling via [90]

$$|\{[(l_\rho l_\lambda)_L s_\rho]_j s_Q\}_{J^P}\rangle = (-1)^{L+s_\rho+\frac{1}{2}+J}\sqrt{2J+1}\sum_S \sqrt{2S+1} \times \begin{pmatrix} L & s_\rho & j \\ s_Q & J & S \end{pmatrix} |\{[(l_\rho l_\lambda)_L (s_\rho s_Q)_S]_J\}\rangle. \tag{16}$$

The quantum number of total spin angular momentum $S = |s_\rho - s_Q|, \ldots, s_\rho + s_Q$. J is the quantum number of total angular momentum.

III. CALCULATIONS AND RESULTS

We calculate the strong decays of 1P-wave and 1D-wave excited Σ_c baryons within the j-j coupling scheme in the framework of the QPC model. Both λ-mode and ρ-mode excitations are considered in the present work. In addition, for a comparison we also give the decay properties of those Σ_c excitations within the ChQM. We hope our calculations being helpful for searching those missing Σ_c states in forthcoming experiments.

A. 1P-wave λ-mode excitations

For the 1P-wave λ-mode Σ_c baryons, there are five states according to the quark model classification, which are $\Sigma_c|J^P = 1/2^-, 0\rangle_\lambda$, $\Sigma_c|J^P = 1/2^-, 1\rangle_\lambda$, $\Sigma_c|J^P = 3/2^-, 1\rangle_\lambda$, $\Sigma_c|J^P = 3/2^-, 2\rangle_\lambda$ and $\Sigma_c|J^P = 5/2^-, 2\rangle_\lambda$. They have not been established in experiments. Their theoretical masses and possible two-body decay channels are listed in Table I.

From the table, it is known that the predicted masses of the 1P-wave λ-mode Σ_c baryons are about $M \simeq (2750\text{–}2850)$ MeV, and the possible two-body decay channels are $\Sigma_c^{(*)}\pi$, $\Lambda_c\pi$, and DN. Adopting the predicted masses from Ref. [53], we calculate their decay properties within the QPC model, the results are collected in Table II. In addition, considering the uncertainty of the mass predictions of the λ-mode 1P-wave Σ_c states, we plot the strong decay properties as a function of the mass in the region of $M = (2750\text{–}2850)$ MeV in Fig. 2 with the QPC model. From the figure, it is found that the decay properties of the five 1P-wave λ-mode Σ_c excitations are sensitive to the masses, especially the two $J^P = 1/2^-$ states $\Sigma_c|J^P = 1/2^-, 0\rangle_\lambda$ and $\Sigma_c|J^P = 1/2^-, 1\rangle_\lambda$. When the masses of $\Sigma_c|J^P = 1/2^-, 0\rangle_\lambda$ and $\Sigma_c|J^P = 1/2^-, 1\rangle_\lambda$ are above the threshold of DN, their decay rates into DN will be significant. Hence, the two $J^P = 1/2^-$ states may be explored in the DN channel in experiments. In Ref. [63], the decay properties were also studied within the ChQM, for a comparison, the results are listed in Table II.

The $\Sigma_c|J^P = 1/2^-, 0\rangle_\lambda$ state mainly decays into $\Lambda_c\pi$. Within the QPC model, this state is a moderate width state with a width of $\Gamma \simeq 49$ MeV. If the mass is taken as the recent quark model prediction $M = 2823$ MeV [53], the $\Sigma_c|J^P = 1/2^-, 0\rangle_\lambda$ state may has a significant decay rate into DN, the branching fraction is predicted to be

TABLE II. The strong decay properties of the λ-mode 1P-wave Σ_c states, which masses are taken from the predictions in Ref. [53]. Γ_{Total} stands for the total decay width. The unit of the width and mass is MeV.

	$\Sigma_c\vert J^P=\frac{1}{2}^-,0\rangle_\lambda$		$\Sigma_c\vert J^P=\frac{1}{2}^-,1\rangle_\lambda$		$\Sigma_c\vert J^P=\frac{3}{2}^-,1\rangle_\lambda$		$\Sigma_c\vert J^P=\frac{3}{2}^-,2\rangle_\lambda$		$\Sigma_c\vert J^P=\frac{5}{2}^-,2\rangle_\lambda$	
	$M=2823$		$M=2809$		$M=2829$		$M=2802$		$M=2835$	
Decay width	QPC	ChQM [63]	QPC	ChQM [63]	QPC	ChQM [63]	QPC	ChQM [63]	QPC	ChQM [63]
$\Gamma[DN]$	10.3	⋯	2.7	⋯	⋯	⋯	⋯	⋯	⋯	⋯
$\Gamma[\Sigma_c\pi]$	0.1	⋯	73.9	30.2	1.0	5.5	0.8	6.6	1.3	4.8
$\Gamma[\Lambda_c\pi]$	38.1	5.7	⋯	⋯	⋯	⋯	3.5	29.8	4.7	38.6
$\Gamma[\Sigma_c^*\pi]$	⋯	⋯	0.3	0.5	68.5	31.2	0.2	2.0	0.8	2.1
Γ_{Total}	48.5	5.7	76.9	30.7	69.5	36.7	4.5	38.4	6.8	45.5

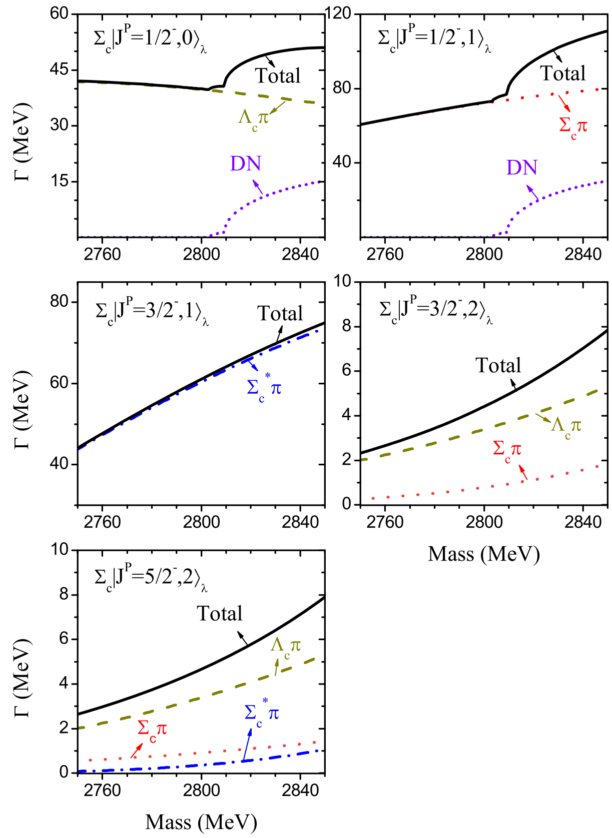

FIG. 2. Partial and total strong decay widths of the $1P$-wave λ-mode Σ_c excitations as functions of their masses. Some decay channels are too small to show in figure.

$$\frac{\Gamma[\Sigma_c|J^P=\frac{1}{2}^-,0\rangle_\lambda \to DN]}{\Gamma_{\text{Total}}} \sim 21\%. \tag{17}$$

However, within the ChQM, the $\Sigma_c|J^P=1/2^-,0\rangle_\lambda$ state might be a narrow state, the predicted partial width of the $\Lambda_c\pi$ channel, $\Gamma[\Sigma_c|J^P=\frac{1}{2}^-,0\rangle_\lambda \to \Lambda_c\pi] \simeq 5.7$ MeV, is about one order of magnitude smaller than that predicted with the QPC model. The decay properties of $\Sigma_c|J^P=1/2^-,0\rangle_\lambda$ predicted within the QPC model are in good agreement with the nature of $\Sigma_c(2800)$ observed in the $\Lambda_c\pi$ channel. It should be mentioned that according to the equal spacing rule, the mass of $\Sigma_c|J^P=1/2^-,0\rangle_\lambda$ is predicted to be about 2755 MeV [63], which is below the DN mass threshold. If the observed state $\Sigma_c(2800)$ corresponds to $\Sigma_c|J^P=1/2^-,0\rangle_\lambda$ indeed and its mass is above the threshold of DN, besides the $\Lambda_c\pi$ channel, the DN may be the other interesting channel for the observation of $\Sigma_c(2800)$ in future experiments.

