Strong decays of the low-lying ρ-mode 1P-wave singly heavy baryons

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(Received 26 August 2022; accepted 29 September 2022; published 20 October 2022)

We have systematically calculated the strong decays of the low-lying ρ-mode 1P-wave $\Lambda_{c(b)}$, $\Sigma_{c(b)}$, $\Xi_{c(b)}$, $\Xi'_{c(b)}$, $\Omega_{c(b)}$ baryons using the chiral quark model within the j-j coupling scheme. For the controversial states, our results indicate the following: (i) For the singly charmed heavy baryons, the newly observed $\Lambda_c(2910)^+$ is a good candidate of the $J^P = 5/2^-$ state $\Lambda_c|J^P = \frac{5}{2}^-, 2\rangle_\rho$. (ii) For the singly bottom heavy baryons, the $\Xi_b(6227)^-$ favors the $J^P = 5/2^-$ state $\Xi_b|J^P = \frac{5}{2}^-, 2\rangle_\rho$. (iii) The other missing ρ-mode 1P-wave excitations in Λ_b, $\Sigma_{c(b)}$, and $\Xi'_{c(b)}$ families appear to be broad structures with $\Gamma \sim (100$–$200)$ MeV, and their strong decay widths are sensitive to their masses. (iv) The ρ-mode 1P-wave $\Xi_{c(b)}$ and $\Omega_{c(b)}$ baryons have a relatively narrow decay width of a few mega-electron-volts (MeV) or a few tens of MeV, and have a good potential to be observed in forthcoming experiments.

DOI: 10.1103/PhysRevD.106.074020

I. INTRODUCTION

Among the fantastic hadron zoo, the singly heavy flavor baryon family plays an important role and is being constructed step by step. Thanks to the large mass difference between the heavy quark (c or b) and the light quarks, its inner structure can roughly be explored within heavy quark symmetry Refs. [1,2], which is a simpler method in hadron physics. Thus, the singly heavy baryons provide a good plot to better understand the nonperturbative nature of the quantum chromodynamics (QCD).

Over the past few decades, great progress has been made in the detection of singly heavy baryons. Except for the ground states, more and more excitations have been found in experiments. For the baryons containing a single charm quark, the excitations listed by the Particle Data Group (PDG) Ref. [3] include $\Lambda_c(2595)^+(\frac{1}{2}^-)$, $\Lambda_c(2625)^+(\frac{3}{2}^-)$, $\Lambda_c(2765)^+$ or $\Sigma_c(2765)^+$, $\Lambda_c(2860)^+(\frac{3}{2}^+)$, $\Lambda_c(2880)^+(\frac{5}{2}^+)$, $\Lambda_c(2940)^+(\frac{3}{2}^-)$, $\Sigma_c(2800)$, $\Xi_c(2790)(\frac{1}{2}^-)$, $\Xi_c(2815)(\frac{3}{2}^-)$, $\Xi_c(2923)$, $\Xi_c(2930)$, $\Xi_c(2970)(\frac{1}{2}^+)$, $\Xi_c(3055)$, $\Xi_c(3080)$, $\Xi_c(3123)$, $\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3065)^0$, $\Omega_c(3090)$, and $\Omega_c(3120)$. A few of the states are not listed since the evidence for their existence is poor and needs further experimental investigation, such as $\Xi_c(2939)$ and $\Xi_c(2965)$ Ref. [4]. Very recently, a possibly new excited Λ_c, namely $\Lambda_c(2910)$, was reported by the Belle Collaboration via investigating the $\bar{B}^0 \to \Sigma_c(2455)\pi\bar{p}$ decay process Ref. [5]. The 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. While, for the states containing single bottom quark, our knowledge is slightly less, the observed excitations listed by PDG are $\Lambda_b(5912)^0(\frac{1}{2}^-)$, $\Lambda_b(5920)^0(\frac{3}{2}^-)$, $\Lambda_b(6070)^0$, $\Lambda_b(6146)^0(\frac{3}{2}^+)$, $\Lambda_b(6152)^0(\frac{5}{2}^+)$, $\Sigma_b(6097)^\pm$, $\Xi_b(6100)^-(\frac{3}{2}^-)$, $\Xi_b(6227)^{-,0}$, $\Omega_b(6316)^-$, $\Omega_b(6330)^-$, $\Omega_b(6340)^-$, and $\Omega_b(6350)^-$ Ref. [3]. Recently, two new excited Ξ_b^0 states $\Xi_b(6327)^0$ and $\Xi_b(6333)^0$ were reported by the LHCb Collaboration in the $\Lambda_b^0K^-\pi^+$ mass spectrum Ref. [6]. Undoubtedly, these observed resonances provide good opportunities to establish the low-lying singly heavy baryon spectrum.

For a singly heavy baryon, there are two kinds of excitations: ρ-mode and λ-mode excitations in theory (see Fig. 1). The ρ-mode excitation appears within the light diquark, while the λ-mode excitation occurs between the light diquark and the heavy quark. Using the simple harmonic oscillator model to estimate the two kinds of excitation energy Ref. [7], one finds that the ρ-mode excitation energy should be pronouncedly larger than that of the λ-mode. This indicates that the λ-mode excitations should be more easily formed than ρ-mode excitations.

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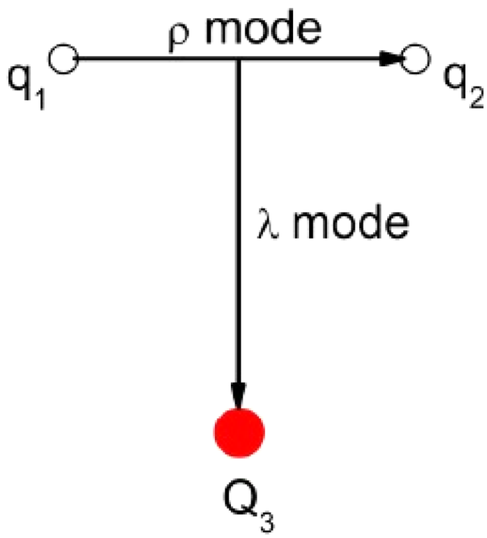


FIG. 1. The $\boldsymbol{\rho}$- and $\boldsymbol{\lambda}$-mode excitations in a singly heavy baryon. Here, ρ and λ are the Jacobi coordinates defined as $\boldsymbol{\rho} = \frac{1}{\sqrt{2}}(\mathbf{r}_1 - \mathbf{r}_2)$ and $\boldsymbol{\lambda} = \frac{1}{\sqrt{6}}(\mathbf{r}_1 + \mathbf{r}_2 - 2\mathbf{r}_3)$, respectively. q_1 and q_2 stand for the light (u, d, s) quark, and Q_3 stands for a heavy charm or bottom quark.

