Possible explanations of the observed Λ_c resonances*

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Abstract: Inspired by the latest experimental progress, we systematically study the Okubo-Zweig-Iizuka (OZI)-allowed two-body strong decay properties of 1P-, 1D-, 2S-, and 2P-wave Λ_c baryons within the j-j coupling scheme in the framework of the quark pair creation model. The calculations indicate the following. (i) Taking the observed states $\Lambda_c(2595)^+$ and $\Lambda_c(2625)^+$ as the 1P-wave λ-mode states $\Lambda_c|J^P=1/2^-,1\rangle_\lambda$ and $\Lambda_c|J^P=3/2^-,1\rangle_\lambda$, respectively, we can reproduce the experimental data well in theory. (ii) Combined with the measured mass and decay properties of $\Lambda_c(2860)^+$, this excited state can be explained as the 1D-wave λ-mode state $\Lambda_c|J^P=3/2^+,1\rangle_{\lambda\lambda}$. (iii) The newly observed state $\Lambda_c(2910)^+$ may be assigned as one of the 1P-wave ρ-mode states $\Lambda_c|J^P=3/2^-,2\rangle_\rho$ or $\Lambda_c|J^P=5/2^-,2\rangle_\rho$. Meanwhile, we notice that the partial decay width ratio between $\Sigma_c\pi$ and $\Sigma_c^*\pi$ for the two candidates is significantly different. Hence, experimental progress in this ratio measurement may elucidate the nature of $\Lambda_c(2910)^+$. (iv) According to the properties of $\Lambda_c(2765)^+$, we find that the 2S-wave λ-mode state $\Lambda_{c1}|J^P=1/2^+,0\rangle_\lambda$ is a potential candidate. (v) The 2P-wave λ-mode state $\Lambda_{c1}|J^P=3/2^-,1\rangle_\lambda$ is most likely to be a good assignment of the controversial state $\Lambda_c(2940)^+$. Both the total decay width and partial decay ratio between pD^0 and $\Sigma_c\pi$ are in good agreement with observations. (vi) In addition, for the missing Λ_c excitations, we obtain their strong decay properties and hope these are useful for future experimental exploration.

Keywords: strong decay, singly-charmed baryons, quark pair creation model

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I. INTRODUCTION

Singly-charmed baryons contain a charm quark and two light quarks, which provide a good opportunity to study the dynamics of quark confinement [1, 2]. Singly-charmed baryon spectroscopy has always been a prominent research topic. To date, especially in the last six years, considerable progress has been achieved experimentally, and many new excited singly-charmed baryons have been discovered [3]. To decode the inner structures of these newly observed states, much effort has been made in both experiment and theory.

The Λ_c baryon spectrum is an important member of the singly-charmed baryons, and valuable data have been obtained experimentally. According to the PDG 2024 [4], there are eight Λ_c baryons: Λ_c^+, $\Lambda_c(2595)^+/\Lambda_c(2625)^+$, $\Lambda_c(2765)^+$(or $\Sigma_c(2765)^+$), $\Lambda_c(2860)^+/\Lambda_c(2880)^+$, $\Lambda_c(2910)^+$, and $\Lambda_c(2940)^+$. The Λ_c^+ ground state is the lowest-lying charmed baryon and was first observed by Fermilab in 1976 [5]. $\Lambda_c(2595)^+$ and $\Lambda_c(2625)^+$ are the Λ_c^+ orbital excitations. They were first reported by the CLEO Collaboration in 1995 [6] and ARGUS Collaboration in 1993 [7], respectively, and soon confirmed by subsequent experiments [6, 8−10]. The spin-parity of $\Lambda_c(2595)^+$ is almost certainly $1/2^-$, and that of $\Lambda_c(2625)^+$ is expected to be $3/2^-$ [4]. $\Lambda_c(2765)^+$ is a rather broad structure first reported in the $\Lambda_c^+\pi^+\pi^-$ channel by the CLEO Collaboration in 2001 [11] and later also observed in the $\Sigma_c^{++/0}\pi^\mp$ decay by the Belle Collaboration in 2007 [12]. However, nothing at all is known about its quantum numbers, including whether it is a Λ_c^+ or Σ_c^+ state. In 2017, the Belle Collaboration determined its isospin to be zero and suggested this particle to be a Λ_c^+ state [13]. The $\Lambda_c(2860)^+$ resonance of spin-parity $3/2^+$ was reported by the LHCb Collaboration in the D^0p amplitude in 2017 [14] and is expected to

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be confirmed by other experiments in the future. Another orbital excitation $\Lambda_c(2880)^+$ of spin-parity $5/2^+$ was first observed by the CLEO Collaboration [11]. The mass, decay width, and quantum number were further determined by later experiments [12, 14−16]. In addition, the BaBar Collaboration reported a new structure $\Lambda_c(2940)^+$ in the same paper [15], and soon after the Belle Collaboration confirmed the existence of this state and reported the first observation of $\Lambda_c(2940)^+ \to \Sigma_c(2455)^{0,++}\pi^{+,-}$ decay [12]. Furthermore, the LHCb Collaboration confirmed this structure in the D^0p amplitude [14] and suggested its spin-parity to be $3/2^-$. More recently, the Belle Collaboration measured the branching fractions of $\Lambda_c(2940)^+$ decaying to $\Lambda_c^+\eta$ and D^0p relative to $\Sigma_c\pi$ [16], which provided a more accurate reference for the theory. The new resonance $\Lambda_c(2910)^+$ was observed by the Belle Collaboration in $\bar{B}^0 \to \Sigma_c(2455)^{0,++}\pi^{\pm}\bar{p}$ decays in 2023 [17], but its spin-parity has not been determined yet.

Meanwhile, there exist many theoretical calculations to decode the inner structures of those observed Λ_c^+ baryons via mass spectrum [18−33] and decay properties [19, 33−47]. Besides the Λ_c^+ ground state, $\Lambda_c(2595)^+$ and $\Lambda_c(2625)^+$ can be well interpreted as the P-wave Λ_c states of $J^P=1/2^-$ and $J^P=3/2^-$ [18−20, 34−39], respectively. Meanwhile, for $\Lambda_c(2860)^+$ and $\Lambda_c(2880)^+$, most of the literature suggests that they together form the D-wave Λ_c doublet of $J^P=3/2^+$ and $J^P=5/2^+$, respectively [23, 25−27, 41, 42]. However, some literature does not support $\Lambda_c(2880)^+$ as the $J^P=5/2^+$ state [27, 41] and maintains that this state is an F-wave Λ_c state of $J^P=5/2^-$ [41]. Hence, the relation between these two states still needs to be carefully examined in future experimental and theoretical studies. Regarding $\Lambda_c(2940)^+$, its internal structure is controversial. In addition to being interpreted as a traditional hadron state of $J^P=1/2^-$ [2], $3/2^{\pm}$ [22, 24, 41, 43], $5/2^{\mp}$ [43, 45], or $7/2^+$ [44], it has been interpreted as a D^*N molecular state with $J^P=3/2^-$ [48, 49]. Meanwhile, some papers [50, 51] discuss the properties of $\Lambda_c(2940)$ to help us clarify its nature. Fortunately, the latest experimental measurements by the Belle Collaboration [16] on the partial decay width ratios of $\Lambda_c(2940)^+$ provide a stronger basis for decoding its inner structure. Compared to $\Lambda_c(2940)^+$, the properties of $\Lambda_c(2765)^+$ (or $\Sigma_c(2765)^+$) and $\Lambda_c(2910)^+$ are more controversial, and it is not even certain whether they are Λ_c or Σ_c states. At present, theoretical explanations suggest that $\Lambda_c(2765)^+$ (or $\Sigma_c(2765)^+$) may be $\Lambda_c(2S)1/2^+$ [21, 22], $\Lambda_c(1P)1/2^-$ [22], or $\Sigma_c(1P)3/2^-$ [21] resonance. For $\Lambda_c(2910)^+$, it can be assigned as Λ_c resonance with spin-parity $1/2^+$ [22] or $1/2^-$ [24]. Moreover, the assignment of the two states as $D^{(*)}N$ molecular states also exists [49, 52].

To decode the inner structures of these undetermined Λ_c resonances, more theoretical and experimental efforts are essential. Meanwhile, studies on the strong decay properties of ρ-mode excitations are scarce. Hence, in this paper, we present a systematic analysis of $1P$-, $1D$-, $2S$-, and $2P$-wave Λ_c states for both ρ- and λ-mode excitations within the quark pair creation model. On the one hand, we explain the properties of controversial states, and on the other hand, we predict the decays for unobserved Λ_c states. The predicted masses and possible decay channels within the quark pair creation model are listed in Table 1.

The remainder of this paper is structured as follows. In Sec. II, we briefly introduce the quark pair creation model. Then, we present our theoretical results and discussions in Sec. III. Finally, a summary is given in Sec. IV.

II. THEORETICAL FRAMEWORK

As a phenomenological method, the quark pair creation model [53−57] has been successfully employed in the description of the OZI-allowed two-body strong decays. The main idea of this model is that the quark-antiquark pair with 0^{++} is created from the vacuum and then regroups with the quarks from the initial hadron to produce two outing hadrons. Hence, for the Λ_c system, there are three decay processes, as shown in Fig. 1.

In the framework of the quark pair creation model, the transition operator for a two-body decay $(A \to B+C)$ in the nonrelativistic limit reads

$$T = -3\gamma\sum_m \langle 1m;1-m|00\rangle \int \mathrm{d}^3\mathbf{p}_4 d^3\mathbf{p}_5\delta^3(\mathbf{p}_4+\mathbf{p}_5) \times \omega_0^{45}\chi_{1,-m}^{45}\phi_0^{45}\mathcal{Y}_1^m\left(\frac{\mathbf{p}_4-\mathbf{p}_5}{2}\right) a_{4i}^{y}(\mathbf{p}_4)b_{5j}^{y}(\mathbf{p}_5). \tag{1}$$

The pair creation strength γ is a dimensionless parameter and fixed by fitting experimental data. $\mathbf{p}_i(i=4,5)$ denotes

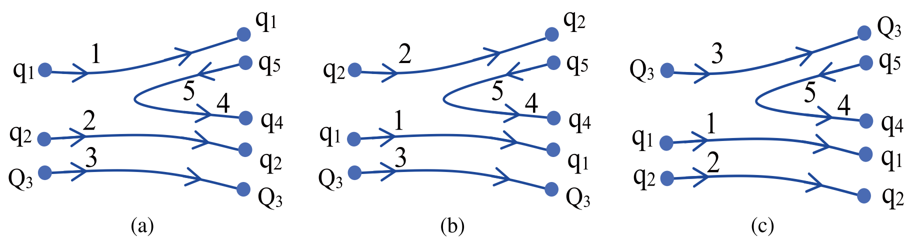

Fig. 1. (color online) Possible manners of decays for the Λ_c system within the quark pair creation model.