The $\Sigma_c|J^P=1/2^-,1\rangle_\lambda$ and $\Sigma_c|J^P=3/2^-,1\rangle_\lambda$ states, dominantly decay into $\Sigma_c\pi$ and $\Sigma_c^*\pi$ channels, respectively. In the QPC model, they are predicted to be moderate width states with a comparable width of $\Gamma \sim 70$ MeV, which is a factor 2 larger than that of the ChQM. The branching fractions of their dominant decay channel can reach up to

$$\frac{\Gamma[\Sigma_c|J^P=\frac{1}{2}^-,1\rangle_\lambda \to \Sigma_c\pi]}{\Gamma_{\text{Total}}} \sim 96\%, \tag{18}$$

$$\frac{\Gamma[\Sigma_c|J^P=\frac{3}{2}^-,1\rangle_\lambda \to \Sigma_c^*\pi]}{\Gamma_{\text{Total}}} \sim 85-99\%. \tag{19}$$

The $\Sigma_c|J^P=1/2^-,1\rangle_\lambda$ and $\Sigma_c|J^P=3/2^-,1\rangle_\lambda$ states are likely to be observed in the $\Lambda_c\pi\pi$ final state via the decay chains $\Sigma_c|J^P=1/2^-(3/2^-),1\rangle_\lambda \to \Sigma_c\pi(\Sigma_c^*\pi) \to \Lambda_c\pi\pi$.

Furthermore, $\Sigma_c|J^P=1/2^-,1\rangle_\lambda$ may have a sizeable decay rate into DN, the predicted branching fraction is

$$\frac{\Gamma[\Sigma_c|J^P=\frac{1}{2}^-,1\rangle_\lambda \to DN]}{\Gamma_{\text{Total}}} \sim 4\%. \tag{20}$$

Hence, DN may be a good channel for looking for the missing state $\Sigma_c|J^P=1/2^-,1\rangle_\lambda$.

The other two $1P$-wave λ-mode states $\Sigma_c|J^P=3/2^-,2\rangle_\lambda$ and $\Sigma_c|J^P=5/2^-,2\rangle_\lambda$ mainly decay into the $\Lambda_c\pi$ channel. The predicted decay widths are very different between the QPC model and the ChQM. Within the QPC model, both $\Sigma_c|J^P=3/2^-,2\rangle_\lambda$ and $\Sigma_c|J^P=5/2^-,2\rangle_\lambda$ are most likely to be narrow states with a width of about several MeV, while according to the ChQM predictions, they may have a moderate width of $\Gamma \sim 40$ MeV. The predicted decay properties within the ChQM are consistent with the observations of $\Sigma_c(2800)$. Thus, in Ref. [63], $\Sigma_c(2800)$ is suggested to be a structure potentially arising from two overlapping $1P$-wave Σ_c states with $J^P=3/2^-$ and $J^P=5/2^-$. Due to the extremely similar decay properties of $\Sigma_c|J^P=3/2^-,2\rangle_\lambda$ and $\Sigma_c|J^P=5/2^-,2\rangle_\lambda$, it will be a big challenge to distinguish them from each other in experiments.

B. $1P$-wave ρ-mode excitations

For the $1P$-wave ρ-mode Σ_c baryons, there are two states $\Sigma_c|J^P=1/2^-,1\rangle_\rho$ and $\Sigma_c|J^P=3/2^-,1\rangle_\rho$. For their masses, there are a few discussions in theoretical references and we have collected in Table I as well. From the table, the masses of the $1P$-wave ρ-mode Σ_c excitations are about $M \sim 2.9$ GeV. Meanwhile, we notice that the masses of the $1P$-wave ρ-mode Σ_c baryons are above the threshold of $\Lambda_c\pi$ and DN, while their strong decays are forbidden due to the orthogonality of spatial wave functions. Hence, we mainly focus on their strong decays into $\Sigma_c\pi$ and $\Sigma_c^*\pi$.

Fixing the masses of the $1P$-wave ρ-mode Σ_c excitations on the predicted masses from Ref. [57], we discuss their decay properties within the QPC model. The results are listed in Table III. It is found that the two $1P$-wave ρ-mode Σ_c excitations may be broad states with a total decay width of about $\Gamma \sim (150–200)$ MeV. The $\Sigma_c|J^P=1/2^-,1\rangle_\rho$ is mostly saturated by the decay channel $\Sigma_c\pi$ and the branching fraction for the $\Sigma_c\pi$ channel is

TABLE III. Partial decay widths (MeV) and branching fractions for the $1P$-wave ρ-mode Σ_c states. The numbers in parentheses stand for the corresponding masses (MeV).

	$\Sigma_c\|J^P=\frac{1}{2}^-,1\rangle_\rho(2909)$				$\Sigma_c\|J^P=\frac{3}{2}^-,1\rangle_\rho(2910)$			
	QPC		ChQM		QPC		ChQM	
	Γ_i	$B_i(\%)$	Γ_i	$B_i(\%)$	Γ_i	$B_i(\%)$	Γ_i	$B_i(\%)$
$\Sigma_c\pi$	174.3	92	50	66	18.8	12	27.5	30
$\Sigma_c^*\pi$	16.0	8	25.5	34	136.0	88	63.5	70
Total	190.3		75.5		154.8		91.0	

$$\frac{\Gamma[\Sigma_c|J^P=\frac{1}{2}^-,1\rangle_\rho\to\Sigma_c\pi]}{\Gamma_{\rm Total}}\sim 92\%. \tag{21}$$

While, the decay of $\Sigma_c|J^P=\frac{3}{2}^-,1\rangle_\rho$ is governed by $\Sigma_c^*\pi$ with branching fraction

$$\frac{\Gamma[\Sigma_c|J^P=\frac{3}{2}^-,1\rangle_\rho\to\Sigma_c^*\pi]}{\Gamma_{\rm Total}}\sim 88\%. \tag{22}$$

For a comparison, the predicted results with the ChQM are collected in Table III as well. It is found that the predicted main decay channels with the two models are agreement to each other, however, the predicted total decay widths with the QPC model are about a factor of 2 larger than that with the ChQM.

Similarly, the predicted masses of the $1P$-wave ρ-mode Σ_c excitations certainly have a large uncertainty, which may bring uncertainties to the theoretical results. To investigate this effect, we analyze the decay properties of the $1P$-wave ρ-mode Σ_c excitations as a function of the mass in Fig. 3 with the QPC model. Within the mass varying in the region of $M=(2850\text{–}2950)$ MeV, the total widths of $\Sigma_c|J^P=1/2^-,1\rangle_\rho$ and $\Sigma_c|J^P=3/2^-,1\rangle_\rho$ are $\Gamma>100$ MeV, which shows some sensitivities to the mass changing. The ρ-mode states $\Sigma_c|J^P=1/2^-,1\rangle_\rho$ and $\Sigma_c|J^P=3/2^-,1\rangle_\rho$ are much broader than the $1P$-wave λ-mode states, thus, they may be difficult to be observed in experiments.

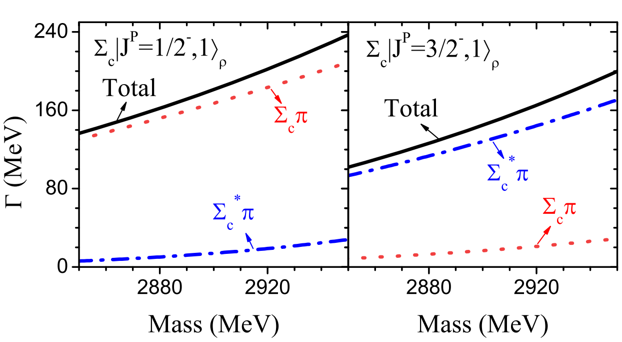

FIG. 3. Partial and total strong decay widths of the $1P$-wave ρ-mode Σ_c states.

C. $1D$-wave λ-mode excitations

For the $1D$-wave λ-mode Σ_c baryons, there are six states $\Sigma_c|J^P=1/2^+,1\rangle_{\lambda\lambda}$, $\Sigma_c|J^P=3/2^+,1\rangle_{\lambda\lambda}$, $\Sigma_c|J^P=3/2^+,2\rangle_{\lambda\lambda}$, $\Sigma_c|J^P=5/2^+,2\rangle_{\lambda\lambda}$, $\Sigma_c|J^P=5/2^+,3\rangle_{\lambda\lambda}$, and $\Sigma_c|J^P=7/2^+,3\rangle_{\lambda\lambda}$. According to the theoretical predictions by various methods, the mass of the $1D$-wave λ-mode Σ_c baryons is about $M\sim 3.0$ GeV. Fixing their masses at the predictions in Ref. [54], we calculate their strong decay properties with both the QPC model and ChQM, the results are listed in Table IV.