Therefore, it is natural to think that most of the low-lying observed single heavy baryons probably are good candidates of the λ-mode excitations. Meanwhile, based on the mass spectrum and strong decay analyses Refs. [7–37], the literature also indicates newly observed states $\Xi_c(2923, 2939, 2965)$ Refs. [22,26,38], $\Omega_c(3000, 3050, 3065, 3090, 3120)^0$ Refs. [18,39–42], $\Sigma_b(6097)$ and $\Xi_b(6227)$ Refs. [17,25,28,43–50], and $\Omega_b(6316, 6330, 6340, 6350)^-$ Refs. [51–53] may be explained with the $1P$-wave λ-mode excitations; $\Lambda_c(2910)$ may be the $2P$-wave λ-mode excitation Ref. [54] and $\Lambda_c(2940)$ is a candidate of the $2P$- or $1D$-wave λ-mode excitation Refs. [8,11,12,15]. However, it should be mentioned that there are other explanations of those observed structures, such as $2S$-wave excitations Refs. [9,15,31,55–57], $1P$-wave ρ-mode excitations Refs. [22,45], and unconventional interpretations Refs. [58–65].

As a whole, the interpretation of the low-lying singly heavy baryons observed in recent years is still controversial. The possibility of some of those states as ρ-mode excitations Refs. [22,45] cannot be excluded completely. Additionally, according to the quark model predictions Refs. [7,22,66,67], the mass of the ρ-mode states is about (70–150) MeV higher than that of λ-mode states. We collect some theoretical predictions of the spectrum for the $1P$-wave ρ-mode singly heavy baryons in Table I. From the table, it is seen that some observed states in experiments are in the predicted mass region of the $1P$-wave ρ-mode states Refs. [7,20,22]. Besides mass spectrum, strong decay property is one of the important aspects for determining hadron's structures. Thus, to better understand the inner structures of the observed low-lying singly heavy baryons, it is crucial to study the decay properties of the $1P$-wave ρ-mode states. However, there are only a few discussions of the strong decays of the $1P$-wave ρ-mode singly heavy baryons Refs. [22,45].

In the present work, we conduct a systematical discussion of the strong decays of the low-lying $1P$-wave ρ-mode $\Lambda_{c(b)}$, $\Sigma_{c(b)}$, $\Xi_{c(b)}$, $\Xi'_{c(b)}$, $\Omega_{c(b)}$ baryons using the chiral quark model within the j-j coupling scheme which includes the heavy quark symmetry. According to our theoretical calculations, we obtain that the newly observed structures $\Lambda_c(2910)^+$ and $\Xi_b(6227)^-$ may be assignments of the $1P$-wave ρ-mode resonances, and we collect our possible explanations in Table II. We hope the predicted strong decay properties of the missing $1P$-wave ρ-mode singly heavy baryons are helpful for future experimental exploring.

This paper is organized as follows. In Sec. II, we present the classification of single heavy baryons in a quark model and give a brief introduction of the chiral quark model. The numerical results are presented and discussed in Sec. III. Finally, a summary is given in Sec. IV.

II. SINGLY HEAVY BARYONS CLASSIFICATION AND CHIRAL QUARK MODEL

The singly heavy baryon contains a heavy quark (c or b) and two light quarks (u, d, or s). The heavy quark violates the SU(4) symmetry, but the SU(3) symmetry between two light quarks is approximately kept. According to the symmetry, the singly heavy baryons belong to two different SU(3) flavor representations: the symmetry sextet 6_F and antisymmetric antitriplet $\bar{3}_F$. In the singly charmed (bottom) baryons, there are two families, Λ_c and Ξ_c (Λ_b and Ξ_b) belonging to $\bar{\mathbf{3}}_F$, while there are three families, Σ_c, Ξ'_c, and Ω_c (Σ_b, Ξ'_b, and Ω_b), belonging to $\mathbf{6}_F$ Ref. [70].

The spatial wave function of a singly heavy baryon is adopted the harmonic oscillator form in the constituent quark model Ref. [23]. For q_1q_2Q system, it contains two light quarks q_1 and q_2 with an nearly equal constituent quark mass m, and a heavy quark Q with a constituent mass m'. The basis states are generated by the oscillator Hamiltonian

$$H = \frac{P^2_{\mathrm{c.m.}}}{2M} + \frac{1}{2m_\rho}P^2_\rho + \frac{1}{2m_\lambda}P^2_\lambda + \frac{3}{2}K(\rho^2 + \lambda^2). \quad (1)$$

Here, the constituent quarks are confined in an oscillator potential with the potential parameter K independent of the flavor quantum number. $\boldsymbol{\rho}$ and $\boldsymbol{\lambda}$ are Jacobi coordinates as shown in Fig. 1, and $\boldsymbol{R}_{\mathrm{c.m.}}$ is the center-mass coordinate. The momenta $\mathbf{P}_\rho$, P_λ, and $\mathbf{P}_{\mathrm{c.m.}}$ are defined as

$$\mathbf{P}_\rho = m_\rho\dot{\boldsymbol{\rho}}, \qquad \mathbf{P}_\lambda = m_\lambda\dot{\boldsymbol{\lambda}}, \qquad \mathbf{P}_{\mathrm{c.m.}} = M\dot{\mathbf{R}}_{\mathrm{c.m.}}, \quad (2)$$

TABLE I. The masses (MeV) of the $1P$-wave ρ-mode single heavy baryons obtained from the quark model. (S_ρ stands for the total spin of the two light quarks; L is the total orbital angular momentum; j represents the total angular momentum of L and S_ρ; J is the total angular momentum; P is the parity; n_ρ and l_ρ represent the nodal quantum number and orbital angular momentum, respectively).