Table 1. Predicted masses of Λ_c states ($1P$-, $1D$-, $2S$-, and $2P$-wave) in various quark models and quark pair creation modes.

Notation	Quantum Number								Mass					Decay channel
$\Lambda_c\left\|J^P,j\right\rangle_{\lambda(\rho)}$	n_λ	n_ρ	l_λ	l_ρ	L	s_ρ	j	J^P	RQM [28]	RQM [30]	RFT [31]	NCQM [25]	QM [32]	
$\Lambda_c\left\|J^P=1/2^-,1\right\rangle_\lambda$	0	0	1	0	1	0	1	$1/2^-$	2598	2630	2591	2614	2625	$\Sigma_c\pi$
$\Lambda_c\left\|J^P=3/2^-,1\right\rangle_\lambda$	0	0	1	0	1	0	1	$3/2^-$	2627	2640	2629	2639	2636	
$\Lambda_c\left\|J^P=1/2^-,0\right\rangle_\rho$	0	0	0	1	1	1	0	$1/2^-$		2780			2816	$\Sigma_c^{(*)}\pi$
$\Lambda_c\left\|J^P=1/2^-,1\right\rangle_\rho$	0	0	0	1	1	1	1	$1/2^-$		2830			2816	
$\Lambda_c\left\|J^P=3/2^-,1\right\rangle_\rho$	0	0	0	1	1	1	1	$3/2^-$		2840			2830	
$\Lambda_c\left\|J^P=3/2^-,2\right\rangle_\rho$	0	0	0	1	1	1	2	$3/2^-$		2885			2830	
$\Lambda_c\left\|J^P=5/2^-,2\right\rangle_\rho$	0	0	0	1	1	1	2	$5/2^-$		2900			2872	
$\Lambda_c\left\|J^P=3/2^+,2\right\rangle_{\lambda\lambda}$	0	0	2	0	2	0	2	$3/2^+$	2874	2910	2857	2843	2887	$\Sigma_c^{(*)}\pi,DN$
$\Lambda_c\left\|J^P=5/2^+,2\right\rangle_{\lambda\lambda}$	0	0	2	0	2	0	2	$5/2^+$	2880	2910	2879	2851	2887	
$\Lambda_c\left\|J^P=3/2^+,2\right\rangle_{\rho\rho}$	0	0	0	2	2	0	2	$3/2^+$		~ 3035			3073	$\Lambda_c^+\omega^0,\Sigma_c^{(*)}\pi,\Xi_c'K,\Sigma_c(1P_\lambda)\pi$
$\Lambda_c\left\|J^P=5/2^+,2\right\rangle_{\rho\rho}$	0	0	0	2	2	0	2	$5/2^+$		~ 3140			3092	
$\Lambda_{c1}\left\|J^P=1/2^+,0\right\rangle_\lambda$	1	0	0	0	0	0	0	$1/2^+$	2769	2775	2766	2772	2791	$\Sigma_c^{(*)}\pi,DN$
$\Lambda_{c1}\left\|J^P=1/2^+,0\right\rangle_\rho$	0	1	0	0	0	0	0	$1/2^+$		2970				$\Sigma_c^{(*)}\pi,D^{(*)}N,\Sigma_c(1P_\lambda)\pi$
$\Lambda_{c1}\left\|J^P=1/2^-,1\right\rangle_\lambda$	1	0	1	0	1	0	1	$1/2^-$	2983	3030	2989	2980		$\Sigma_c^{(*)}\pi,D^{(*)}N,\Sigma_c(1P_\lambda)\pi$
$\Lambda_{c1}\left\|J^P=3/2^-,1\right\rangle_\lambda$	1	0	1	0	1	0	1	$3/2^-$	3005	3035	3000	3004		
$\Lambda_{c1}\left\|J^P=1/2^-,0\right\rangle_\rho$	0	1	0	1	1	1	0	$1/2^-$		3200				$\Lambda_c^+\omega^0/\eta,\Sigma_c^{(*)}\pi,\Xi_cK,\Xi_c'^{(*)}K$, $\Sigma_c(1P_{\lambda/\rho})\pi$, $\Lambda_c^+(1P_\lambda)\eta$
$\Lambda_{c1}\left\|J^P=1/2^-,1\right\rangle_\rho$	0	1	0	1	1	1	1	$1/2^-$		3240				
$\Lambda_{c1}\left\|J^P=3/2^-,1\right\rangle_\rho$	0	1	0	1	1	1	1	$3/2^-$		3240				
$\Lambda_{c1}\left\|J^P=3/2^-,2\right\rangle_\rho$	0	1	0	1	1	1	2	$3/2^-$		3255				
$\Lambda_{c1}\left\|J^P=5/2^-,2\right\rangle_\rho$	0	1	0	1	1	1	2	$5/2^-$		3130				

the three-vector momentum of the ith quark of the created quark pair. $\omega_0^{45}=\delta_{ij}$ and $\chi_{1,-m}^{45}$ represent the color singlet and spin triplet of the quark pair, respectively. $\phi_0^{45}=(u\bar{u}+d\bar{d}+s\bar{s})/\sqrt{3}$ represents the flavor function. The solid harmonic polynomial $\mathcal{Y}_1^m=|\mathbf{p}|\mathrm{Y}_1^m(\theta_p\phi_p)$ corresponds to the momentum-space distribution. The creation operator $a_{4i}^{\mathcal{Y}}d_{5j}^{\mathcal{Y}}$ represents quark pair-creation in vacuum.

According to the definition of the mock state [58], the wave functions of the baryon (denoted as $|A\rangle$) and meson (denoted as $|C\rangle$) are respectively given by

$$
\begin{aligned}
&|A(N_A\,{}^{2S_A+1}L_AJ_AM_{J_A})(\mathbf{p}_A)\rangle\\
&=\sqrt{2E_A}\varphi_A^{123}\omega_A^{123}\sum_{M_{L_A},M_{S_A}}\langle L_AM_{L_A};S_AM_{S_A}|J_AM_{J_A}\rangle\\
&\times\int \mathrm{d}^3\mathbf{p}_1d^3\mathbf{p}_2d^3\mathbf{p}_3\delta^3(\mathbf{p}_1+\mathbf{p}_2+\mathbf{p}_3-\mathbf{p}_A)\\
&\times\Psi_{N_AL_AM_{L_A}(\mathbf{p}_1,\mathbf{p}_2,\mathbf{p}_3)}\chi_{S_AM_{S_A}}^{123}|q_1(\mathbf{p}_1)q_2(\mathbf{p}_2)q_3(\mathbf{p}_3)\rangle,
\end{aligned}\tag{2}
$$

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

$\mathbf{p}_i$ ($i=1,2,3$ and a,b) represents the momentum of quarks in baryon $|A\rangle$ and meson $|C\rangle$. $\mathbf{p}_A(\mathbf{p}_C)$ denotes the momentum of the hadron $|A\rangle(|C\rangle)$. The spatial wave functions of hadrons are described with simple harmonic oscillator wave functions. For a baryon without the radial excitation,

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

and for a baryon with one radial excitation ($n_{\lambda/\rho}=1$),

$$
\begin{aligned}
&\psi^{n_{\lambda/\rho}=1}(l_\rho,m_\rho,l_\lambda,m_\lambda)\\
&=3^{\frac{3}{4}}(-i)^{l_{\lambda/\rho}+2}\left[\frac{2^{l_{\lambda/\rho}+3}}{\sqrt{\pi}(2l_{\lambda/\rho}+3)!!}\right]^{1}/2\left(\frac{1}{\alpha_{\lambda/\rho}}\right)^{l_{\lambda/\rho}+3/2}\\
&\times\exp\left(-\frac{\mathbf{p}^2_{\lambda/\rho}}{2\alpha^2_{\lambda/\rho}}\right)\mathcal{Y}^{m_{\lambda/\rho}}_{l_{\lambda/\rho}}(\mathbf{p}_{\lambda/\rho})\left(\frac{2l_{\lambda/\rho}+3}{2}-\frac{\mathbf{p}^2_{\lambda/\rho}}{\alpha^2_{\lambda/\rho}}\right)\\
&\times(-i)^{l_{\rho/\lambda}}\left[\frac{2^{l_{\rho/\lambda}+2}}{\sqrt{\pi}(2l_{\rho/\lambda}+1)!!}\right]^{1}/2\left(\frac{1}{\alpha_{\rho/\lambda}}\right)^{l_{\rho/\lambda}+3/2}\\
&\times\exp\left(-\frac{\mathbf{p}^2_{\rho/\lambda}}{2\alpha^2_{\rho/\lambda}}\right)\mathcal{Y}^{m_{\rho/\lambda}}_{l_{\rho/\lambda}}(\mathbf{p}_{\rho/\lambda}).
\end{aligned}
\tag{5}
$$

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

$$
\psi_{0,0}=\left(\frac{R^2}{\pi}\right)^{\frac{3}{4}}\exp\left(-\frac{R^2\mathbf{p}^2_{ab}}{2}\right),
\tag{6}
$$

where $\mathbf{p}_{ab}$ is the relative momentum between the quark and antiquark in the meson.