For the $\Sigma_c|J^P=1/2^+,1\rangle_{\lambda\lambda}$, similar decay properties are predicted within the two models. The $\Sigma_c|J^P=1/2^+,1\rangle_{\lambda\lambda}$ may have a width of about 10 s–100 MeV. The main decay channels of $\Sigma_c|J^P=1/2^+,1\rangle_{\lambda\lambda}$ are $\Lambda_c|J^P=1/2^-,1\rangle_\lambda\pi$ and $\Sigma_c|J^P=1/2^-,1\rangle_\lambda\pi$. With the QPC model, the branching fractions are predicted to be

$$\frac{\Gamma[\Sigma_c|J^P=\frac{1}{2}^+,1\rangle_{\lambda\lambda}\to\Lambda_c|J^P=\frac{1}{2}^-,1\rangle_\lambda\pi]}{\Gamma_{\rm Total}}\sim 33\%, \tag{23}$$

$$\frac{\Gamma[\Sigma_c|J^P=\frac{1}{2}^+,1\rangle_{\lambda\lambda}\to\Sigma_c|J^P=\frac{1}{2}^-,1\rangle_\lambda\pi]}{\Gamma_{\rm Total}}\sim 25\%. \tag{24}$$

The large branching ratios indicate the state $\Sigma_c|J^P=1/2^+,1\rangle_{\lambda\lambda}$ is very likely be observed in the $\Sigma_c\pi\pi$ final state via the decay chains $\Sigma_c|J^P=1/2^+,1\rangle_{\lambda\lambda}\to\Lambda_c(\Sigma_c)|J^P=1/2^-,1\rangle_\lambda\pi\to\Sigma_c\pi\pi$.

Meanwhile, according to the QPC model prediction, the state $\Sigma_c|J^P=1/2^+,1\rangle_{\lambda\lambda}$ may have a significant decay rate into DN with a branching fraction

$$\frac{\Gamma[\Sigma_c|J^P=\frac{1}{2}^+,1\rangle_{\lambda\lambda}\to DN]}{\Gamma_{\rm Total}}\sim 15\%. \tag{25}$$

Hence, the $\Sigma_c|J^P=1/2^+,1\rangle_{\lambda\lambda}$ may be observed in the DN decay channel.

The $\Sigma_c|J^P=3/2^+,1\rangle_{\lambda\lambda}$ state may be a moderate state. Within the QPC model, the total decay width is predicted to be $\Gamma\sim 68$ MeV, which is about a factor of 2 larger than that predicted within the ChQM. The $\Sigma_c|J^P=3/2^+,1\rangle_{\lambda\lambda}$ has a large decay rate into $\Lambda_c|J^P=3/2^-,1\rangle_\lambda\pi$. Within the QPC model, the branching fraction is predicted to be

$$\frac{\Gamma[\Sigma_c|J^P=\frac{3}{2}^+,1\rangle_{\lambda\lambda}\to\Lambda_c|J^P=\frac{3}{2}^-,1\rangle_\lambda\pi]}{\Gamma_{\rm Total}}\sim 56\%. \tag{26}$$

Moreover, the state $\Sigma_c|J^P=3/2^+,1\rangle_{\lambda\lambda}$ may have a sizable decay rate into D^*N with a branching fraction of

$$\frac{\Gamma[\Sigma_c|J^P=\frac{3}{2}^+,1\rangle_{\lambda\lambda}\to D^*N]}{\Gamma_{\rm Total}}\sim 11\%. \tag{27}$$

TABLE IV. The strong decay properties of the λ-mode $1D$-wave Σ_c states, which masses are taken from the predictions in Ref. [54]. $\Gamma_{\rm Total}$ stands for the total decay width. The unit of the width and mass is MeV.

	$\Sigma_c\|J^P=\frac{1}{2}^+,1\rangle_{\lambda\lambda}$		$\Sigma_c\|J^P=\frac{3}{2}^+,1\rangle_{\lambda\lambda}$		$\Sigma_c\|J^P=\frac{3}{2}^+,2\rangle_{\lambda\lambda}$		$\Sigma_c\|J^P=\frac{5}{2}^+,2\rangle_{\lambda\lambda}$		$\Sigma_c\|J^P=\frac{5}{2}^+,3\rangle_{\lambda\lambda}$		$\Sigma_c\|J^P=\frac{7}{2}^+,3\rangle_{\lambda\lambda}$	
	$M=3041$		$M=3043$		$M=3040$		$M=3038$		$M=3023$		$M=3013$	
Decay width	QPC	ChQM	QPC	ChQM	QPC	ChQM	QPC	ChQM	QPC	ChQM	QPC	ChQM
$\Gamma[DN]$	17.1	...	1.1	...	9.6	...	0.3	...	...	...	0.6	...
$\Gamma[D^*N]$	3.9	...	7.5	...	4.6	...	6.8	...	0.1	...	...	...
$\Gamma[\Sigma_c\pi]$	2.5	3.5	0.7	0.9	5.3	7.9	0.3	4.8	0.3	4.7	0.1	2.4
$\Gamma[\Lambda_c\pi]$	2.8	2.3	2.4	2.2	0.1	...	...	...	0.7	15.5	0.6	14.5
$\Gamma[\Sigma_c^*\pi]$	1.0	1.7	2.8	4.3	3.5	6.0	5.5	10.8	0.2	5.2	0.2	1.5
$\Gamma[\Xi_c K]$	0.9	3.4	0.8	3.6	...	...	...	...	...	...	...	...
$\Gamma[\Lambda_c\|J^P=\frac{1}{2}^-,1\rangle_\lambda\pi]$	37.2	13.8	...	8.1	0.4	0.2	0.2	...	1.7	2.2	...	...
$\Gamma[\Lambda_c\|J^P=\frac{3}{2}^-,1\rangle_\lambda\pi]$	0.1	1.4	37.3	10.8	0.3	0.2	0.5	1.9	0.3	1.2	1.0	8.0
$\Gamma[\Sigma_c\|J^P=\frac{1}{2}^-,0\rangle_\lambda\pi]$	4.3	0.3	...	0.4	0.2	1.3	...	0.5	...	0.2	1.0	...
$\Gamma[\Sigma_c\|J^P=\frac{1}{2}^-,1\rangle_\lambda\pi]$	27.9	24.9	0.3	0.5	0.5	4.3	0.2	0.1	...	3.9	0.8	...
$\Gamma[\Sigma_c\|J^P=\frac{3}{2}^-,1\rangle_\lambda\pi]$	...	3.4	6.7	0.6	4.0	2.9	2.0	0.1	2.3	...	2.7	0.1
$\Gamma[\Sigma_c\|J^P=\frac{3}{2}^-,2\rangle_\lambda\pi]$	...	1.5	4.6	0.3	55.6	22.9	0.5	...	1.0	0.3	0.5	0.2
$\Gamma[\Sigma_c\|J^P=\frac{5}{2}^-,2\rangle_\lambda\pi]$	14.7	0.9	3.3	1.3	5.0	0.9	8.6	7.6	6.9	0.8	1.4	0.4
$\Gamma_{\rm Total}$	112.4	57.0	67.5	33.0	89.1	46.6	24.9	25.8	13.5	34.0	8.9	27.1