State	n_ρ	l_ρ	L	S_ρ	j	J^P	Constituent quark model Ref. [7]	Relativized quark model Ref. [67]	A quark model Ref. [20]	Mass formula Ref. [22]	Strong decay channels
$\Sigma_c\lvert J^P=\frac{1}{2}^-,1\rangle_\rho$	0	1	1	0	1	$\frac{1}{2}^-$	2909	2840	2848		$\Sigma_c\pi, \Sigma_c^*\pi$
$\Sigma_c\lvert J^P=\frac{3}{2}^-,1\rangle_\rho$	0	1	1	0	1	$\frac{3}{2}^-$	2910	2865	2860		
$\Lambda_c\lvert J^P=\frac{1}{2}^-,0\rangle_\rho$	0	1	1	1	0	$\frac{1}{2}^-$	2890	2780	2816		$\Sigma_c\pi, \Sigma_c^*\pi$
$\Lambda_c\lvert J^P=\frac{1}{2}^-,1\rangle_\rho$	0	1	1	1	1	$\frac{1}{2}^-$	2933	2830	2816		
$\Lambda_c\lvert J^P=\frac{3}{2}^-,1\rangle_\rho$	0	1	1	1	1	$\frac{3}{2}^-$	2917	2840	2830		
$\Lambda_c\lvert J^P=\frac{3}{2}^-,2\rangle_\rho$	0	1	1	1	2	$\frac{3}{2}^-$	2956	2885	2830		
$\Lambda_c\lvert J^P=\frac{5}{2}^-,2\rangle_\rho$	0	1	1	1	2	$\frac{5}{2}^-$	2960	2900	2872		
$\Xi_c'\lvert J^P=\frac{1}{2}^-,1\rangle_\rho$	0	1	1	0	1	$\frac{1}{2}^-$				3060	$\Xi_c'\pi, \Sigma_c K, \Xi_c^*\pi, \Sigma_c^*$K
$\Xi_c'\lvert J^P=\frac{3}{2}^-,1\rangle_\rho$	0	1	1	0	1	$\frac{3}{2}^-$				3096	
$\Xi_c\lvert J^P=\frac{1}{2}^-,0\rangle_\rho$	0	1	1	1	0	$\frac{1}{2}^-$				2951	$\Xi_c\pi, \Xi_c'\pi, \Sigma_c K, \Xi_c^*\pi, \Lambda_c K,$
$\Xi_c\lvert J^P=\frac{1}{2}^-,1\rangle_\rho$	0	1	1	1	1	$\frac{1}{2}^-$				2980	$\Xi_c(2790)\pi, \Xi_c(2815)\pi$
$\Xi_c\lvert J^P=\frac{3}{2}^-,1\rangle_\rho$	0	1	1	1	1	$\frac{3}{2}^-$				2987	
$\Xi_c\lvert J^P=\frac{3}{2}^-,2\rangle_\rho$	0	1	1	1	2	$\frac{3}{2}^-$				3016	
$\Xi_c\lvert J^P=\frac{5}{2}^-,2\rangle_\rho$	0	1	1	1	2	$\frac{5}{2}^-$				3076	
$\Omega_c\lvert J^P=\frac{1}{2}^-,1\rangle_\rho$	0	1	1	0	1	$\frac{1}{2}^-$	3110		3046		Ξ_c'K
$\Omega_c\lvert J^P=\frac{3}{2}^-,1\rangle_\rho$	0	1	1	0	1	$\frac{3}{2}^-$	3112		3056		
$\Sigma_b\lvert J^P=\frac{1}{2}^-,1\rangle_\rho$	0	1	1	0	1	$\frac{1}{2}^-$	6246	6170	6200		$\Sigma_b\pi, \Sigma_b^*\pi$
$\Sigma_b\lvert J^P=\frac{3}{2}^-,1\rangle_\rho$	0	1	1	0	1	$\frac{3}{2}^-$	6246	6180	6202		
$\Lambda_b\lvert J^P=\frac{1}{2}^-,0\rangle_\rho$	0	1	1	1	0	$\frac{1}{2}^-$	6236	6100	6180		$\Sigma_b\pi, \Sigma_b^*\pi$
$\Lambda_b\lvert J^P=\frac{1}{2}^-,1\rangle_\rho$	0	1	1	1	1	$\frac{1}{2}^-$	6273	6165	6206		
$\Lambda_b\lvert J^P=\frac{3}{2}^-,1\rangle_\rho$	0	1	1	1	1	$\frac{3}{2}^-$	6273	6185	6211		
$\Lambda_b\lvert J^P=\frac{3}{2}^-,2\rangle_\rho$	0	1	1	1	2	$\frac{3}{2}^-$	6285	6190	6191		
$\Lambda_b\lvert J^P=\frac{5}{2}^-,2\rangle_\rho$	0	1	1	1	2	$\frac{5}{2}^-$	6289	6205	6206		
$\Xi_b'\lvert J^P=\frac{1}{2}^-,1\rangle_\rho$	0	1	1	0	1	$\frac{1}{2}^-$			6305	6356	$\Xi_b'\pi, \Sigma_b K, \Xi_b^*\pi, \Sigma_b^*$K
$\Xi_b'\lvert J^P=\frac{3}{2}^-,1\rangle_\rho$	0	1	1	0	1	$\frac{3}{2}^-$			6308	6364	
$\Xi_b\lvert J^P=\frac{1}{2}^-,0\rangle_\rho$	0	1	1	1	0	$\frac{1}{2}^-$				6214	$\Xi_b\pi, \Xi_b'\pi, \Sigma_b K, \Xi_b^*\pi, \Lambda_b K, \Sigma_b^*$K
$\Xi_b\lvert J^P=\frac{1}{2}^-,1\rangle_\rho$	0	1	1	1	1	$\frac{1}{2}^-$				6226	
$\Xi_b\lvert J^P=\frac{3}{2}^-,1\rangle_\rho$	0	1	1	1	1	$\frac{3}{2}^-$				6222	
$\Xi_b\lvert J^P=\frac{3}{2}^-,2\rangle_\rho$	0	1	1	1	2	$\frac{3}{2}^-$				6234	
$\Xi_b\lvert J^P=\frac{5}{2}^-,2\rangle_\rho$	0	1	1	1	2	$\frac{5}{2}^-$				6247	
$\Omega_b\lvert J^P=\frac{1}{2}^-,1\rangle_\rho$	0	1	1	0	1	$\frac{1}{2}^-$	6437		6388		Ξ_b'K
$\Omega_b\lvert J^P=\frac{3}{2}^-,1\rangle_\rho$	0	1	1	0	1	$\frac{3}{2}^-$	6438		6390		