Then, in the center of mass frame, we can obtain the partial decay amplitude as

$$
\begin{aligned}
&\mathcal{M}^{M_{J_A}M_{J_B}M_{J_C}}(A\to B+C)\\
&=\gamma\sqrt{8E_AE_BE_C}\prod_{A,B,C}\langle\chi^{124}_{S_BM_{S_B}}\chi^{35}_{S_CM_{S_C}}|\chi^{123}_{S_AM_{S_A}}\chi^{45}_{1-m}\rangle\\
&\langle\varphi^{124}_B\varphi^{35}_C|\varphi^{123}_A\varphi^{45}_0\rangle I^{M_{L_A},m}_{M_{L_B},M_{L_C}}(\mathbf{p}).
\end{aligned}
\tag{7}
$$

$I^{M_{L_A},m}_{M_{L_B},M_{L_C}}(\mathbf{p})$ denotes the spatial integration, and the Clebsch-Gorden coefficient $\prod_{A,B,C}$ reads

$$
\begin{aligned}
&\sum\langle L_BM_{L_B};S_BM_{S_B}|J_B,M_{J_B}\rangle\langle L_CM_{L_C};S_CM_{S_C}|J_C,M_{J_C}\rangle\\
&\times\langle L_AM_{L_A};S_AM_{S_A}|J_A,M_{J_A}\rangle\langle 1m;1-m|00\rangle.
\end{aligned}
\tag{8}
$$

Considering that the vertex given by the quark pair creation model is too complicated at high momenta, we modify the vertex by adopting a form factor $\mathrm{e}^{-\frac{\mathbf{p}^2}{2\Lambda^2}}$ as in previous literature [59−61], which gives the quark-pair-creation vertex a finite-size rather than point-like behavior. It reads

$$
\mathcal{M}^{M_{J_A}M_{J_B}M_{J_C}}(A\to B+C)\to\mathcal{M}^{M_{J_A}M_{J_B}M_{J_C}}(A\to B+C)\mathrm{e}^{-\frac{\mathbf{p}^2}{2\Lambda^2}}.
\tag{9}
$$

In this equation, we fix the cut-off parameter $\Lambda=780$ MeV, which is the same value used in Ref. [62]. $\mathbf{p}$ represents the momentum of the daughter baryon B in the center of mass frame of the parent baryon A and reads

$$
|\mathbf{p}|=\frac{\sqrt{[M_A^2-(M_B-M_C)^2][M_A^2-(M_B+M_C)^2]}}{2M_A}.
\tag{10}
$$

Finally, the decay width $\Gamma[A\to BC]$ can be calculated by the following formula:

$$
\Gamma(A\to BC)=\pi^2\frac{|\mathbf{p}|}{M_A^2}\frac{1}{2J_A+1}\sum_{M_{J_A},M_{J_B},M_{J_C}}|\mathcal{M}^{M_{J_A},M_{J_B},M_{J_C}}|^2.
\tag{11}
$$

In this work, we adopt m_u=m_d=330 MeV, m_s=450 MeV, and m_c=1700 MeV for the constituent quark mass. The masses of the final baryons and mesons involved in our calculations are listed in Table 2. The harmonic oscillator strength $R=2.5$ GeV^{-1} for light flavor mesons $\pi/K^{(*)}/\omega/\eta$, $R=1.67$ GeV^{-1} for the D meson, and $R=1.94$ GeV^{-1} for the D^* meson [64]. The parameter of the ρ-mode excitation between the two light quarks is taken as α_ρ=0.4 GeV. The other parameter α_λ is obtained by the relation [45]

$$
\alpha_\lambda=\left(\frac{3m_Q}{2m_q+m_Q}\right)^{\frac{1}{4}}\alpha_\rho.
\tag{12}
$$

The value of vacuum pair-production strength γ is determined by fitting the well measured decay $\Sigma_c^{++}(2520)\to\Lambda_c^+\pi^+$ and is obtained as $\gamma=11.51$.

III. CALCULATIONS AND RESULTS

The two-body strong decays of $1P$-, $1D$-, $2S$-, and $2P$-wave excited Λ_c baryons within the j-j coupling scheme are systematically investigated by the quark pair creation model. Both λ-mode and ρ-mode excitations are considered in this calculation. We attempt to decode the inner structures of the observed controversial Λ_c excitations while providing strong decay predictions for the missing Λ_c states, which may be helpful for the observations in forthcoming experiments.

A. 1*P*-wave *λ*-mode excitations

For the $1P$-wave λ-mode Λ_c baryons, there are two states according to the quark model classification: $\Lambda_c|J^P=1/2^-,1\rangle_\lambda$ and $\Lambda_c|J^P=3/2^-,1\rangle_\lambda$. They correspond to the well determined states $\Lambda_c(2595)^+$ and $\Lambda_c(2625)^+$, respectively. Hence, we fix the masses of the two states at the physical masses and list their decay properties in Table 3.

Considering the uncertainties for the experimental data and theoretical calculations, the theoretical value is roughly consistent with the observations, which proves the applicability of the quark pair creation model. In addi-

Table 2. Masses (MeV) of the final baryons and mesons [4, 29, 63].

State	Mass	State	Mass	State	Mass
p	938.27	π^0	134.98	η'	957.78
n	939.57	$\pi^\pm$	139.57	ρ	775.26
Λ_c^+	2286.46	η	547.862	$\Lambda_c\|J^P=1/2^-,1\rangle_\lambda$	2592.25
Σ_c^0	2453.75	ω	782.66	$\Lambda_c\|J^P=3/2^-,1\rangle_\lambda$	2628.00
Σ_c^+	2452.65	K^0	497.611	$\Sigma_c\|J^P=1/2^-,0\rangle_\lambda$	2823
Σ_c^{++}	2453.97	K^+	493.677	$\Sigma_c\|J^P=1/2^-,1\rangle_\lambda$	2809
Ξ_c^+	2467.71	K^{0*}	895.55	$\Sigma_c\|J^P=3/2^-,1\rangle_\lambda$	2829
Ξ_c^0	2470.44	K^{+*}	891.67	$\Sigma_c\|J^P=3/2^-,2\rangle_\lambda$	2802
$\Xi_c'^+$	2578.2	D^0	1864.84	$\Sigma_c\|J^P=5/2^-,2\rangle_\lambda$	2835
$\Xi_c'^0$	2578.7	D^+	1869.66	$\Sigma_c\|J^P=1/2^-,1\rangle_\rho$	2909
$\Xi_c'^{+*}$	2645.1	D^{0*}	2006.85	$\Sigma_c\|J^P=3/2^-,1\rangle_\rho$	2910
$\Xi_c'^{0*}$	2646.16	D^{+*}	2010.26		

Table 3. Strong decay properties of the λ-mode $1P$-wave Λ_c states, which are taken as $\Lambda_c(2595)^+$ and $\Lambda_c(2625)^+$, respectively. $\Gamma_{\rm Total}$ represents the total decay width, and Expt. denotes the experimental value. The units are MeV.

Decay width	$\Lambda_c\left\|J^P=1/2^-,1\right\rangle_\lambda$	$\Lambda_c\left\|J^P=3/2^-,1\right\rangle_\lambda$
	$\Lambda_c(2595)^+$	$\Lambda_c(2625)^+$
$\Gamma[\Sigma_c^0\pi^+]$	–	0.02
$\Gamma[\Sigma_c^+\pi^0]$	7.07	0.01
$\Gamma[\Sigma_c^{++}\pi^-]$	–	0.01
$\Gamma_{\rm Total}$	7.07	0.04
Expt.	$2.59\pm0.30\pm0.47$	<0.52

tion, it should be noted that the mass of $\Lambda_c(2595)^+$ is very close to the threshold of $\Sigma_c\pi$, and the partial decay widths are highly sensitive to the precision of mass.

B. 1*P*-wave *ρ*-mode excitations

For the $1P$-wave ρ-mode Λ_c baryons, there are five states: $\Lambda_c\left|J^P=1/2^-,0\right\rangle_\rho$, $\Lambda_c\left|J^P=1/2^-,1\right\rangle_\rho$, $\Lambda_c\left|J^P=3/2^-,1\right\rangle_\rho$, $\Lambda_c\left|J^P=3/2^-,2\right\rangle_\rho$, and $\Lambda_c\left|J^P=5/2^-,2\right\rangle_\rho$. According to the theoretical predictions by various methods, the mass of the $1P$-wave ρ-mode Λ_c baryons is approximately $M\sim 2.85$ GeV. Meanwhile, we notice that their masses are above the threshold of ND, while their strong decays are forbidden due to the orthogonality of spatial wave functions. This is true for all of the ρ-mode excitations. Hence, we mainly focus on their strong decays into $\Sigma_c\pi$ and $\Sigma_c^*\pi$. Fixing the masses of $1P$-wave ρ-mode Λ_c baryons at the predictions in Ref. [30], we study their strong decay properties, as listed in Table 4.

Within the $j-j$ coupling scheme, the total decay width of $\Lambda_c|J^P=1/2^-,0\rangle_\rho$ is most likely to be near zero. We know that the states in the $j-j$ coupling scheme can be expressed by a linear combination of the configurations in the $L-S$ coupling scheme, which reads

$$\left|\left\{\left[(l_\rho l_\lambda)_L\, s_\rho\right]_j s_Q\right\}_{J^P}\right\rangle=(-1)^{L+s_\rho+1/2+J}\sqrt{2J+1}\sum_S\sqrt{2S+1}\times\begin{pmatrix} L & s_\rho & j\\ s_Q & J & S\end{pmatrix}\left|\left\{\left[(l_\rho l_\lambda)_L\,(s_\rho s_Q)_S\right]_J\right\}\right\rangle. \tag{13}$$

In this expression, l_ρ and l_λ are the ρ- and λ-mode quantum numbers of the orbital angular momentum, respectively. The total orbital angular momentum $L=|l_\rho-l_\lambda|,\cdots,l_\rho+l_\lambda$. s_ρ is the quantum number of the total spin of the two light quarks, and s_Q is the spin of the heavy quark. The total spin angular momentum $S=|s_\rho-s_Q|,\cdots,s_\rho+s_Q$. J is the total angular momentum. This means the states in the $j-j$ coupling scheme have a mixing angle θ. Considering the heavy quark symmetry not being strictly true and slightly breaking in the Λ_c system, the mixing angle θ fluctuates around the center value ($\theta\simeq 35°$). To investigate this effect, we plot the strong decay widths of $\Lambda_c|J^P=1/2^-,0\rangle_\rho$ as a function of the mixing angle in Fig 2. We obtain that $\Lambda_c|J^P=1/2^-,0\rangle_\rho$ is still a very narrow state, and the $\Sigma_c\pi$ decay channel almost saturates its total decay widths.