	$\Sigma_c\|J^P=\frac{1}{2}^+,1\rangle_{\rho\rho}$		$\Sigma_c\|J^P=\frac{3}{2}^+,1\rangle_{\rho\rho}$		$\Sigma_c\|J^P=\frac{3}{2}^+,2\rangle_{\rho\rho}$		$\Sigma_c\|J^P=\frac{5}{2}^+,2\rangle_{\rho\rho}$		$\Sigma_c\|J^P=\frac{5}{2}^+,3\rangle_{\rho\rho}$		$\Sigma_c\|J^P=\frac{7}{2}^+,3\rangle_{\rho\rho}$	
	$M=3141$		$M=3143$		$M=3140$		$M=3138$		$M=3123$		$M=3113$	
Decay width	QPC	ChQM	QPC	ChQM	QPC	ChQM	QPC	ChQM	QPC	ChQM	QPC	ChQM
$\Gamma[\Sigma_c\pi]$	69.0	14.1	29.0	3.5	126.4	31.7	11.1	10.2	11.1	10.4	5.7	5.4
$\Gamma[\Lambda_c\pi]$	136.8	14.3	137.8	14.2	...	...	...	...	21.7	24.3	20.3	23.1
$\Gamma[\Sigma_c^*\pi]$	24.8	6.9	62.6	17.3	33.3	17.3	136.3	39.4	7.4	18.8	8.9	9.3
$\Gamma[\Xi_c K]$	23.1	19.6	37.5	19.9	...	...	...	...	1.0	0.6	0.8	0.5
$\Gamma[\Xi_c' K]$	1.9	2.1	0.6	0.5	3.8	4.6	...	...	...	...	...	...
$\Gamma[\Lambda_c\|J^P=\frac{1}{2}^-,1\rangle_\lambda\pi]$	9.2	1.1	1.2	1.5	...	...	...	...	1.7	0.6	...	0.5
$\Gamma[\Lambda_c\|J^P=\frac{3}{2}^-,1\rangle_\lambda\pi]$	1.8	1.9	8.8	2.4	...	...	...	...	0.4	0.8	1.8	0.6
$\Gamma[\Sigma_c\|J^P=\frac{1}{2}^-,0\rangle_\lambda\pi]$	...	0.2	...	0.1	...	0.1	0.1	0.1	...	...	...	...
$\Gamma[\Sigma_c\|J^P=\frac{1}{2}^-,1\rangle_\lambda\pi]$	7.0	0.1	0.2	0.1	1.6	0.2	0.7	...	1.3	0.1	...	...
$\Gamma[\Sigma_c\|J^P=\frac{3}{2}^-,1\rangle_\lambda\pi]$	1.3	0.2	2.1	...	1.3	...	0.2	0.1	0.1	...	0.2	...
$\Gamma[\Sigma_c\|J^P=\frac{3}{2}^-,2\rangle_\lambda\pi]$	...	0.4	0.1	0.5	6.5	0.1	0.1	...	0.2	...	0.1	...
$\Gamma[\Sigma_c\|J^P=\frac{5}{2}^-,2\rangle_\lambda\pi]$	1.9	0.1	0.8	...	1.1	0.1	5.5	0.5	0.1	...	0.3	...
$\Gamma_{\rm Total}$	276.7	61.0	280.7	60.0	174.0	54.1	153.9	50.3	44.9	55.6	38.1	39.4

Hence, besides the decay chain $\Sigma_c|J^P=3/2^+,1\rangle_{\lambda\lambda}\to\Lambda_c|J^P=3/2^-,1\rangle_\lambda\pi\to\Lambda_c\pi\pi\pi$, the decay chain $\Sigma_c|J^P=3/2^+,1\rangle_{\lambda\lambda}\to D^*N\to D\pi N$ may be also the other optional decay precess to investigate the nature of $\Sigma_c|J^P=3/2^+,1\rangle_{\lambda\lambda}$.

For the other $J^P=3/2^+$ state, $\Sigma_c|J^P=3/2^+,2\rangle_{\lambda\lambda}$, with the QPC model the width is predicted to be $\Gamma\sim 89$ MeV, which is about a factor of 2 larger than that predicted with the ChQM. This state dominantly decays into $\Sigma_c|J^P=3/2^-,2\rangle_\lambda\pi$. Its predicted fraction is

$$\frac{\Gamma[\Sigma_c|J^P=\frac{3}{2}^+,2\rangle_{\lambda\lambda}\to\Sigma_c|J^P=\frac{3}{2}^-,2\rangle_\lambda\pi]}{\Gamma_{\rm Total}}\sim 50\text{–}60\%. \quad (28)$$

Thanks to the large branching fraction, the state $\Sigma_c|J^P=3/2^+,2\rangle_{\lambda\lambda}$ may be observed in the $\Lambda_c\pi\pi$ decay channel via the decay chain $\Sigma_c|J^P=3/2^+,2\rangle_{\lambda\lambda}\to\Sigma_c|J^P=\frac{3}{2}^-,2\rangle_\lambda\pi\to\Lambda_c\pi\pi$.

Furthermore, the $\Sigma_c|J^P=3/2^+,2\rangle_{\lambda\lambda}$ state has a sizeable decay rate into DN, with the QPC model the branching fraction is predicted to be

$$\frac{\Gamma[\Sigma_c|J^P=\frac{3}{2}^+,2\rangle_{\lambda\lambda}\to DN]}{\Gamma_{\rm Total}}\sim 11\%. \tag{29}$$

Therefore, DN may be another decay channel for exploring the state $\Sigma_c|J^P=3/2^+,2\rangle_{\lambda\lambda}$.

The $\Sigma_c|J^P=5/2^+,2\rangle_{\lambda\lambda}$ may have a narrow width of $\Gamma\sim 25$ MeV. This state may have significant decay rates into D^*N, $\Sigma_c^*\pi$ and $\Sigma_c|J^P=5/2^-,2\rangle_\lambda\pi$ with comparable branching fractions ~20–30%, according to the predictions of the QPC model. Due to the narrow decay width, the state $\Sigma_c|J^P=5/2^+,2\rangle_{\lambda\lambda}$ has a good potential to be observed in experiment.

For the last two $1D$-wave λ-mode states $\Sigma_c|J^P=5/2^+,3\rangle_{\lambda\lambda}$ and $\Sigma_c|J^P=7/2^+,3\rangle_{\lambda\lambda}$, they are probably narrow states with a total decay width of $\Gamma\sim$ (9–14) MeV predicted within the QPC model. With the ChQM, their widths are predicted to be $\Gamma\sim 30$ MeV, which is slightly broader than the prediction of the QPC model. The predicted decay properties with the two strong decay models are very different from each other. In the ChQM, both $\Sigma_c|J^P=5/2^+,3\rangle_{\lambda\lambda}$ and $\Sigma_c|J^P=7/2^+,3\rangle_{\lambda\lambda}$ dominantly decay into the $\Lambda_c\pi$ channel. However, in the QPC model, the main decay channel of $\Sigma_c|J^P=5/2^+,3\rangle_{\lambda\lambda}$ is predicted to be $\Sigma_c|J^P=5/2^-,2\rangle_\lambda\pi$, while the dominant decay channel of $\Sigma_c|J^P=7/2^+,3\rangle_{\lambda\lambda}$ is $\Sigma_c|J^P=3/2^-,1\rangle_\lambda\pi$. If the predictions of the ChQM are reliable, both $\Sigma_c|J^P=5/2^+,3\rangle_{\lambda\lambda}$ and $\Sigma_c|J^P=7/2^+,3\rangle_{\lambda\lambda}$ may be observed in the $\Lambda_c\pi$ channel. If the predictions of the QPC model are reliable, they mainly decay into the $1P$-wave Σ_c states via pionic decay processes.

We also plot the partial decay widths of the $1D$-wave λ-mode Σ_c baryons within the QPC model as a function of the mass in region of $M=(2950$–$3120)$ MeV. The sensitivities of the decay properties of these states to their masses are shown in Fig. 4. Within the masses varied in the region we considered in present work, the $1D$-wave λ-mode Σ_c baryons have a large potential to be observed in their main decay channels in experiments.

D. 1D-wave ρ-mode excitations

For the $1D$-wave ρ-mode Σ_c baryons, there are also six states $\Sigma_c|J^P=1/2^+,1\rangle_{\rho\rho}$, $\Sigma_c|J^P=3/2^+,1\rangle_{\rho\rho}$, $\Sigma_c|J^P=3/2^+,2\rangle_{\rho\rho}$, $\Sigma_c|J^P=5/2^+,2\rangle_{\rho\rho}$, $\Sigma_c|J^P=5/2^+,3\rangle_{\rho\rho}$, and $\Sigma_c|J^P=7/2^+,3\rangle_{\rho\rho}$. So far, numerical values of their masses are still missing. While, according to the quark model predictions [20,52,57,62] the mass of the ρ-mode excitations is about (70–150) MeV higher than that of the λ-mode excitations. Thus, we fix masses of the $1D$-wave ρ-mode states on the values which are 100 MeV higher than those of the corresponding $1D$-wave λ-mode states. We predict the strong decay properties with both the QPC model and ChQM, and our results are collected in Table IV. It should be mentioned that the DN and D^*N decay channels are forbidden in present work, although the masses of the $1D$-wave ρ-mode Σ_c states are above the threshold of DN and D^*N.