with $M = 2m + m'$, $m_\rho = m$, and $m_\lambda = \frac{3mm'}{2m+m'}$. For an oscillator, the wave function is given by

$$\psi^{n_\sigma}_{l_\sigma m}(\sigma) = R_{n_\sigma l_\sigma}(\sigma) Y_{l_\sigma m}(\sigma), \tag{3}$$

where $\sigma = \rho$, λ. Thus, in the spatial wave functions of singly heavy baryons, there are two oscillator parameters, i.e., the potential strengths α_ρ and α_λ. The parameters α_ρ and α_λ satisfy the following relation:

$$\alpha_\lambda^2 = \sqrt{\frac{3m'}{2m+m'}}\alpha_\rho^2. \tag{4}$$

The spatial wave function is a product of the ρ-oscillator and λ-oscillator states. With the standard notation, the principle quantum numbers of the ρ-mode and λ-mode oscillators are $N_\rho = (2n_\rho + l_\rho)$ and $N_\lambda = (2n_\lambda + l_\lambda)$, and the energy of a state is given by

TABLE II. The parameters of the states (taken from PDG Ref. [3]) and possible interpretations. The unit of the width is MeV.

State	Main decay channels	Total width	Possible interpretations	Our results
$\Lambda_c(2910)^+$ Ref. [5]	$\Sigma_c(2455)^{0,++}\pi^\pm$	$51.8\pm20.0\pm18.8$	$2P$-wave with $J^P=1/2^-$ Ref. [54]	$\Lambda_c\vert J^P=5/2^-,2\rangle_\rho$
$\Xi_b(6227)^-$	$\Lambda_b K, \Xi_b\pi$	18 ± 6	$1P$-wave Ξ_b' with $J^P=3/2^-$ Refs. [17,28,32,44,50]	$\Xi_b\vert J^P=5/2^-,2\rangle_\rho$
			$1P$-wave Ξ_b' with $J^P=5/2^-$ Refs. [17,28]	
			$1P$-wave or $2S$-wave state with $J=3/2$ Ref. [35]	
			Pentaquark molecular state with $J^P=1/2^\pm$ Refs. [65,68,69]	
			$\Sigma_b\bar{K}$ molecular state with $J^P=1/2^-$ Ref. [61]	

$$E=\left(N_\rho+\frac{3}{2}\right)\omega_\rho+\left(N_\lambda+\frac{3}{2}\right)\omega_\lambda \tag{5}$$

with the ρ-mode and λ-mode frequencies

$$\omega_\rho=(3K/m_\rho)^{1/2},\qquad \omega_\lambda=(3K/m_\lambda)^{1/2}. \tag{6}$$

Finally, the total wave function of a singly heavy baryon can be obtained, which is made up of color, spin, flavor, and spatial wave functions. Considering the color wave function is antisymmetric, the product of spin, flavor, and spatial wave functions must be symmetric. More details about the classification of the heavy baryons in the quark model can be found in Ref. [23].

With the obtained total wave functions of the singly heavy baryons, we can further discuss their decay properties. In this work, we study the strong decay properties of the singly heavy baryons with a chiral quark model. This model has been successfully applied to study the strong decays of baryons and heavy-light mesons in previous works Refs. [24–30]. In the chiral quark model, the effective low energy quark-pseudoscalar-meson coupling in the SU(3) flavor basis at tree level is described by

$$H_m=\sum_j\frac{1}{f_m}\bar{\psi}_j\gamma_\mu^j\gamma_5^j\psi_j\partial^\mu\phi_m, \tag{7}$$

where ψ_j stands for the jth quark field in a baryon, f_m is the pseudoscalar meson decay constant, and ϕ_m is the pseudoscalar meson octet

$$\phi_m=\begin{pmatrix}\frac{1}{\sqrt{2}}\pi^0+\frac{1}{\sqrt{6}}\eta & \pi^+ & K^+\\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0+\frac{1}{\sqrt{6}}\eta & K^0\\ K^- & \bar{K}^0 & -\sqrt{\frac{2}{3}}\end{pmatrix}. \tag{8}$$

To match the nonrelativistic harmonic oscillator spatial wave function $^N\Psi_{LL_z}$ in this work, we adopt a nonrelativistic form of the quark-pseudoscalar couplings with the form as follows Refs. [71–73]:

$$H_m^{nr}=\sum_j\left\{\frac{\omega_m}{E_f+M_f}\boldsymbol{\sigma}_j\cdot\mathbf{P}_f+\frac{\omega_m}{E_i+M_i}\boldsymbol{\sigma}_j\cdot\mathbf{P}_i-\boldsymbol{\sigma}_j\cdot\mathbf{q}+\frac{\omega_m}{2\mu_q}\boldsymbol{\sigma}_j\cdot\mathbf{p}_j'\right\}I_j\phi_m, \tag{9}$$