The two states $\Lambda_c|J^P=1/2^-,1\rangle_\rho$ and $\Lambda_c|J^P=3/2^-,1\rangle_\rho$ are probably broad states with a total decay width around $\Gamma_{\rm Total}\sim 780$ MeV. $\Lambda_c|J^P=1/2^-,1\rangle_\lambda$ dominantly decays into the $\Sigma_c\pi$ channel, while $\Lambda_c|J^P=3/2^-,1\rangle_\rho$ mainly decays into the $\Sigma_c^*\pi$ channel. In this case, $\Lambda_c|J^P=1/2^-,1\rangle_\rho$ and $\Lambda_c|J^P=3/2^-,1\rangle_\rho$ might be too broad to be observed experimentally.

The states $\Lambda_c|J^P=3/2^-,2\rangle_\rho$ and $\Lambda_c|J^P=5/2^-,2\rangle_\rho$ may be moderate states with a total width of several tens of MeV, and their strong decays are governed by the $\Sigma_c\pi$

Table 4. Strong decay properties of the ρ-mode $1P$- and $2P$-wave Λ_c states within the quark pair creation model, where masses are taken from the predictions in Ref. [30]. $\Gamma_{\rm Total}$ represents the total decay width, and Expt. denotes the experimental value. The units are MeV.

Decay width	$\Lambda_c\|J^P=1/2^-,0\rangle_\rho$	$\Lambda_c\|J^P=1/2^-,1\rangle_\rho$	$\Lambda_c\|J^P=3/2^-,1\rangle_\rho$	$\Lambda_c\|J^P=3/2^-,2\rangle_\rho$		$\Lambda_c\|J^P=5/2^-,2\rangle_\rho$	
	M=2780	M=2830	M=2840	M=2885	$\Lambda_c(2910)^+$	M=2900	$\Lambda_c(2910)^+$
$\Gamma[\Sigma_c\pi]$	0.00	782.44	10.33	31.53	41.96	16.34	16.65
$\Gamma[\Sigma_c^*\pi]$	0.00	6.42	768.63	14.37	21.12	27.50	32.85
$\Gamma_{\rm Total}$	0.00	788.86	778.96	45.90	63.08	43.84	49.50
Expt.	-	-	-	$51.8\pm20.0\pm18.8$			

Decay width	$\Lambda_{c1}\|J^P=1/2^-,0\rangle_\rho$	$\Lambda_{c1}\|J^P=1/2^-,1\rangle_\rho$	$\Lambda_{c1}\|J^P=3/2^-,1\rangle_\rho$	$\Lambda_{c1}\|J^P=3/2^-,2\rangle_\rho$	$\Lambda_{c1}\|J^P=5/2^-,2\rangle_\rho$
	M=3200	M=3240	M=3240	M=3255	M=3130
$\Gamma[\Sigma_c\pi]$	0.00	19.02	7.10	12.15	6.78
$\Gamma[\Sigma_c^*\pi]$	0.00	16.47	21.08	14.47	22.55
$\Gamma[\Lambda_c\omega]$	0.00	7.30	7.30	12.58	2.10
$\Gamma[\Lambda_c\eta]$	3.61	0.00	0.00	3.38	4.15
$\Gamma[\Lambda_c\eta']$	-	-	-	3.38	-
$\Gamma[\Sigma_c\rho]$	-	0.23	0.11	176.79	-
$\Gamma[\Xi_c K]$	0.13	0.00	0.00	2.65	1.36
$\Gamma[\Xi_c' K]$	0.00	1.86	0.58	1.21	0.05
$\Gamma[\Xi_c^* K]$	0.00	0.44	6.05	0.53	-
$\Gamma[\Lambda_c\|J^P=1/2^-,1\rangle_\lambda\eta]$	0.00	0.04	0.01	1.95	-
$\Gamma[\Lambda_c\|J^P=3/2^-,1\rangle_\lambda\eta]$	0.00	0.01	0.03	0.25	-
$\Gamma[\Sigma_c\|J^P=1/2^-,0\rangle_\lambda\pi]$	0.00	2.58	2.58	0.00	0.00
$\Gamma[\Sigma_c\|J^P=1/2^-,1\rangle_\lambda\pi]$	0.15	6.64	1.66	13.51	0.02
$\Gamma[\Sigma_c\|J^P=3/2^-,1\rangle_\lambda\pi]$	0.28	2.77	6.92	1.41	6.84
$\Gamma[\Sigma_c\|J^P=3/2^-,2\rangle_\lambda\pi]$	0.00	0.24	0.41	3.76	0.14
$\Gamma[\Sigma_c\|J^P=5/2^-,2\rangle_\lambda\pi]$	0.00	0.40	0.05	3.29	0.90
$\Gamma[\Sigma_c\|J^P=1/2^-,1\rangle_\rho\pi]$	57.44	10.96	2.74	33.77	0.01
$\Gamma[\Sigma_c\|J^P=3/2^-,1\rangle_\rho\pi]$	113.60	5.44	14.27	7.94	6.94
$\Gamma_{\rm Total}$	175.21	74.40	70.89	293.02	51.84

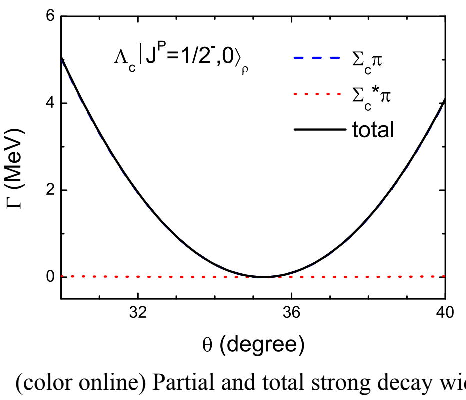

Fig. 2. (color online) Partial and total strong decay widths of $\Lambda_c|J^P=1/2^-,0\rangle_\rho$ as a function of mixing angle.

and $\Sigma_c^*\pi$ channels. We note that the new state $\Lambda_c(2910)^+$ was observed in the $\Sigma_c\pi$ channel by the Belle Collaboration [17]. Its mass and width were measured to be $M=2913.8\pm5.6\pm3.8$ MeV and $\Gamma=51.8\pm20.0\pm18.8$ MeV, respectively. Combining the predicted masses and decay properties, $\Lambda_c|J^P=3/2^-,2\rangle_\rho$ and $\Lambda_c|J^P=5/2^-,2\rangle_\rho$ may be candidates of $\Lambda_c(2910)^+$. Hence, we fix the masses of the two states as $M=2914$ MeV, and their decays are listed in Table 4. It is found that the total decay width of $\Lambda_c|J^P=3/2^-,2\rangle_\rho$ is approximately

$$\Gamma_{\rm Total}\simeq 63.08\ {\rm MeV}, \tag{14}$$

which is consistent with the observation. Meanwhile, the main decay channel is $\Sigma_c\pi$, and the predicted partial decay width ratio is

$$\frac{\Gamma[\Lambda_c|J^P=3/2^-,2\rangle_\rho]\to\Sigma_c\pi}{\Gamma[\Lambda_c|J^P=3/2^-,2\rangle_\rho\to\Sigma_c^*\pi]}\simeq 1.99. \quad (15)$$

This calculation is consistent with the fact that $\Lambda_c(2910)^+$ was first observed in the $\Sigma_c\pi$ invariant mass distribution by the Belle Collaboration [17].

Regarding $\Lambda_c|J^P=5/2^-,2\rangle_\rho$, its total decay width is approximately

$$\Gamma_{\rm Total}\simeq 49.50\ \rm MeV, \quad (16)$$

which is in good agreement with the observation. The dominant decay channel is $\Sigma_c^*\pi$, and the corresponding branching fraction is

$$\frac{\Gamma[\Lambda_c|J^P=5/2^-,2\rangle_\rho]\to\Sigma_c^*\pi}{\Gamma_{\rm Total}}\simeq 66\%. \quad (17)$$

Meanwhile, the predicted branching ratio of the $\Sigma_c\pi$ channel is

$$\frac{\Gamma[\Lambda_c|J^P=5/2^-,2\rangle_\rho]\to\Sigma_c\pi}{\Gamma_{\rm Total}}\simeq 34\%, \quad (18)$$

which is sufficiently large to be observed experimentally. To further decode the nature of $\Lambda_c(2910)^+$ and determine whether it is $\Lambda_c|J^P=3/2^-,2\rangle_\rho$ or $\Lambda_c|J^P=5/2^-,2\rangle_\rho$, the partial decay width ratio between $\Sigma_c\pi$ and $\Sigma_c^*\pi$ may be a good criterion.

Nevertheless, considering that the current experimental data are limited and bare large errors, there are other possible explanations, such as the D^*N molecular state [49, 52] or Λ_c resonances with different spin-parity [22, 24]. To further clarify the nature of $\Lambda_c(2910)^+$, more discussions are necessary.

C. 1*D*-wave *λ*-mode excitations

According to the symmetry of wave functions, there are two λ-mode $1D$-wave Λ_c states (see Table 1): $\Lambda_c|J^P=3/2^+,2\rangle_{\lambda\lambda}$ and $\Lambda_c|J^P=5/2^+,2\rangle_{\lambda\lambda}$. As listed in Table 1, the masses of the two $1D$ λ-mode Λ_c states fluctuate around ~ 2.85 GeV. Based on the predicted masses, $\Lambda_c|J^P=3/2^+,2\rangle_{\lambda\lambda}$ and $\Lambda_c|J^P=5/2^+,2\rangle_{\lambda\lambda}$ are probably assignments of observed states $\Lambda_c(2860)^+$ and $\Lambda_c(2880)^+$, respectively. Hence, we fix the masses of $\Lambda_c|J^P=3/2^+,2\rangle_{\lambda\lambda}$ and $\Lambda_c|J^P=5/2^+,2\rangle_{\lambda\lambda}$ at $M=2856$ MeV and $M=2882$ MeV, respectively, and list their decays in Table 5.

The total width of $\Lambda_c|J^P=3/2^+,2\rangle_{\lambda\lambda}$ is obtained as

$$\Gamma_{\rm Total}\simeq 68.56\ \rm MeV, \quad (19)$$

which is in good agreement with the experimental central value. Furthermore, pD^0 is one of the main decay modes,

Table 5. Partial decay widths of $\Lambda_c(2860)^+$ and $\Lambda_c(2880)^+$ assigned as λ-mode $1D$-wave Λ_c states $\Lambda_c|J^P=3/2^+,2\rangle_{\lambda\lambda}$ and $\Lambda_c|J^P=5/2^+,2\rangle_{\lambda\lambda}$, respectively. The units are MeV.