According to the QPC model predictions, it is obtained that the four states $\Sigma_c|J^P=1/2^+,1\rangle_{\rho\rho}$, $\Sigma_c|J^P=3/2^+,1\rangle_{\rho\rho}$, $\Sigma_c|J^P=3/2^+,2\rangle_{\rho\rho}$, and $\Sigma_c|J^P=5/2^+,2\rangle_{\rho\rho}$ may be broad

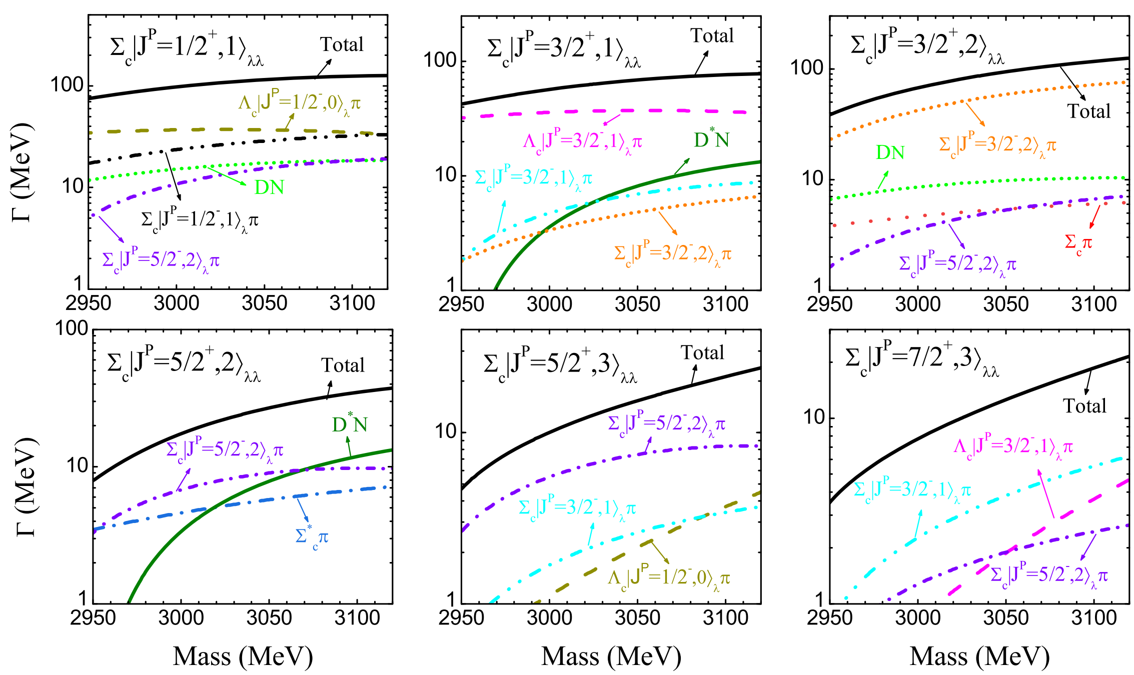

FIG. 4. Partial and total strong decay widths of the $1D$-wave λ-mode Σ_c states as functions of their masses. Some decay channels are too small to show in the figure.

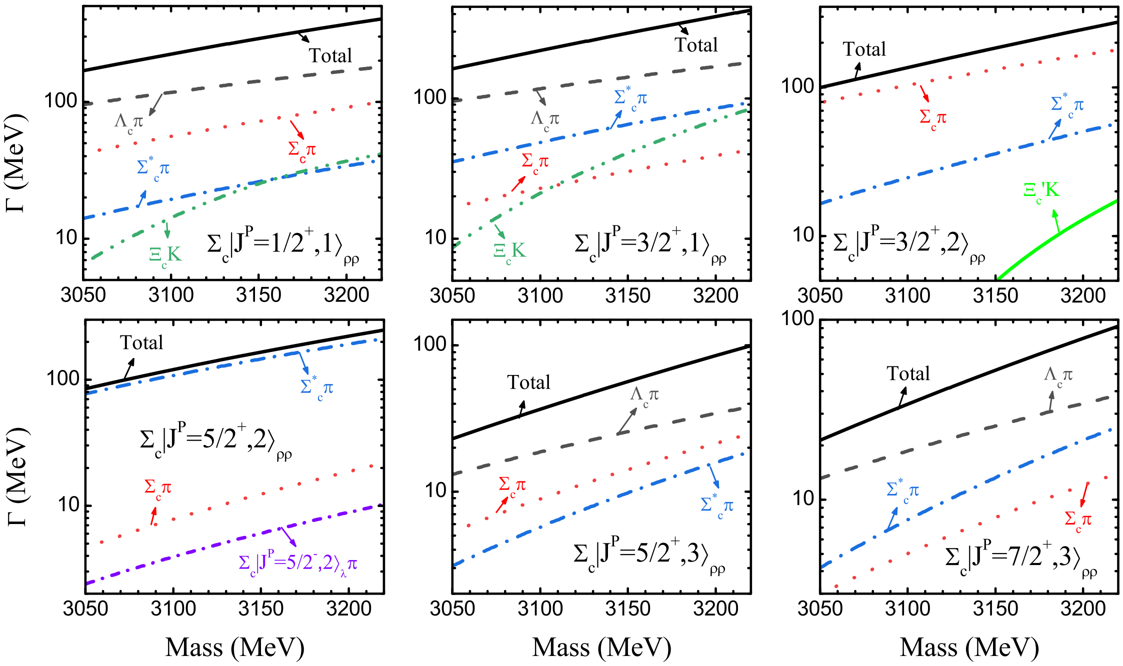

FIG. 5. Partial and total strong decay widths of the $1D$-wave ρ-mode Σ_c states as functions of their masses. Some decay channels are too small to show in the figure.

states with a width of $\Gamma \sim (150\text{–}280)$ MeV; while the other two states $\Sigma_c|J^P = 5/2^+, 3\rangle_{\rho\rho}$ and $\Sigma_c|J^P = 7/2^+, 3\rangle_{\rho\rho}$ have a moderate width of around $\Gamma \sim (40\text{–}45)$ MeV, and may have good potential to be observed in forthcoming experiments. However, with the ChQM all of the six ρ-mode states are predicted to be moderate states with a width of $\Gamma \sim (40\text{–}60)$ MeV.

For the four broad states predicted in the QPC model, the $\Sigma_c|J^P = 1/2^+, 1\rangle_{\rho\rho}$ and $\Sigma_c|J^P = 3/2^+, 1\rangle_{\rho\rho}$ states have similar decay properties, they mainly decay into $\Lambda_c\pi$, $\Sigma_c\pi$, $\Sigma_c^*\pi$, and $\Xi_c K$ channels; while the other two states $\Sigma_c|J^P = 3/2^+, 2\rangle_{\rho\rho}$ and $\Sigma_c|J^P = 5/2^+, 2\rangle_{\rho\rho}$ have a similar decay width, they dominantly decay into the $\Sigma_c\pi$ and $\Sigma_c^*\pi$ channels, respectively. Both $\Sigma_c|J^P = 5/2^+, 3\rangle_{\rho\rho}$ and $\Sigma_c|J^P = 7/2^+, 3\rangle_{\rho\rho}$ are most likely to be moderate states with a comparable width of $\Gamma \sim (40\text{–}50)$ MeV. They have similar decay properties, and mainly decay into $\Lambda_c\pi$, $\Sigma_c\pi$ and $\Sigma_c^*\pi$ channels. To looking for the missing $1D$-wave ρ-mode Σ_c baryons, the $\Lambda_c\pi$, $\Sigma_c\pi$ and $\Sigma_c^*\pi$ channels are worth observing around the mass range of ∼3.1–3.2 GeV in future experiments.

Considering the uncertainty of the masses of the $1D$-wave ρ-mode states, we further investigate the strong decay widths of the $1D$-wave ρ-mode Σ_c states with the QPC model as a function of the mass in Fig. 5. It is shown that the decay properties of the $1D$-wave ρ-mode Σ_c excitations are sensitive to their masses varying in region of $M = (3050\text{–}3220)$ MeV.

IV. SUMMARY

In this work, we systematically investigated the two-body strong decays of low-lying $1P$- and $1D$-wave Σ_c excitations in the QPC model within the j-j coupling scheme. For a comparison, we also give our predictions within the chiral quark model. The main theoretical results are summarized as follows.