where the $\boldsymbol{\sigma}_j$ and μ_q stand for the Pauli spin vector and the reduced mass of the jth quark in the initial and final baryons, respectively. $\varphi_m=e^{(-)i\mathbf{q}\cdot\mathbf{r}_j}$ denotes (emitting) absorbing a meson. $\mathbf{p}_j'=\mathbf{p}_j-(m_j/M)\mathbf{P}_{\mathrm{c.m.}}$ is the internal momentum of the jth quark in the baryon rest frame. ω_m and $\mathbf{q}$ are the energy and three-vector momentum of the meson, respectively. I_j is the isospin operator associated with the pseudoscalar mesons. For the emission of a light pseudoscalar meson, the partial decay width is

$$\Gamma_m=\left(\frac{\delta}{f_m}\right)^2\frac{(E_f+M_f)|q|}{4\pi M_i}\frac{1}{2J_i+1}\sum_{J_{iz}J_{fz}}|M_{J_{iz},J_{fz}}|^2, \tag{10}$$

where $M_{J_{iz},J_{fz}}$ is the transition amplitude; J_{iz} and J_{fz} stand for the third components of the total angular momenta of the initial and final baryons, respectively; and δ is a global parameter and accounts for the strength of the quark-meson coupling. In Ref. [23], the authors have determined this parameter value by fitting the decay properties of the state $\Sigma_c(2520)$. Research shows that this fitted value has general applicability and can be applied to study the similar strong decay processes of the heavy hadron system. Hence, in the present work, we fix its value the same as that in Refs. [23,25,27,30], i.e., $\delta=0.557$.

In the $L-S$ coupling scheme, the states are constructed by Ref. [20]

$$|^{2s+1}L_J\rangle=|[(l_\rho l_\lambda)_L(s_\rho s_Q)_S]_{J^P}\rangle, \tag{11}$$

where l_ρ and l_λ are the quantum numbers of the orbital angular momenta for the ρ-mode and λ-mode (see Fig. 1) oscillators, respectively. L corresponds to the quantum number of the total orbital angular momentum $\mathbf{L}=\mathbf{l}_\rho+\mathbf{l}_\lambda$, which determines the parity of a state by $P=(-1)^{l_\rho+l_\lambda}$. s_ρ and s_Q stand for the quantum numbers of the total spin of the two light quarks and the spin of the heavy quark, respectively. S is the quantum number of the total spin angular momentum $\mathbf{S}=\mathbf{s}_\rho+\mathbf{s}_Q$. Because of the heavy quark symmetry, the physical states may be closer to the j-j coupling scheme for the singly heavy baryons. Hence, in the present work, we study the decay properties of the singly heavy baryons in the j-j coupling scheme. Within the j-j coupling scheme, the states are denoted as $|J^P,j\rangle$ and can be expressed as linear combinations of the states within the L-S coupling scheme by the following relationship Ref. [20]:

$$|[[(l_\rho l_\lambda)_L s_\rho]_j s_Q]_J\rangle = (-1)^{L+s_\rho+1/2+J}\sqrt{2j+1}\sum_S \sqrt{2S+1} \times \begin{pmatrix} L & s_\rho & j \\ s_Q & J & S \end{pmatrix} |[(l_\rho l_\lambda)_L (s_\rho s_Q)_S]_{J^P}\rangle. \quad (12)$$

In the calculations, the standard quark model parameters are adopted. Namely, we set $m_u=m_d=330$ MeV, $m_s=450$ MeV, $m_c=1700$ MeV, and $m_b=5000$ MeV for the constituent quark masses. Considering the mass differences between the u/d and s constituent quarks, the harmonic oscillator parameter α_ρ in the wave function ${}^N\Psi_{LL_z}$ for $uu/ud/dd$, us/ds, and ss diquark systems should be different from each other. Thus, we take $\alpha_\rho=400$, 420, and 440 MeV for $uu/ud/dd$, us/ds, and ss diquark systems, respectively Ref. [70]. The decay constants for π and K mesons are taken as $f_\pi=132$ MeV, $f_K=160$ MeV, respectively. The masses of the well-established hadrons used in the calculations are adopted from the PDG Ref. [3]. With these parameters, the strong decay properties of the well-known heavy-light mesons and single heavy baryons have been described reasonably.

III. CALCULATIONS AND RESULTS

Inspired by the ambiguity states observed by the collaborations, we carry out a systematic study of the strong decay behaviors of the low-lying $1P$-wave ρ-mode singly heavy baryons within the j-j coupling scheme in the framework of the chiral quark model. Our theoretical results are presented as follows.

A. Λ_c and Λ_b baryons

In the Λ_c and Λ_b families, there are five ρ-mode $1P$ excitations according to the quark model classification, which are

$$\left|J^P=\frac{1}{2}^-,0\right\rangle_\rho = -\sqrt{\frac{1}{3}}\left|{}^2P_\rho\frac{1}{2}^-\right\rangle + \sqrt{\frac{2}{3}}\left|{}^4P_\rho\frac{1}{2}^-\right\rangle, \quad (13)$$

$$\left|J^P=\frac{1}{2}^-,1\right\rangle_\rho = \sqrt{\frac{2}{3}}\left|{}^2P_\rho\frac{1}{2}^-\right\rangle + \sqrt{\frac{1}{3}}\left|{}^4P_\rho\frac{1}{2}^-\right\rangle, \quad (14)$$

$$\left|J^P=\frac{3}{2}^-,1\right\rangle_\rho = -\sqrt{\frac{1}{6}}\left|{}^2P_\rho\frac{3}{2}^-\right\rangle + \sqrt{\frac{5}{6}}\left|{}^4P_\rho\frac{3}{2}^-\right\rangle, \quad (15)$$

$$\left|J^P=\frac{3}{2}^-,2\right\rangle_\rho = \sqrt{\frac{5}{6}}\left|{}^2P_\rho\frac{3}{2}^-\right\rangle + \sqrt{\frac{1}{6}}\left|{}^4P_\rho\frac{3}{2}^-\right\rangle, \quad (16)$$

$$\left|J^P=\frac{5}{2}^-,2\right\rangle_\rho = \left|{}^4P_\rho\frac{5}{2}^-\right\rangle. \quad (17)$$