Decay width	$\Lambda_c\|J^P=3/2^+,2\rangle_{\lambda\lambda}$	$\Lambda_c\|J^P=5/2^+,2\rangle_{\lambda\lambda}$
	$\Lambda_c(2860)^+$	M=2882
$\Gamma[\Sigma_c\pi]$	24.32	1.74
$\Gamma[\Sigma_c^*\pi]$	3.86	24.28
$\Gamma[pD^0]$	21.61	0.35
$\Gamma[nD^+]$	18.77	0.27
$\Gamma_{\rm Total}$	68.56	26.64
Expt.	$67.6^{+10.1}_{-8.1}\pm1.4^{+5.9}_{-20.0}$	$5.6^{+0.8}_{-0.6}$

and the predicted branching fraction is

$$\frac{\Gamma[\Lambda_c|J^P=3/2^+,2\rangle_{\lambda\lambda}]\to pD^0}{\Gamma_{\rm Total}}\simeq 32\%. \quad (20)$$

This result is consistent with the fact that $\Lambda_c(2860)^+$ was observed in the pD^0 invariant mass distribution [14]. In addition, we obtain

$$\frac{\Gamma[\Lambda_c|J^P=3/2^+,2\rangle_{\lambda\lambda}\to\Sigma_c\pi]}{\Gamma[\Lambda_c|J^P=3/2^+,2\rangle_{\lambda\lambda}\to pD^0]}\simeq 1.13, \quad (21)$$

$$\frac{\Gamma[\Lambda_c|J^P=3/2^+,2\rangle_{\lambda\lambda}\to nD^+]}{\Gamma[\Lambda_c|J^P=3/2^+,2\rangle_{\lambda\lambda}\to pD^0]}\simeq 0.87. \quad (22)$$

If the observed state $\Lambda_c(2860)^+$ corresponds to $\Lambda_c|J^P=3/2^+,2\rangle_{\lambda\lambda}$, besides the pD^0 channel, $\Sigma_c\pi$ and nD^+ may be two interesting channels for the observation of $\Lambda_c(2860)^+$ in future experiments. The $\Lambda_c(2860)^+$ resonance should be observed in the $\Lambda_c\pi\pi$ and nD^+ final states as well.

For the state $\Lambda_c|J^P=5/2^+,2\rangle_{\lambda\lambda}$(see Table 5), fixing its mass to M=2882 MeV, the total decay width

$$\Gamma_{\rm Total}\simeq 26.64\ \rm MeV, \quad (23)$$

is approximately five times that of the observation for $\Lambda_c(2880)^+$. Meanwhile, the predicted partial decay width ratio between pD^0 and $\Sigma_c\pi$ is

$$\frac{\Gamma[\Lambda_c|J^P=5/2^+,2\rangle_{\lambda\lambda}\to pD^0]}{\Gamma[\Lambda_c|J^P=5/2^+,2\rangle_{\lambda\lambda}\to\Sigma_c\pi]}\simeq 0.20. \quad (24)$$

This value is much smaller than the ratio measured $(0.75\pm0.03\pm0.07)$ by the Belle Collaboration [16]. Meanwhile, our theoretical calculation indicates that the $\Sigma_c^*\pi$ decay channel almost saturates the total decay widths. The partial decay width ratio between $\Sigma_c^*\pi$ and $\Sigma_c\pi$ is

$$\frac{\Gamma[\Lambda_c|J^P=5/2^+,2\rangle_{\lambda\lambda}\to\Sigma_c^*\pi]}{\Gamma[\Lambda_c|J^P=5/2^+,2\rangle_{\lambda\lambda}\to\Sigma_c\pi]}\simeq 13.95, \tag{25}$$

which is inconsistent with the analysis from the CLEO Collaboration [11]. Hence, according to our investigation, the experimental widths and some partial decay width ratios cannot be reproduced. To further clarify the properties of the $\Lambda_c(2880)^+$ resonance, more experimental and theoretical investigations may be necessary.

D. 1*D*-wave *ρ*-mode excitations

Within the quark model, there are two ρ-mode $1D$-wave Λ_c states: $\Lambda_c|J^P=3/2^+,2\rangle_{\rho\rho}$ and $\Lambda_c|J^P=5/2^+,2\rangle_{\rho\rho}$. According to the mass predictions listed in Table 1, their masses are approximately $M\sim 3.10$ GeV. First, we fix the masses at the predictions within a relativized quark potential model in Ref. [30] and list the decay properties in Table 6.

The $\Lambda_c|J^P=3/2^+,2\rangle_{\rho\rho}$ state may be a moderate state with a width of $\Gamma_{\rm Total}\simeq 120$ MeV and mainly decays into $\Sigma_c\pi$. The predicted branching fraction is

$$\frac{\Gamma[\Lambda_c|J^P=3/2^+,2\rangle_{\rho\rho}\to\Sigma_c\pi]}{\Gamma_{\rm Total}}\simeq 69\%. \tag{26}$$

Hence, the $\Lambda_c|J^P=3/2^+,2\rangle_{\rho\rho}$ state is likely to be observed in the $\Lambda_c\pi\pi$ final state via the decay chain $\Lambda_c|J^P=3/2^+,2\rangle_{\rho\rho}\to\Sigma_c\pi\to\Lambda_c\pi\pi$.

Meanwhile, the partial decay width of $\Sigma_c^*\pi$ is sizable, and the branching fraction is

$$\frac{\Gamma[\Lambda_c|J^P=3/2^+,2\rangle_{\rho\rho}\to\Sigma_c^*\pi]}{\Gamma_{\rm Total}}\simeq 21\%. \tag{27}$$

Table 6. Partial decay widths of the two ρ-mode $1D$-wave Λ_c states, with masses taken from the predictions in Ref. [30]. $\Gamma_{\rm Total}$ represents the total decay width, and units are MeV.

Decay width	$\Lambda_c\|J^P=3/2^+,2\rangle_{\rho\rho}$	$\Lambda_c\|J^P=5/2^+,2\rangle_{\rho\rho}$
	M=3035	M=3140
$\Gamma[\Sigma_c\pi]$	82.20	33.38
$\Gamma[\Sigma_c^*\pi]$	25.66	107.24
$\Gamma[\Lambda_c\omega]$	-	31.25
$\Gamma[\Xi_c'K]$	-	0.02
$\Gamma[\Sigma_c\|J^P=1/2^-,0\rangle_\lambda\pi]$	0.01	0.29
$\Gamma[\Sigma_c\|J^P=1/2^-,1\rangle_\lambda\pi]$	0.13	0.79
$\Gamma[\Sigma_c\|J^P=3/2^-,1\rangle_\lambda\pi]$	0.06	1.91
$\Gamma[\Sigma_c\|J^P=3/2^-,2\rangle_\lambda\pi]$	11.81	0.11
$\Gamma[\Sigma_c\|J^P=5/2^-,2\rangle_\lambda\pi]$	0.00	2085
$\Gamma_{\rm Total}$	119.87	195.84

Thus, $\Lambda_c|J^P=3/2^+,2\rangle_{\rho\rho}\to\Sigma_c^*\pi\to\Lambda_c\pi\pi$ may be another interesting decay chain for experimental exploration.

The other ρ-mode $1D$-wave state $\Lambda_c|J^P=5/2^+,2\rangle_{\rho\rho}$ has a width of $\Gamma_{\rm Total}\simeq 196$ MeV and mainly decays into $\Sigma_c^*\pi$ with a branching fraction

$$\frac{\Gamma[\Lambda_c|J^P=5/2^+,2\rangle_{\rho\rho}\to\Sigma_c^*\pi]}{\Gamma_{\rm Total}}\simeq 55\%. \tag{28}$$

Furthermore, $\Lambda_c|J^P=5/2^+,2\rangle_{\rho\rho}$ may have a considerable decay rate into $\Sigma_c\pi$ and $\Lambda_c\omega$. The predicted branching fractions are

$$\frac{\Gamma[\Lambda_c|J^P=5/2^+,2\rangle_{\rho\rho}\to\Sigma_c\pi/\Lambda_c\omega]}{\Gamma_{\rm Total}}\simeq 17/16\%. \tag{29}$$

However, this state may be too broad to be observed experimentally.

Then, accounting for the uncertainty of the predicted masses, which may bring uncertainties to the theoretical results, we plot the decay properties of the $1D$-wave ρ-mode Λ_c as functions of masses within the range of $M=(3.00-3.15)$ GeV, as shown in Fig. 3. We can find that the total decay widths vary within the scope of $\Gamma_{\rm Total}<200$ MeV as the mass increases. In addition, when the masses of the $1D$-wave ρ-mode Λ_c states are above the threshold of $\Lambda_c\omega$, the partial decay width of this channel becomes sizable and increases dramatically with mass.

E. 2*S*-wave excitations

The $2S$-wave states are the first radial excited states, and the radial quantum number $n_\lambda=1$ or $n_\rho=1$. Hence, according to the symmetry of the wave function, there are two $2S$-wave Λ_c states: $\Lambda_{c1}|J^P=1/2^+,0\rangle_\lambda(n_\lambda=1)$ and $\Lambda_{c1}|J^P=1/2^+,0\rangle_\rho(n_\rho=1)$. As listed in Table 1, the mass of the $\Lambda_{c1}|J^P=1/2^+,0\rangle_\lambda$ state is approximately $M\sim(2.76$–$2.79)$ MeV, while the mass of the $\Lambda_{c1}|J^P=1/2^+,0\rangle_\rho$ state is slightly higher at approximately $M\sim 2.97$ MeV. Fixing the masses at the predictions in Ref. [30], we analyze

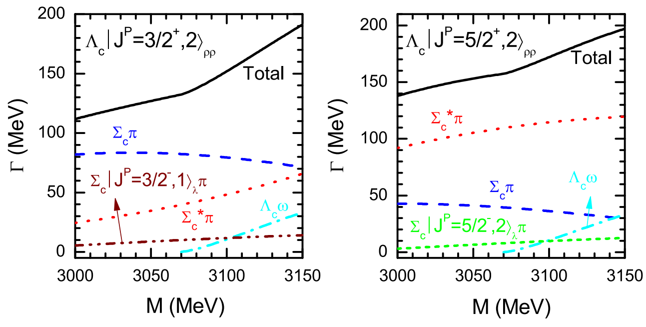

Fig. 3. (color online) Partial and total strong decay widths of the two ρ-mode $1D$-wave Λ_c states as functions of the masses. Some decay channels are too small to show in the figure.

the decay properties of the two 2S-wave Λ_c states and list their partial strong decay widths in Table 7.