In the $1P$-wave λ-mode states, the three states $\Sigma_c|J^P{=}1/2^-{,}0\rangle_\lambda$, $\Sigma_c|J^P{=}3/2^-{,}2\rangle_\lambda$, and $\Sigma_c|J^P{=}5/2^-{,}2\rangle_\lambda$ dominantly decay into $\Lambda_c\pi$. The predicted decay widths have a strong model dependency. In the QPC model, the $\Sigma_c|J^P = 1/2^-, 0\rangle_\lambda$ has a moderate width of $\Gamma \sim 50$ MeV, while the other two states are very narrow states with a width of $\Gamma \sim 4\text{–}7$ MeV. However, in the ChQM, the $\Sigma_c|J^P = 1/2^-, 0\rangle_\lambda$ is predicted to be a narrow state, while both $\Sigma_c|J^P = 3/2^-, 2\rangle_\lambda$ and $\Sigma_c|J^P = 5/2^-, 2\rangle_\lambda$ have a moderate width of $\Gamma \sim 40$ MeV. The $\Sigma_c(2800)$ structure may be contributed by the $\Sigma_c|J^P = 1/2^-, 0\rangle_\lambda$ state or potentially arises from the overlapping the three $1P$-wave Σ_c states with different quantum numbers $J^P = 1/2^-$, $J^P = 3/2^-$ and $J^P = 5/2^-$. The $\Sigma_c|J^P = 1/2^-, 0\rangle_\lambda$ may a large decay rate into the DN channel. The observations of this channel may be useful to distinguish the $\Sigma_c|J^P = 1/2^-, 0\rangle_\lambda$ from the other P-wave states. The two $1P$-wave λ-mode states $\Sigma_c|J^P = 1/2^-, 1\rangle_\lambda$, $\Sigma_c|J^P = 3/2^-, 1\rangle_\lambda$ dominantly decay into $\Sigma_c\pi$ and $\Sigma_c^*\pi$, respectively. Both the QPC model and ChQM give consistent predictions of their decay properties. These two $1P$-wave states may be moderate width states with a width of ~10s MeV. They are most likely to be observed in the $\Lambda_c\pi\pi$ invariant mass spectrum around the energy range of ~2.75–2.85 GeV in experiments.

The 1P-wave ρ-mode states $\Sigma_c|J^P=1/2^-,1\rangle_\rho$ and $\Sigma_c|J^P=3/2^-,2\rangle_\rho$ dominantly decay into $\Sigma_c\pi$ and $\Sigma_c^*\pi$, respectively. They may have a broad width of $\Gamma\sim(100\text{–}200)$ MeV. To looking for these 1P-wave ρ-mode states, the $\Lambda_c\pi\pi$ invariant mass spectrum around the energy range of ~2.85–2.95 GeV is worth to observing in future experiments.

For the 1D-wave λ-mode Σ_c baryons, the main decay channels predicted within the QPC model and ChQM are roughly consistent with each other. Most of these 1D-wave λ-mode states have a relatively narrow width of ~10s MeV, and dominantly decay into the 1P-wave Σ_c and/or Λ_c states. According to the QPC model predictions, both $\Sigma_c|J^P=1/2^+,1\rangle_{\lambda\lambda}$ and $\Sigma_c|J^P=3/2^+,2\rangle_{\lambda\lambda}$ have sizable decay rates decaying into the DN channel, which may be an interesting decay channel for experimental observations. In the ChQM, both $\Sigma_c|J^P=5/2^+,3\rangle_{\lambda\lambda}$ and $\Sigma_c|J^P=7/2^+,3\rangle_{\lambda\lambda}$ mainly decay into the $\Lambda_c\pi$ channel, which is worth to observing in future experiments.

For the 1D-wave ρ-mode Σ_c baryons, both $\Sigma_c|J^P=1/2^+,1\rangle_{\rho\rho}$ and $\Sigma_c|J^P=3/2^+,1\rangle_{\rho\rho}$ have similar decay properties. They have large decay rates into the $\Lambda_c\pi$, $\Sigma_c\pi$, $\Sigma_c^*\pi$, and Ξ_cK channels. According to the QPC model predictions, they may be broad states with a width of about $\Gamma\sim(150\text{–}280)$ MeV, which is about a factor of 4–5 larger than that predicted with ChQM. The $\Sigma_c|J^P=3/2^+,2\rangle_{\rho\rho}$ and $\Sigma_c|J^P=5/2^+,2\rangle_{\rho\rho}$ mainly decay into the $\Sigma_c\pi$ and $\Sigma_c^*\pi$ channels, respectively. They have a similar decay width of $\Gamma\sim(50\text{–}180)$ MeV, which shows some model dependencies. The $\Sigma_c|J^P=5/2^+,3\rangle_{\rho\rho}$ and $\Sigma_c|J^P=7/2^+,3\rangle_{\rho\rho}$ are most likely to be moderate states with a comparable width of $\Gamma\sim(40\text{–}50)$ MeV. They have similar decay properties, and mainly decay into $\Lambda_c\pi$, $\Sigma_c\pi$, and $\Sigma_c^*\pi$ channels. To looking for the missing 1D-wave ρ-mode Σ_c baryons, the $\Lambda_c\pi$, $\Sigma_c\pi$, and $\Sigma_c^*\pi$ channels are worth observing around the mass range of ~3.1–3.2 GeV in future experiments.

Finally, it should be mentioned for some states very different predictions are obtained within the QPC model and ChQM. In fact, these two strong decay modes have some obvious differences with each other. (i) Within the QPC model, the strong decay takes place via the creation of quark-antiquark pair from the vacuum with quantum numbers 0^{++}, while in the ChQM, the quantum numbers of the quark-antiquark pair creating from the vacuum are not defined. (ii) Within the QPC model, the all the hadrons in the final and initial states are taken as particles containing internal structures, while in the ChQM, the emitting light pseudoscalar mesons, π, K, η, and η', are considered to be structureless goldstone bosons. (iii) Within the ChQM, the couplings of the light pseudoscalar mesons with the quarks are described with the chiral Lagrangian, which satisfies the spirit of QCD, while in the QPC model, the chiral symmetry of the interactions for the pseudoscalar mesons with the quarks are not considered. Both models have achieved some successes in describing the strong decays of hadrons. Hence, the results obtained in this work await experimental verification in future.

ACKNOWLEDGMENTS

We would like to thank Kai-Lei Wang for very helpful discussions. This work is supported by the National Natural Science Foundation of China under Grants No. 12005013, No. 12175065, No. 12235018, and No. 11947048.

[1] Roel Aaij *et al.*, Observation of Two Resonances in the $\Lambda_b^0\pi^\pm$ Systems and Precise Measurement of $\Sigma_b^\pm$ and $\Sigma_b^{*\pm}$ Properties, Phys. Rev. Lett. **122**, 012001 (2019).

[2] Roel Aaij *et al.*, Observation of a New Ξ_b^- Resonance, Phys. Rev. Lett. **121**, 072002 (2018).

[3] Roel Aaij *et al.*, Observation of New Resonances in the $\Lambda_b^0\pi^+\pi^-$ System, Phys. Rev. Lett. **123**, 152001 (2019).

[4] Roel Aaij *et al.*, First Observation of Excited Ω_b^- States, Phys. Rev. Lett. **124**, 082002 (2020).

[5] Albert M. Sirunyan *et al.*, Observation of a New Excited Beauty Strange Baryon Decaying to $\Xi_b^-\pi^+\pi^-$, Phys. Rev. Lett. **126**, 252003 (2021).

[6] Roel Aaij *et al.*, Observation of Two New Excited Ξ_b^0 States Decaying to $\Lambda_b^0K^-\pi^+$, Phys. Rev. Lett. **128**, 162001 (2022).

[7] Roel Aaij *et al.*, Observation of Five New Narrow Ω_c^0 States Decaying to $\Xi_c^+K^-$, Phys. Rev. Lett. **118**, 182001 (2017).

[8] J. Yelton *et al.*, Observation of excited Ω_c charmed baryons in e^+e^- collisions, Phys. Rev. D **97**, 051102 (2018).

[9] Roel Aaij *et al.*, Study of the D^0p amplitude in $\Lambda_b^0\to D^0p\pi^-$ decays, J. High Energy Phys. 05 (2017) 030.

[10] Bing Chen, Ke-Wei Wei, Xiang Liu, and Takayuki Matsuki, Low-lying charmed and charmed-strange baryon states, Eur. Phys. J. C **77**, 154 (2017).