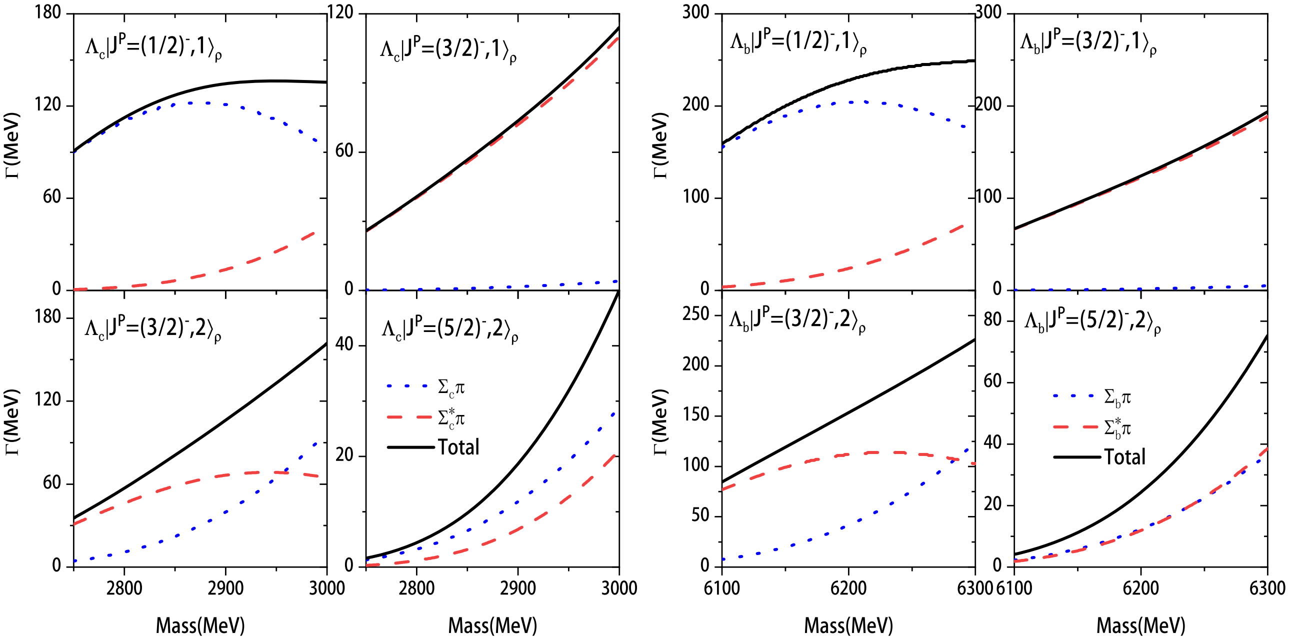
The predicted masses and possible two-body strong decay channels of these states are listed in Table I.

From the table, we can see that in the quark model the predicted masses of the $1P$-wave ρ-mode Λ_c excitations are about $M\simeq(2780$–$3000)$ MeV, and their Okubo-Zweig-Iizuka (OZI)-allowed two body strong decay channels are $\Sigma_c\pi$ and $\Sigma_c^*\pi$. However, we notice that the mass of $\Lambda_c|J^P=1/2^-,0\rangle_\rho$ is above the threshold of $\Sigma_c\pi$ and $\Sigma_c^*\pi$, while their strong decays are forbidden due to the orthogonality of spatial wave functions if we adopt the simple harmonic oscillator wave functions. Thus, we mainly focus on the strong decay properties of the other four states. Considering the uncertainties of the predicted masses, we plot the strong decay widths as a function of their masses in Fig. 2.

Our results indicate that the decay properties of the four $1P$-wave ρ-mode Λ_c states are sensitive to the masses. With the mass in the region of $M=(2780$–$3000)$ MeV, the states $\Lambda_c|J^P=\frac{1}{2}^-,1\rangle_\rho$, $\Lambda_c|J^P=\frac{3}{2}^-,1\rangle_\rho$, and $\Lambda_c|J^P=\frac{3}{2}^-,2\rangle_\rho$ are predicted to be moderate states with a width of $\Gamma\simeq(50$–$150)$ MeV. It should be pointed out that the mainly decay channel of $\Lambda_c|J^P=\frac{1}{2}^-,1\rangle_\rho$ is $\Sigma_c\pi$, while that of $\Lambda_c|J^P=\frac{3}{2}^-,1\rangle_\rho$ is $\Sigma_c^*\pi$. For the $\Lambda_c|J^P=\frac{3}{2}^-,2\rangle_\rho$ state, if its mass is less than $M<2958$ MeV, its dominant decay channel is $\Sigma_c^*\pi$. Otherwise its dominant decay channel is $\Sigma_c\pi$. As to the $\Lambda_c|J^P=\frac{5}{2}^-,2\rangle_\rho$ state, it is likely to be a narrow state with a width of $\Gamma\simeq(10$–$50)$ MeV when the mass varies in the region of what we considered in the present work. The mainly decay channel is $\Sigma_c\pi$, while the $\Sigma_c^*\pi$ partial decay width is considerable as well.

Combining the natures of the newly observed state $\Lambda_c(2910)^+$ at Belle Ref. [5], we find that this new state may be an assignment of the narrow state $\Lambda_c|J^P=\frac{5}{2}^-,2\rangle_\rho$. Fixing the mass of $\Lambda_c|J^P=\frac{5}{2}^-,2\rangle_\rho$ at $M=2914$ MeV, the predicted total decay width

$$\Gamma_{\rm Total}\simeq 22\ \text{MeV}, \quad (18)$$



(a)$1P_\rho$-wave Λ_c states (b)$1P_\rho$-wave Λ_b states

FIG. 2. Partial and total strong decay widths of the ρ-mode $1P$ states in the Λ_c and Λ_b families as functions of their masses.