The $\Lambda_{c1}|J^P=1/2^+,0\rangle_\lambda$ state probably has a narrow width of several tens of MeV and mainly decays into the $\Sigma_c\pi$ and $\Sigma_c^*\pi$ channels. In this case, this state has a good potential to be observed in the $\Lambda_c\pi\pi$ final state by the intermediate channels $\Sigma_c\pi$ and $\Sigma_c^*\pi$. Combining the predicted mass and our calculations, the $\Lambda_{c1}|J^P=1/2^+,0\rangle_\lambda$ state may be an assignment of the observed state $\Lambda_c(2765)^+$. Hence, we further take this state as $\Lambda_c(2765)^+$ and list its decay properties in Table 7. With the mass of $\Lambda_{c1}|J^P=1/2^+,0\rangle_\lambda$ fixed at $M=2767$ MeV, the total decay width

$$\Gamma_{\text{Total}} \simeq 21.14\ \text{MeV} \tag{30}$$

is approximately half of the experimental value ($\Gamma_{\text{Expt.}}=$ 50 MeV). The predicted partial decay width ratio between the dominant modes $\Sigma_c\pi$ and $\Sigma_c^*\pi$ is

$$\frac{\Gamma[\Lambda_{c1}|J^P=1/2^+,0\rangle_\lambda\to\Sigma_c\pi]}{\Gamma[\Lambda_{c1}|J^P=1/2^+,0\rangle_\lambda\to\Sigma_c^*\pi]}\simeq 1.01. \tag{31}$$

This result is consistent with the fact that $\Lambda_c(2765)^+$ was first observed in the $\Sigma_c\pi$ and $\Sigma_c^*\pi$ channels by the CLEO Collaboration [11]. Thus, the state $\Lambda_{c1}|J^P=1/2^+,0\rangle_\lambda$ may be a candidate of $\Lambda_c(2765)^+$.

For the other 2S-wave state $\Lambda_{c1}|J^P=1/2^+,0\rangle_\rho$, the main decay channels are $\Sigma_c\pi$ and $\Sigma_c^*\pi$ as well, and the partial width ratio is

$$\frac{\Gamma[\Lambda_{c1}|J^P=1/2^+,0\rangle_\rho\to\Sigma_c\pi]}{\Gamma[\Lambda_{c1}|J^P=1/2^+,0\rangle_\rho\to\Sigma_c^*\pi]}\simeq 0.54. \tag{32}$$

This state is most likely to be a broad state with a width of approximately $\Gamma_{\text{Total}}\simeq 245$ MeV. Thus, it is difficult to observe the $\Lambda_{c1}|J^P=1/2^+,0\rangle_\rho$ state in experiments due to its broad decay width.

Table 7. Partial decay widths of the two 2S-wave Λ_c states, with masses taken from the predictions in Ref. [30]. Γ_{Total} represents the total decay width, and the units are MeV.

Decay width	$\Lambda_{c1}\|J^P=1/2^+,0\rangle_\lambda$		$\Lambda_{c1}\|J^P=1/2^+,0\rangle_\rho$
	M=2775	$\Lambda_c(2765)^+$	M=2970
$\Gamma[\Sigma_c\pi]$	11.63	10.90	81.48
$\Gamma[\Sigma_c^*\pi]$	11.57	10.24	149.88
$\Gamma[\Sigma_c\|J^P=1/2^-,0\rangle_\lambda\pi]$	–	–	13.15
$\Gamma[\Sigma_c\|J^P=1/2^-,1\rangle_\lambda\pi]$	–	–	0.00
$\Gamma[\Sigma_c\|J^P=3/2^-,1\rangle_\lambda\pi]$	–	–	0.00
$\Gamma[\Sigma_c\|J^P=3/2^-,2\rangle_\lambda\pi]$	–	–	0.01
Γ_{Total}	23.20	21.14	244.52
Expt.	50		–

Considering the uncertainty of the masses of the 2S-wave Λ_c states, we further investigate the strong decay widths as a function of the mass in Fig. 4. It is shown that the decay properties of the 2S-wave Λ_c excitations are sensitive to their masses varying in the considered region. Furthermore, if the mass of $\Lambda_{c1}|J^P=1/2^+,0\rangle_\lambda$ is above the threshold of ND, the corresponding partial decay width of ND increases dramatically with mass and is crucial in the strong decay.

F. 2P-wave λ-mode excitations

In these calculations, the 2P-wave λ-mode Λ_c excitations correspond to the radial quantum number $n_\lambda=1$ and orbital quantum number $l_\lambda=1$. Hence, based on the quark model classification, there are two 2P-wave λ-mode Λ_c states: $\Lambda_{c1}|J^P=1/2^-,1\rangle_\lambda$ and $\Lambda_{c1}|J^P=3/2^-,1\rangle_\lambda$. Their theoretical masses and possible two-body decay channels are listed in Table 1.

From the table, it is known that the predicted masses of the two 2P-wave λ-mode Λ_c baryons are approximately $M\sim 3.00$ GeV, which is close to the measured mass of the observed state $\Lambda_c(2940)^+$. As a possible assignment, it is crucial to investigate the decay behaviors of the two 2P-wave λ-mode Λ_c baryons. Considering the uncertainties of the predicted masses of $\Lambda_{c1}|J^P=1/2^-,1\rangle_\lambda$ and $\Lambda_{c1}|J^P=3/2^-,1\rangle_\lambda$, we plot the decay width as a function of the mass in the range of $M=(2.90-3.05)$ GeV in Fig. 5.

From Fig. 5, the total decay widths of the two 2P-wave λ-mode Λ_c baryons are approximately dozens of MeV within the mass range that we considered. When their masses lie below the threshold of ND^*, their strong decays are dominated by the ND channel. However, if their masses are above the threshold of ND^*, the dominant decay channel should be ND^*, and their total decay widths show a strong dependence on the masses.

In addition, we notice that the measured mass and total decay width of $\Lambda_c(2940)^+$ are consistent with the

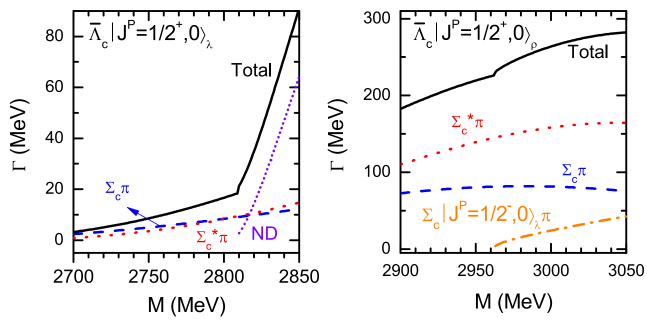

Fig. 4. (color online) Partial and total strong decay widths of the two 2S-wave Λ_c states as functions of the masses. Some decay channels are too small to show in the figure.

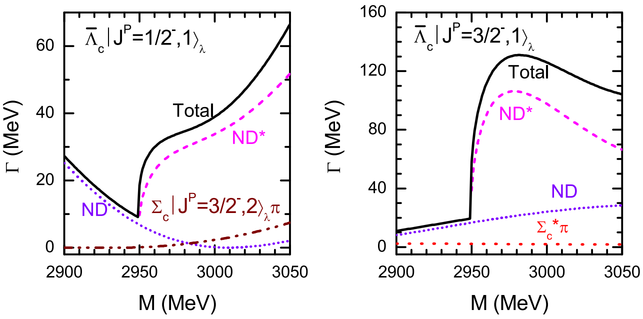

Fig. 5. (color online) Partial and total strong decay widths of the two λ-mode $2P$-wave Λ_c states as functions of the masses. Some decay channels are too small to show in the figure.

properties the two $2P$-wave λ-mode Λ_c baryons. Hence, we further fix the masses of $\Lambda_{c1}|J^P=1/2^-,1\rangle_\lambda$ and $\Lambda_{c1}|J^P=3/2^-,1\rangle_\lambda$ at $M=2940$ MeV and list their decay properties in Table 8.

It can be seen that the total decay width of $\Lambda_{c1}|J^P=1/2^-,1\rangle_\lambda$ is

$$\Gamma_{\rm Total}\simeq 16.47\ {\rm MeV}, \tag{33}$$

which is in agreement with the experimental observation. The dominant decay channels are pD^0 and nD^+ with predicted branching fractions of

$$\frac{\Gamma[\Lambda_{c1}|J^P=1/2^-,1\rangle_\lambda\to pD^0/nD^+]}{\Gamma_{\rm Total}}\simeq 35/42\%. \tag{34}$$

Meanwhile, the $\Sigma_c^*\pi$ decay channel occupies a sizable branching fraction, and the corresponding branching fraction is approximately

$$\frac{\Gamma[\Lambda_{c1}|J^P=1/2^-,1\rangle_\lambda\to\Sigma_c^*\pi]}{\Gamma_{\rm Total}}\simeq 19\%. \tag{35}$$

However, we notice that the partial decay width of $\Lambda_{c1}|J^P=1/2^-,1\rangle_\lambda\to\Sigma_c\pi$ seems slightly small, which does not accord with the fact that $\Lambda_c(2940)$ was observed in the $\Sigma_c\pi$ channel. Meanwhile, the partial decay width ratio between pD^0 and $\Sigma_c\pi$

$$\frac{\Gamma[\Lambda_{c1}|J^P=1/2^-,1\rangle_\lambda\to pD^0]}{\Gamma[\Lambda_{c1}|J^P=1/2^-,1\rangle_\lambda\to\Sigma_c\pi]}\simeq 8.41 \tag{36}$$

is significantly greater than the latest experimental value $(3.59\pm0.21\pm0.56)$ measured by the LHCb Collaboration [16].