[11] Hua-Xing Chen, Qiang Mao, Atsushi Hosaka, Xiang Liu, and Shi-Lin Zhu, D-wave charmed and bottomed baryons from QCD sum rules, Phys. Rev. D **94**, 114016 (2016).

[12] Qi-Fang Lü, Yubing Dong, Xiang Liu, and Takayuki Matsuki, Puzzle of the Λ_c spectrum, Nucl. Phys. Rev. **35**, 1 (2018).

[13] Roel Aaij *et al.*, Observation of New Ξ_c^0 Baryons Decaying to $\Lambda_c^+ K^-$, Phys. Rev. Lett. **124**, 222001 (2020).

[14] Y. B. Li *et al.*, Evidence of a New Excited Charmed Baryon Decaying to $\Sigma_c(2455)^{0,++}\pi^\pm$, Phys. Rev. Lett. **130**, 031901 (2023).

[15] Observation of new Ω_c^0 states decaying to the $\Xi_c^+ K^-$ final state (2023).

[16] Kai-Lei Wang, Li-Ye Xiao, Xian-Hui Zhong, and Qiang Zhao, Understanding the newly observed Ω_c states through their decays, Phys. Rev. D **95**, 116010 (2017).

[17] Hai-Yang Cheng and Cheng-Wei Chiang, Quantum numbers of Ω_c states and other charmed baryons, Phys. Rev. D **95**, 094018 (2017).

[18] Bing Chen, Ke-Wei Wei, Xiang Liu, and Ailin Zhang, Role of newly discovered $\Xi_b(6227)^-$ for constructing excited bottom baryon family, Phys. Rev. D **98**, 031502 (2018).

[19] Bing Chen and Xiang Liu, New Ω_c^0 baryons discovered by LHCb as the members of $1P$ and $2S$ states, Phys. Rev. D **96**, 094015 (2017).

[20] Roelof Bijker, Hugo García-Tecocoatzi, Alessandro Giachino, Emmanuel Ortiz-Pacheco, and Elena Santopinto, Masses and decay widths of $\Xi_{c/b}$ and $\Xi'_{c/b}$ baryons, Phys. Rev. D **105**, 074029 (2022).

[21] Li-Ye Xiao and Xian-Hui Zhong, Toward establishing the low-lying P-wave Σ_b states, Phys. Rev. D **102**, 014009 (2020).

[22] Kai-Lei Wang, Li-Ye Xiao, and Xian-Hui Zhong, Understanding the newly observed Ξ_c^0 states through their decays, Phys. Rev. D **102**, 034029 (2020).

[23] Kai-Lei Wang, Qi-Fang Lü, and Xian-Hui Zhong, Interpretation of the newly observed $\Sigma_b(6097)^\pm$ and $\Xi_b(6227)^-$ states as the P-wave bottom baryons, Phys. Rev. D **99**, 014011 (2019).

[24] Qi-Fang Lü, Canonical interpretations of the newly observed $\Xi_c(2923)^0$, $\Xi_c(2939)^0$, and $\Xi_c(2965)^0$ resonances, Eur. Phys. J. C **80**, 921 (2020).

[25] Wei Wang and Rui-Lin Zhu, Interpretation of the newly observed Ω_c^0 resonances, Phys. Rev. D **96**, 014024 (2017).

[26] M. Padmanath and Nilmani Mathur, Quantum Numbers of Recently Discovered Ω_c^0 Baryons from Lattice QCD, Phys. Rev. Lett. **119**, 042001 (2017).

[27] Marek Karliner and Jonathan L. Rosner, Very narrow excited Ω_c baryons, Phys. Rev. D **95**, 114012 (2017).

[28] Zhi-Gang Wang, Analysis of $\Omega_c(3000)$, $\Omega_c(3050)$, $\Omega_c(3066)$, $\Omega_c(3090)$ and $\Omega_c(3119)$ with QCD sum rules, Eur. Phys. J. C **77**, 325 (2017).

[29] Hui-Min Yang, Hua-Xing Chen, Er-Liang Cui, Atsushi Hosaka, and Qiang Mao, Decay properties of P-wave bottom baryons within light-cone sum rules, Eur. Phys. J. C **80**, 80 (2020).

[30] Er-Liang Cui, Hui-Min Yang, Hua-Xing Chen, and Atsushi Hosaka, Identifying the $\Xi_b(6227)$ and $\Sigma_b(6097)$ as P-wave bottom baryons of $J^P = 3/2^-$, Phys. Rev. D **99**, 094021 (2019).

[31] Hui-Min Yang and Hua-Xing Chen, P-wave bottom baryons of the $SU(3)$ flavor $\mathbf{6}_F$, Phys. Rev. D **101**, 114013 (2020); **102**, 079901(E) (2020).

[32] T. M. Aliev, K. Azizi, Y. Sarac, and H. Sundu, Determination of the quantum numbers of $\Sigma_b(6097)^\pm$ via their strong decays, Phys. Rev. D **99**, 094003 (2019).

[33] Bing Chen and Xiang Liu, Assigning the newly reported $\Sigma_b(6097)$ as a P-wave excited state and predicting its partners, Phys. Rev. D **98**, 074032 (2018).

[34] Pei Yang, Jing-Jing Guo, and Ailin Zhang, Identification of the newly observed $\Sigma_b(6097)^\pm$ baryons from their strong decays, Phys. Rev. D **99**, 034018 (2019).

[35] Duojie Jia, Wen-Nian Liu, and Atsushi Hosaka, Regge behaviors in orbitally excited spectroscopy of charmed and bottom baryons, Phys. Rev. D **101**, 034016 (2020).

[36] Hui-Zhen He, Wei Liang, Qi-Fang Lü, and Yu-Bing Dong, Strong decays of the low-lying bottom strange baryons, Sci. China Phys. Mech. Astron. **64**, 261012 (2021).

[37] Zhi-Gang Wang, Analysis of the $\Omega_b(6316)$, $\Omega_b(6330)$, $\Omega_b(6340)$ and $\Omega_b(6350)$ with QCD sum rules, Int. J. Mod. Phys. A **35**, 2050043 (2020).

[38] Halil Mutuk, A study of excited Ω_b^- states in hypercentral constituent quark model via artificial neural network, Eur. Phys. J. A **56**, 146 (2020).

[39] Wei Liang and Qi-Fang Lü, Strong decays of the newly observed narrow Ω_b structures, Eur. Phys. J. C **80**, 198 (2020).

[40] S. S. Agaev, K. Azizi, and H. Sundu, Interpretation of the new Ω_c^0 states via their mass and width, Eur. Phys. J. C **77**, 395 (2017).

[41] S. S. Agaev, K. Azizi, and H. Sundu, Newly discovered Ξ_c^0 resonances and their parameters, Eur. Phys. J. A **57**, 201 (2021).

[42] Hongxia Huang, Jialun Ping, and Fan Wang, Investigating the excited Ω_c^0 states through $\Xi_c K$ and $\Xi'_c K$ decay channels, Phys. Rev. D **97**, 034027 (2018).

[43] Raj Kishore, Asmita Mukherjee, and Sangem Rajesh, Sivers asymmetry in the photoproduction of a J/ψ and a jet at the EIC, Phys. Rev. D **101**, 054003 (2020).

[44] Yin Huang, Cheng-jian Xiao, Li-Sheng Geng, and Jun He, Strong decays of the $\Xi_b(6227)$ as a $\Sigma_b\bar{K}$ molecule, Phys. Rev. D **99**, 014008 (2019).

[45] Hui-Juan Wang, Zun-Yan Di, and Zhi-Gang Wang, Analysis of the excited Ω c states as the $\pm$ pentaquark states with QCD sum rules, Commun. Theor. Phys. **73**, 035201 (2021).

[46] Xiaohuang Hu, Yue Tan, and Jialun Ping, Investigation of Ξ_c^0 in a chiral quark model, Eur. Phys. J. C **81**, 370 (2021).

[47] Ming-Zhu Liu, Tian-Wei Wu, Ju-Jun Xie, Manuel Pavon Valderrama, and Li-Sheng Geng, $D\Xi$ and $D^*\Xi$ molecular states from one boson exchange, Phys. Rev. D **98**, 014014 (2018).

[48] Q. X. Yu, R. Pavao, V. R. Debastiani, and E. Oset, Description of the Ξ_c and Ξ_b states as molecular states, Eur. Phys. J. C **79**, 167 (2019).