is close to the lower limit of the observed one $\Gamma_{\text{Expt}} = 51.8 \pm 20.0 \pm 18.8$ MeV. The branching fraction for the dominant decay channel $\Sigma_c\pi$ can reach up to

$$\frac{\Gamma[\Lambda_c|J^P=\frac{5}{2}^-,2\rangle_\rho \to \Sigma_c\pi]}{\Gamma_{\text{Total}}} \sim 63\%. \tag{19}$$

Meanwhile, the decay rate of $\Lambda_c|J^P=\frac{5}{2}^-,2\rangle_\rho$ into $\Sigma_c^*\pi$ is considerable, and the predicted branching fraction is

$$\frac{\Gamma[\Lambda_c|J^P=\frac{5}{2}^-,2\rangle_\rho \to \Sigma_c^*\pi]}{\Gamma_{\text{Total}}} \sim 37\%. \tag{20}$$

The significant branching fraction indicates this strong decay process may be measured in future experiments and can be used to confirm the $\Lambda_c(2910)^+$ structure as well. It should be pointed out that we cannot exclude the possibility of $\Lambda_c(2910)^+$ as a candidate of the broader states $\Lambda_c|J^P=\frac{3}{2}^-,2\rangle_\rho$ and $\Lambda_c|J^P=\frac{1}{2}^-,1\rangle_\rho$ since there are large uncertainties in the observed width of $\Lambda_c(2910)^+$.

In the Λ_b family, according to the predicted masses collected in Table I, the masses of the five ρ-mode $1P$ Λ_b excitations are in the region of $M \simeq (6100\text{–}6300)$ MeV. Similarly, although the mass of the $\Lambda_b|J^P=\frac{1}{2}^-,0\rangle_\rho$ is above the threshold of $\Sigma_b\pi$ and $\Sigma_b^*\pi$, their strong decays are forbidden in this work since we adopt the simple harmonic oscillator wave functions. Then, we calculate the decay properties of the other four ρ-mode $1P$ Λ_b states as a function of the mass within the possible range allowed, as shown in Fig. 2. From the figure, it is found that the four Λ_b resonances are slightly broader states compared to the corresponding states in the Λ_c family. Meanwhile the variation curves between the partial decay width and the mass are similar to that for Λ_c states. Among the four ρ-mode $1P$ Λ_b states, $\Lambda_b|J^P=\frac{5}{2}^-,2\rangle_\rho$ is the narrowest state with a total width of $\Gamma_{\text{Total}} \simeq 5\text{–}74$ MeV in the range of (6100–6300) MeV. This state mainly decays into $\Sigma_b\pi$ and $\Sigma_b^*\pi$, and their partial width ratio is predicted to be

$$\frac{\Gamma[\Lambda_b|J^P=\frac{5}{2}^-,2\rangle_\rho \to \Sigma_b\pi]}{\Gamma[\Lambda_b|J^P=\frac{5}{2}^-,2\rangle_\rho \to \Sigma_b^*\pi]} \simeq 1. \tag{21}$$

The $\Lambda_b|J^P=\frac{5}{2}^-,2\rangle_\rho$ state may be observed in the $\Lambda_b\pi\pi$ final state via the decay chains $\Lambda_b|J^P=\frac{5}{2}^-,2\rangle_\rho \to \Sigma_b\pi/\Sigma_b^*\pi \to \Lambda_b\pi\pi$. The $\Lambda_b|J^P=\frac{1}{2}^-,1\rangle_\rho$ and $\Lambda_b|J^P=\frac{3}{2}^-,1\rangle_\rho$ dominantly decay into $\Sigma_b\pi$ and $\Sigma_b^*\pi$, respectively, and they have a comparable width of $\Gamma \simeq 120\text{–}200$ MeV. The $\Lambda_b|J^P=\frac{3}{2}^-,2\rangle_\rho$ mainly decay into $\Sigma_b^*\pi$ and $\Sigma_b\pi$ channels, and their partial width ratio is predicted to be

$$\frac{\Gamma[\Lambda_b|J^P=\frac{3}{2}^-,2\rangle_\rho \to \Sigma_b\pi]}{\Gamma[\Lambda_b|J^P=\frac{3}{2}^-,2\rangle_\rho \to \Sigma_b^*\pi]} \simeq 0.4\text{–}1.2. \tag{22}$$

B. Σ_c and Σ_b baryons

In the Σ_c and Σ_b families, there are two ρ-mode $1P$-wave excitations:

$$\left|J^P=\frac{1}{2}^-,1\right\rangle_\rho = \left|{}^2P_\rho\frac{1}{2}^-\right\rangle, \tag{23}$$

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

	$\Sigma_c\vert J^P=\frac{1}{2}^-,1\rangle_\rho(2909)$		$\Sigma_c\vert J^P=\frac{3}{2}^-,1\rangle_\rho(2910)$	
	Γ_i	$B_i(\%)$	Γ_i	$B_i(\%)$
$\Sigma_c\pi$	100	66	55	30
$\Sigma_c^*\pi$	51	34	127	70
Total	151		182	

	$\Sigma_b\vert J^P=\frac{1}{2}^-,1\rangle_\rho(6246)$		$\Sigma_b\vert J^P=\frac{3}{2}^-,1\rangle_\rho(6246)$	
	Γ_i	$B_i(\%)$	Γ_i	$B_i(\%)$
$\Sigma_b\pi$	99	53	54	27
$\Sigma_b^*\pi$	87	47	145	73
Total	145		199	

$$\left|J^P=\frac{3^-}{2},1\right\rangle_\rho=\left|{}^2P_\rho\frac{3^-}{2}\right\rangle. \tag{24}$$

The masses of the ρ-mode 1P-wave Σ_c and Σ_b excitations are predicted to be $M\simeq(2840\text{–}2910)$ MeV and $M\simeq(6170\text{–}6250)$ MeV, respectively. Adopting the predicted masses from Ref. [7], we collect their decay properties in Table III. It is shown that all of the ρ-mode 1P-wave excitations may be broad states with a total decay width of around $\Gamma\sim(150\text{–}200)$ MeV.