The total decay width of $\Lambda_{c1}|J^P=3/2^-,1\rangle_\lambda$

$$\Gamma_{\rm Total}\simeq 23.65\ {\rm MeV} \tag{37}$$

agrees with the experimental value as well. Meanwhile, the decays are governed by pD^0 and nD^+, and the predicted branching fractions are

$$\frac{\Gamma[\Lambda_{c1}|J^P=3/2^-,1\rangle_\lambda\to pD^0/nD^+]}{\Gamma_{\rm Total}}\simeq 43/40\%. \tag{38}$$

In addition, $\Lambda_{c1}|J^P=3/2^-,1\rangle_\lambda$ has a sizable decay width in $\Sigma_c\pi$. The predicted partial decay width ratio between pD^0 and $\Sigma_c\pi$ is

$$\frac{\Gamma[\Lambda_{c1}|J^P=3/2^-,1\rangle_\lambda\to pD^0]}{\Gamma[\Lambda_{c1}|J^P=3/2^-,1\rangle_\lambda\to\Sigma_c\pi]}\simeq 4.48, \tag{39}$$

which is close to the upper limit of the measurement [16].

In conclusion, our calculation indicates that the strong decay properties of $\Lambda_{c1}|J^P=3/2^-,1\rangle_\lambda$ are in good agreement with the nature of $\Lambda_c(2940)$, and $\Lambda_{c1}|J^P=3/2^-,1\rangle_\lambda$ is a good candidate. It should be pointed out that the threshold of the main decay channel DN is close to the mass of $\Lambda_c(2940)$, which may suggest the importance of the coupled-channel effects for understanding the $\Lambda_c(2940)^+$ state.

Table 8. Partial decay widths of $\Lambda_c(2940)^+$ assigned as the two $2P$-wave λ-mode Λ_c states $\Lambda_{c1}|J^P=1/2^-,1\rangle_\lambda$ and $\Lambda_{c1}|J^P=3/2^-,1\rangle_\lambda$.

Decay width	$\Lambda_{c1}\|J^P=1/2^-,1\rangle_\lambda$	$\Lambda_{c1}\|J^P=3/2^-,1\rangle_\lambda$
	M=2940	$\Lambda_c(2940)^+$
$\Gamma[\Sigma_c\pi]$	0.68	2.28
$\Gamma[\Sigma_c^*\pi]$	3.18	1.61
$\Gamma[pD^0]$	5.72	10.21
$\Gamma[nD^+]$	6.89	9.55
$\Gamma_{\rm Total}$	16.47	23.65
Expt.	20^{+6}_{-5}	

G. 2*P*-wave *ρ*-mode excitations

In the present study, the $2P$-wave ρ-mode excitations correspond to the radial quantum number n_ρ=1 and orbital quantum number l_ρ=1. According to the quark model, there are five $2P$-wave ρ-mode Λ_c baryons: $\Lambda_{c1}|J^P=1/2^-,0\rangle_\rho$, $\Lambda_{c1}|J^P=1/2^-,1\rangle_\rho$, $\Lambda_{c1}|J^P=3/2^-,1\rangle_\rho$, $\Lambda_{c1}|J^P=3/2^-,2\rangle_\rho$, and $\Lambda_{c1}|J^P=5/2^-,2\rangle_\rho$. For their masses, there are a few discussions in theoretical references, and we list them in Table 1. From the table, the masses of the $2P$-wave ρ-mode $\Lambda_c$excitations are approximately $M\sim3.20$ GeV. Fixing the masses of the $2P$-wave ρ-mode Λ_c excitations on the predicted masses from Ref. [30], we discuss their decay properties and list the results in Table 4.

For the $\Lambda_{c1}|J^P=1/2^-,0\rangle_\rho$ state, the total decay width is approximately $\Gamma_{\rm Total} \simeq 175$ MeV. The dominant decay modes are $\Sigma_c|J^P = 1/2^-, 1\rangle_\rho\pi$ and $\Sigma_c|J^P = 3/2^-, 1\rangle_\rho\pi$ with the partial decay ratio

$$\frac{\Gamma[\Lambda_{c1}|J^P = 1/2^-, 0\rangle_\rho \to \Sigma_c|J^P = 1/2^-, 1\rangle_\rho\pi]}{\Gamma[\Lambda_{c1}|J^P = 1/2^-, 0\rangle_\rho \to \Sigma_c|J^P = 3/2^-, 1\rangle_\rho\pi]} \simeq 0.51. \quad (40)$$

Hence, this state may be observed in the $\Lambda_c\pi\pi\pi$ final state via the decay chains $\Lambda_{c1}|J^P = 1/2^-, 0\rangle_\rho \to \Sigma_c|J^P = 1/2^-, 1\rangle_\rho\pi \to \Sigma_c\pi\pi \to \Lambda_c\pi\pi\pi$ and $\Lambda_{c1}|J^P = 1/2^-, 0\rangle_\rho \to \Sigma_c|J^P = 3/2^-, 1\rangle_\rho\pi \to \Sigma_c^*\pi\pi \to \Lambda_c\pi\pi\pi$.

Meanwhile, the partial decay width of $\Gamma[\Lambda_{c1}|J^P = 1/2^-, 0\rangle_\rho \to \Lambda_c\eta]$ is considerable. The branching fraction is

$$\frac{\Gamma[\Lambda_{c1}|J^P = 1/2^-, 0\rangle_\rho \to \Lambda_c\eta]}{\Gamma_{\rm Total}} \simeq 2\%. \quad (41)$$

The $\Lambda_c\eta$ channel may also be a notable decay mode for future exploration of the $\bar{\Lambda}_c|J^P = 1/2^-, 0\rangle_\rho$ state.

The states $\Lambda_{c1}|J^P = 1/2^-, 1\rangle_\rho$ and $\Lambda_{c1}|J^P = 3/2^-, 1\rangle_\rho$ are most likely to be the moderate states with a total decay width of $\Gamma_{\rm Total} \sim 70$ MeV. Meanwhile, their dominant decay channels are different. $\Lambda_{c1}|J^P = 1/2^-, 1\rangle_\rho$ mainly decays via the $\Sigma_c\pi$ and $\Sigma_c^*\pi$ channels, and the branching fractions are

$$\frac{\Gamma[\Lambda_{c1}|J^P = 1/2^-, 1\rangle_\rho \to \Sigma_c\pi/\Sigma_c^*\pi]}{\Gamma_{\rm Total}} \simeq 26/22\%. \quad (42)$$

In addition, the $\Lambda_{c1}|J^P = 1/2^-, 1\rangle_\rho$ state has sizable partial widths decaying into $\Sigma_c|J^P = 1/2^-, 1\rangle_\rho\pi$, $\Lambda_c\omega$, and $\Sigma_c|J^P = 1/2^-, 1\rangle_\lambda\pi$. The predicted branching fractions of these channels are approximately $9\% - 15\%$.

As for $\Lambda_{c1}|J^P = 3/2^-, 1\rangle_\rho$, it decays mainly through the $\Sigma_c^*\pi$ channel. The predicted branching fraction is

$$\frac{\Gamma[\Lambda_{c1}|J^P = 3/2^-, 1\rangle_\rho \to \Sigma_c^*\pi]}{\Gamma[\rm Total]} \simeq 30\%. \quad (43)$$

Meanwhile, the partial decay widths of $\Sigma_c|J^P = 3/2^-, 1\rangle_\rho\pi$, $\Sigma_c|J^P = 3/2^-, 1\rangle_\lambda\pi$, $\Lambda_c\omega$, and $\Sigma_c\pi$ are considerable, and the corresponding branching fractions are approximately $(10\% - 20\%)$.

The decay width of the state $\Lambda_{c1}|J^P = 3/2^-, 2\rangle_\rho$ is approximately $\Gamma \simeq 293$ MeV. Its strong decays are governed by the $\Sigma_c\rho$ channel with the branching fraction around ~60%. Meanwhile, this state has a sizable decay rate, decaying into the $\Sigma_c|J^P = 1/2^-, 1\rangle_\rho\pi$ channel, and the predicted branching ratio is approximately ~12%. However, $\Lambda_{c1}|J^P = 3/2^-, 2\rangle_\rho$ might be too broad to be observed experimentally.

The state $\Lambda_{c1}|J^P = 5/2^-, 2\rangle_\rho$ may be a narrow state with a total decay width around $\Gamma \simeq 52$ MeV, and it mainly decays into the $\Sigma_c^*\pi$ channel. The predicted branching fraction is

$$\frac{\Gamma[\Lambda_{c1}|J^P = 5/2^-, 2\rangle_\rho \to \Sigma_c^*\pi]}{\Gamma[\rm Total]} \simeq 43\%. \quad (44)$$

Thus, this state is most likely to be observed in the $\Lambda_c\pi\pi$ final state via the decay chain $\Lambda_{c1}|J^P = 5/2^-, 2\rangle_\rho \to \Sigma_c^*\pi \to \Lambda_c\pi\pi$. In addition, the partial widths of $\Sigma_c\pi$ and $\Sigma_c|J^P = 3/2^-, 1\rangle_{\lambda/\rho}\pi$ are sizable as well, and all of the branching fractions are approximately 13%. Hence, the $\Lambda_c\pi\pi$ and $\Lambda_c\pi\pi\pi$ final states via the decay chains $\Lambda_{c1}|J^P = 5/2^-, 2\rangle_\rho \to \Sigma_c\pi \to \Lambda_c\pi\pi$ and $\Lambda_{c1}|J^P = 5/2^-, 2\rangle_\rho \to \Sigma_c|J^P = 3/2^-, 1\rangle_{\lambda/\rho}\pi \to \Sigma_c^*\pi\pi \to \Lambda_c\pi\pi\pi$ may also be interesting decay channels for experimental observations.

Similarly, we also plot the partial decay widths of the $2P$-wave ρ-mode Λ_c baryons as a function of mass in the region of $M = (3.10 - 3.30)$ GeV. The sensitivities of the decay properties of these states to their masses are shown in Fig. 6. From the figure, the partial widths of dominant decay channels for most of the states vary slightly with increasing mass. In addition, if the $2P$-wave ρ-mode Λ_c baryons are above the threshold of $\Sigma_c\rho$, most of the states can decay via $\Sigma_c\rho$ with a partial width of several MeV or more.