[49] Hui-Juan Wang, Zun-Yan Di, and Zhi-Gang Wang, Analysis of the $\Xi_b(6227)$ as the $\frac{1}{2}^\pm$ pentaquark molecular states with QCD sum rules, Int. J. Theor. Phys. **59**, 3124 (2020).

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

[51] R. Mizuk *et al.*, Observation of an Isotriplet of Excited Charmed Baryons Decaying to $\Lambda_c^+\pi$, Phys. Rev. Lett. **94**, 122002 (2005).

[52] Simon Capstick and Nathan Isgur, Baryons in a relativized quark model with chromodynamics, Phys. Rev. D **34**, 2809 (1986).

[53] Guo-Liang Yu, Zhen-Yu Li, Zhi-Gang Wang, Jie Lu, and Meng Yan, Systematic analysis of single heavy baryons Λ_Q, Σ_Q and Ω_Q (2022).

[54] D. Ebert, R. N. Faustov, and V. O. Galkin, Spectroscopy and Regge trajectories of heavy baryons in the relativistic quark-diquark picture, Phys. Rev. D **84**, 014025 (2011).

[55] D. Ebert, R. N. Faustov, and V. O. Galkin, Masses of excited heavy baryons in the relativistic quark model, Phys. Lett. B **659**, 612 (2008).

[56] Sascha Migura, Dirk Merten, Bernard Metsch, and Herbert-R. Petry, Charmed baryons in a relativistic quark model, Eur. Phys. J. A **28**, 41 (2006).

[57] Tetsuya Yoshida, Emiko Hiyama, Atsushi Hosaka, Makoto Oka, and Katsunori Sadato, Spectrum of heavy baryons in the quark model, Phys. Rev. D **92**, 114029 (2015).

[58] Zalak Shah, Kaushal Thakkar, Ajay Kumar Rai, and P. C. Vinodkumar, Mass spectra and Regge trajectories of Λ_c^+, Σ_c^0, Ξ_c^0 and Ω_c^0 baryons, Chin. Phys. C **40**, 123102 (2016).

[59] Huseyin Bahtiyar, Kadir Utku Can, Guray Erkol, Philipp Gubler, Makoto Oka, and Toru T. Takahashi, Charmed baryon spectrum from lattice QCD near the physical point, Phys. Rev. D **102**, 054513 (2020).

[60] Paula Pérez-Rubio, Sara Collins, and Gunnar S. Bali, Charmed baryon spectroscopy and light flavor symmetry from lattice QCD, Phys. Rev. D **92**, 034504 (2015).

[61] Hua-Xing Chen, Wei Chen, Qiang Mao, Atsushi Hosaka, Xiang Liu, and Shi-Lin Zhu, *P*-wave charmed baryons from QCD sum rules, Phys. Rev. D **91**, 054034 (2015).

[62] Bing Chen, Si-Qiang Luo, and Xiang Liu, Universal behavior of mass gaps existing in the single heavy baryon family, Eur. Phys. J. C **81**, 474 (2021).

[63] Kai-Lei Wang and Xian-Hui Zhong, Toward establishing the low-lying *P*-wave excited Σ_c baryon states, Chin. Phys. C **46**, 023103 (2022).

[64] Ya-Xiong Yao, Kai-Lei Wang, and Xian-Hui Zhong, Strong and radiative decays of the low-lying *D*-wave singly heavy baryons, Phys. Rev. D **98**, 076015 (2018).

[65] H. Garcia-Tecocoatzi, A. Giachino, J. Li, A. Ramirez-Morales, and E. Santopinto, Strong decay widths and mass spectra of charmed baryons (2022).

[66] K. U. Can, G. Erkol, M. Oka, and T. T. Takahashi, $\Lambda_c\Sigma_c\pi$ coupling and $\Sigma_c \to \Lambda_c\pi$ decay in lattice QCD, Phys. Lett. B **768**, 309 (2017).

[67] K. Azizi, M. Bayar, and A. Ozpineci, $\Sigma_Q\Lambda_Q\pi$ coupling constant in light cone QCD sum rules, Phys. Rev. D **79**, 056002 (2009).

[68] Hai-Yang Cheng and Chun-Khiang Chua, Strong decays of charmed baryons in heavy hadron chiral perturbation theory: An update, Phys. Rev. D **92**, 074014 (2015).

[69] Hideko Nagahiro, Shigehiro Yasui, Atsushi Hosaka, Makoto Oka, and Hiroyuki Noumi, Structure of charmed baryons studied by pionic decays, Phys. Rev. D **95**, 014023 (2017).

[70] C. Albertus, E. Hernandez, J. Nieves, and J. M. Verde-Velasco, Study of the strong $\Sigma_c \to \Lambda_c\pi, \Sigma_c^* \to \Lambda_c\pi$ and $\Xi_c^* \to \Xi_c\pi$ decays in a nonrelativistic quark model, Phys. Rev. D **72**, 094022 (2005).

[71] L. Micu, Decay rates of meson resonances in a quark model, Nucl. Phys. **B10**, 521 (1969).

[72] R. Carlitz and M. Kislinger, Regge amplitude arising from $\mathrm{SU}(6)_w$ vertices, Phys. Rev. D **2**, 336 (1970).

[73] A. Le Yaouanc, L. Oliver, O. Pene, and J. C. Raynal, Naive quark pair creation model of strong interaction vertices, Phys. Rev. D **8**, 2223 (1973).

[74] A. Le Yaouanc, L. Oliver, O. Pene, and J. C. Raynal, Strong decays of psi-prime-prime (4.028) as a radial excitation of charmonium, Phys. Lett. **71B**, 397 (1977).

[75] LeYaovanc, *Hadron Transitions in the Quark Model* (Gordon and Breach Science publishers, New York, 1988).

[76] Chong Chen, Xiao-Lin Chen, Xiang Liu, Wei-Zhen Deng, and Shi-Lin Zhu, Strong decays of charmed baryons, Phys. Rev. D **75**, 094017 (2007).

[77] Ze Zhao, Dan-Dan Ye, and Ailin Zhang, Nature of charmed strange baryons $\Xi_c(3055)$ and $\Xi_c(3080)$, Phys. Rev. D **94**, 114020 (2016).

[78] Bing Chen, Xiang Liu, and Ailin Zhang, Newly observed $\Lambda_c(2860)^+$ at LHCb and its D-wave partners $\Lambda_c(2880)^+$, $\Xi_c(3055)^+$ and $\Xi_c(3080)^+$, Phys. Rev. D **95**, 074022 (2017).

[79] Ayut Limphirat, Chinorat Kobdaj, Prasart Suebka, and Yupeng Yan, Decay widths of ground-state and excited Ξ_b baryons in a nonrelativistic quark model, Phys. Rev. C **82**, 055201 (2010).

[80] Qi-Fang Lü, Li-Ye Xiao, Zuo-Yun Wang, and Xian-Hui Zhong, Strong decay of $\Lambda_c(2940)$ as a 2*P* state in the Λ_c family, Eur. Phys. J. C **78**, 599 (2018).

[81] Cameron Hayne and Nathan Isgur, Beyond the wave function at the origin: Some momentum dependent effects in the nonrelativistic quark model, Phys. Rev. D **25**, 1944 (1982).

[82] Stephen Godfrey and Kenneth Moats, Properties of excited charm and charm-strange mesons, Phys. Rev. D **93**, 034035 (2016).

[83] Xian-Hui Zhong and Qiang Zhao, Charmed baryon strong decays in a chiral quark model, Phys. Rev. D **77**, 074008 (2008).

[84] Li-Ye Xiao, Qi-Fang Lü, and Shi-Lin Zhu, Strong decays of the 1P and 2D doubly charmed states, Phys. Rev. D **97**, 074005 (2018).

[85] Aneesh Manohar and Howard Georgi, Chiral quarks and the nonrelativistic quark model, Nucl. Phys. **B234**, 189 (1984).

[86] Zhen-Ping Li, The threshold pion photoproduction of nucleons in the chiral quark model, Phys. Rev. D **50**, 5639 (1994).

[87] Zhen-ping Li, Hong-xing Ye, and Ming-hui Lu, An unified approach to pseudoscalar meson photoproductions off nucleons in the quark model, Phys. Rev. C **56**, 1099 (1997).

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

[89] Xian-hui Zhong and Qiang Zhao, Strong decays of heavy-light mesons in a chiral quark model, Phys. Rev. D **78**, 014029 (2008).

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