IV. SUMMARY

In the present study, we systematically investigated the strong decay properties of the low-lying $1P$-, $1D$-, $2S$-, and $2P$-wave Λ_c baryons in the framework of the quark pair creation model within the $j - j$coupling scheme. Our main results are summarized as follows.

The two $1P$-wave λ-mode Λ_c baryons $\Lambda_c|J^P = 1/2^-, 1\rangle_\lambda$ and $\Lambda_c|J^P = 3/2^-, 1\rangle_\lambda$ correspond to the well determined states $\Lambda_c(2595)^+$ and $\Lambda_c(2625)^+$, respectively, and we can reproduce the experimental data well in theory. Meanwhile, we notice that the mass of $\Lambda_c(2595)^+$ is very close to the threshold of $\Sigma_c\pi$, and this causes the decay widths to be highly sensitive to its mass precision.

For the $1P$-wave ρ-mode Λ_c baryons, $\Lambda_c|J^P = 1/2^-, 0\rangle_\rho$ is most likely to be a very narrow state, and the $\Sigma_c\pi$ decay mode almost saturates its total decay widths. Hence, the $\Lambda_c\pi\pi$ final state may be an ideal decay channel to explore $\Lambda_c|J^P = 1/2^-, 0\rangle_\rho$ in future experiments. The states $\Lambda_c|J^P = 1/2^-, 1\rangle_\rho$ and $\Lambda_c|J^P = 3/2^-, 1\rangle_\rho$ are probably relatively broad states with a width of approximately $\Gamma_{\rm Total} \sim 780$ MeV. Their dominant decay channels are $\Sigma_c\pi$ and $\Sigma_c^*\pi$, respectively. Considering that the decay widths are too broad, the two states may be difficult to observe experimentally. The total decay widths of $\Lambda_c|J^P = 3/2^-, 2\rangle_\rho$ and $\Lambda_c|J^P = 5/2^-, 2\rangle_\rho$ are several tens of MeV, and their strong decays are governed by the $\Sigma_c\pi$ and $\Sigma_c^*\pi$ channels. Combining the mass and decay properties of the newly observed state $\Lambda_c(2910)^+$, both $\Lambda_c|J^P =$

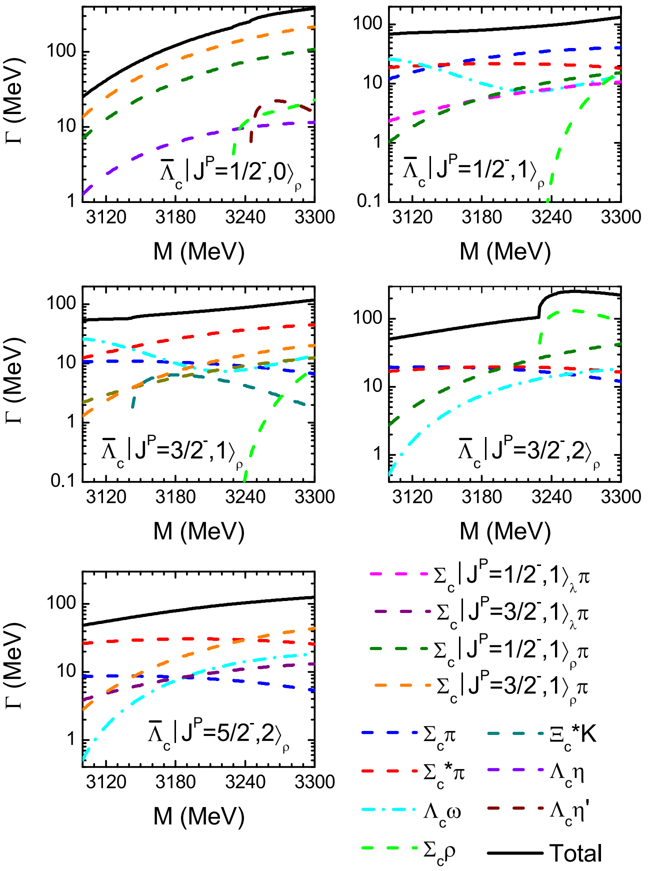

Fig. 6. (color online) Partial and total strong decay widths of the ρ-mode $2P$-wave Λ_c states as functions of mass. Some decay channels are too small to show in the figure.

$3/2^-,2\rangle_\rho$ and $\Lambda_c|J^P=5/2^-,2\rangle_\rho$ may be good candidates. To further determine which of the two is the most suitable one, the partial decay width ratio between $\Sigma_c\pi$ and $\Sigma_c^*\pi$ may be a good criterion.

As for the $1D$-wave λ-mode Λ_c excitations, $\Lambda_c|J^P=3/2^+,2\rangle_{\lambda\lambda}$ is probably a good assignment of the observed state $\Lambda_c(2860)^+$. In addition, if the observed state $\Lambda_c(2860)^+$ corresponds to $\Sigma_c|J^P=3/2^+,2\rangle_{\lambda\lambda}$, besides the pD^0 channel, $\Sigma_c\pi$ and nD^+ may be two interesting channels for future experimental observation. The state $\Lambda_c|J^P=5/2^+,2\rangle_{\lambda\lambda}$ may be a moderate state with a width of approximately $(20-30)$ MeV and mainly decays via the $\Sigma_c^*\pi$ channel. According to our investigation, if we take the observed state $\Lambda_c(2880)^+$ as $\Lambda_c|J^P=5/2^+,2\rangle_{\lambda\lambda}$, the measured total decay widths and some partial decay width ratios cannot be reproduced. To further clarify the inner structure of the $\Lambda_c(2880)^+$ resonance, more experimental and theoretical efforts are needed.

For the $1D$-wave ρ-mode Λ_c excitations, $\Lambda_c|J^P=3/2^+,2\rangle_{\rho\rho}$ may be a moderate state with a width of $\Gamma_{\rm Total}\sim 120$ MeV, and it mainly decays into $\Sigma_c\pi$. Meanwhile, the partial decay width of $\Sigma_c^*\pi$ is sizable. Hence, $\Lambda_c|J^P=3/2^+,2\rangle_{\rho\rho}$ has the possibility to be observed in the $\Lambda_c\pi\pi$ final state via the decay chains $\Sigma_c|J^P=3/2^+,2\rangle_{\rho\rho}\to\Sigma_c^{(*)}\pi\to\Lambda_c\pi\pi$. The other $1D$-wave ρ-mode state $\Lambda_c|J^P=5/2^+,2\rangle_{\rho\rho}$ has a width of $\Gamma_{\rm Total}\sim 196$ MeV and dominantly decays into $\Sigma_c^*\pi$. Moreover, the decay rates into $\Sigma_c\pi$ and $\Lambda_c\omega$ are considerable. However, this state may be too broad to be observed experimentally.

The $2S$-wave state $\Lambda_{c1}|J^P=1/2^+,0\rangle_\lambda$ probably has a width of dozens of MeV and mainly decays into the $\Sigma_c\pi$ and $\Sigma_c^*\pi$ channels. Combining the predicted mass and our calculations, the possibility of $\Lambda_{c1}|J^P=1/2^+,0\rangle_\lambda$ being an assignment of the observed state $\Lambda_c(2765)^+$ cannot be ruled out entirely. For the other $2S$-wave state $\Lambda_{c1}|J^P=1/2^+,0\rangle_\rho$, the main decay channels are $\Sigma_c\pi$ and $\Sigma_c^*\pi$. However, this state is most likely to be a broad state with a width of approximately $\Gamma_{\rm Total}\sim 245$MeV. Thus, it is highly challenging to observe the $\Lambda_{c1}|J^P=1/2^+,0\rangle_\rho$ state in experiments for its broad decay width.

The total decay widths of the two $2P$-wave λ-mode Λ_c states $\Lambda_{c1}|J^P=1/2^-,1\rangle_\lambda$ and $\Lambda_{c1}|J^P=3/2^-,1\rangle_\lambda$ are dozens of MeV, and the ND decay channel almost saturates their decay widths. Comparing the masses and total decay widths, $\Lambda_{c1}|J^P=1/2^-,1\rangle_\lambda$ and $\Lambda_{c1}|J^P=3/2^-,1\rangle_\lambda$ are allowed as good assignments of $\Lambda_c(2940)^+$. Meanwhile, the partial decay width ratio between pD^0 and $\Sigma_c\pi$ for $\Lambda_{c1}|J^P=3/2^-,1\rangle_\lambda$ is predicted to be 4.48, which is close to the upper limit of the newest measured value by the Belle Collaboration. In this case, $\Lambda_{c1}|J^P=3/2^-,1\rangle_\lambda$ is more favorable.

For the $2P$-wave ρ-mode Λ_c states, $\Lambda_{c1}|J^P=1/2^-,0\rangle_\rho$ probably has a width of $\Gamma_{\rm Total}\sim 175$ MeV and dominantly decays into $\Sigma_c|J^P=1/2^-,1\rangle_\rho\pi$ and $\Sigma_c|J^P=3/2^-,1\rangle_\rho\pi$. The states $\Lambda_{c1}|J^P=1/2^-,1\rangle_\rho$ and $\Lambda_{c1}|J^P=3/2^-,1\rangle_\rho$ are most likely to be moderate states with a width of approximately $\Gamma_{\rm Total}\sim 70$ MeV. Besides the main decay channels $\Sigma_c\pi$ and $\Sigma_c^*\pi$, the partial decay widths of the final states containing a P-wave baryon are considerable. The state $\Lambda_{c1}|J^P=3/2^-,2\rangle_\rho$ may be a broad state with a width of $\Gamma_{\rm Total}\sim 293$ MeV, and it mainly decays into $\Sigma_c^*\pi$ and $\Sigma_c\pi$. Meanwhile, if its mass lies above the threshold of $\Sigma_c\rho$, the strong decays are governed by the $\Sigma_c\rho$ channel. As for $\Lambda_{c1}|J^P=5/2^-,2\rangle_\rho$, it may be a relatively narrow state with a total width of $\Gamma_{\rm Total}\sim 52$ MeV, and it mainly decays into $\Sigma_c^*\pi$. Thus, this state is most likely to be observed in the $\Lambda_c\pi\pi$ final state via the decay chain $\Lambda_{c1}|J^P=5/2^-,2\rangle_\rho\to\Sigma_c^*\pi\to\Lambda_c\pi\pi$.

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