In the Σ_c family, the dominant decay channel of $\Sigma_c|J^P=\frac{1}{2}^-,1\rangle_\rho$ is $\Sigma_c\pi$, while that of $\Sigma_c|J^P=\frac{3}{2}^-,1\rangle_\rho$ is $\Sigma_c^*\pi$. The predicted branching fractions are

$$\frac{\Sigma_c|J^P=\frac{1}{2}^-,1\rangle_\rho\to\Sigma_c\pi}{\Gamma_{\text{Total}}}\sim 66\%, \tag{25}$$

$$\frac{\Sigma_c|J^P=\frac{3}{2}^-,1\rangle_\rho\to\Sigma_c^*\pi}{\Gamma_{\text{Total}}}\sim 70\%, \tag{26}$$

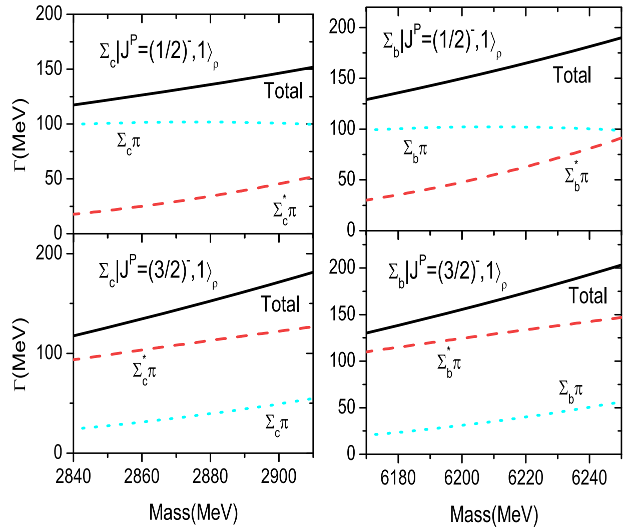
which can be used to distinguish $\Sigma_c|J^P=\frac{1}{2}^-,1\rangle_\rho$ from $\Sigma_c|J^P=\frac{3}{2}^-,1\rangle_\rho$ in future experiments.

In the Σ_b family, the $J^P=1/2^-$ state $\Sigma_b|J^P=\frac{1}{2}^-,1\rangle_\rho$ mainly decays into $\Sigma_b\pi$ and $\Sigma_b^*\pi$. Their branching fractions are

$$\frac{\Sigma_b|J^P=\frac{1}{2}^-,1\rangle_\rho\to\Sigma_b\pi}{\Gamma_{\text{Total}}}\sim 53\%, \tag{27}$$

$$\frac{\Sigma_b|J^P=\frac{1}{2}^-,1\rangle_\rho\to\Sigma_b^*\pi}{\Gamma_{\text{Total}}}\sim 47\%. \tag{28}$$

The $J^P=3/2^-$ state $\Sigma_b|J^P=\frac{3}{2}^-,1\rangle_\rho$ is governed by $\Sigma_b^*\pi$, and the branching fraction is predicted to be



(a)1P_ρ-wave Σ_c states (b)1P_ρ-wave Σ_b states

FIG. 3. Partial and total strong decay widths of the ρ-mode 1P states in the Σ_c and Σ_b families as functions of their masses.

$$\frac{\Sigma_b|J^P=\frac{3}{2}^-,1\rangle_\rho\to\Sigma_b^*\pi}{\Gamma_{\text{Total}}}\sim 73\%. \tag{29}$$

Considering the uncertainty of the mass predictions of the ρ-mode 1P-wave Σ_c and Σ_b excitations, we plot the strong decay widths as a function of the mass in Fig. 3. The sensitivities of the decay properties of those states to their masses can be clearly seen from the figure.

C. Ξ_c and Ξ_b baryons

In the Ξ_c and Ξ_b families, there are each five ρ-mode 1P-wave excitations: $|J^P=\frac{1}{2}^-,0\rangle_\rho$, $|J^P=\frac{1}{2}^-,1\rangle_\rho$, $|J^P=\frac{3}{2}^-,1\rangle_\rho$, $|J^P=\frac{3}{2}^-,2\rangle_\rho$, and $|J^P=\frac{5}{2}^-,2\rangle_\rho$. For their masses, there are a few discussions in theoretical references, and we have collected them in Table I. From the table, the typical masses of the ρ-mode 1P-wave Ξ_c and Ξ_b states are about $M\sim 2.9$ and $M\sim 6.2$ GeV, respectively. Adopting the predicted masses based on the mass formula Ref. [22], we calculate their two-body strong decay properties and list them in Table IV.

In the Ξ_c family, the $J^P=1/2^-$ state $\Xi_c|J^P=\frac{1}{2}^-,0\rangle_\rho$ has a moderate width of $\Gamma\simeq 113$ MeV and dominantly decays into $\Xi_c\pi$ and Λ_cK with predicted branching fractions

$$\frac{\Gamma[\Xi_c|J^P=\frac{1}{2}^-,0\rangle_\rho\to\Xi_c\pi]}{\Gamma_{\text{Total}}}\sim 43\%, \tag{30}$$

$$\frac{\Gamma[\Xi_c|J^P=\frac{1}{2}^-,0\rangle_\rho\to\Lambda_cK]}{\Gamma_{\text{Total}}}\sim 57\%. \tag{31}$$

The $\Xi_c\pi$ and Λ_cK channels can be used to search for the missing $\Xi_c|J^P=\frac{1}{2}^-,0\rangle_\rho$ state.

TABLE IV. The strong decay properties of the ρ-mode $1P$-wave states in the Ξ_c and Ξ_b families. Γ_{Total} stands for the total decay width. The unit of the width and mass is MeV. The masses for the unestablished ρ-mode $1P$ Ξ_c and Ξ_b states are taken from the predictions in Ref. [22].

	$\Xi_c\|J^P=\frac{1}{2}^-,0\rangle_\rho$	$\Xi_c\|J^P=\frac{1}{2}^-,1\rangle_\rho$	$\Xi_c\|J^P=\frac{3}{2}^-,1\rangle_\rho$	$\Xi_c\|J^P=\frac{3}{2}^-,2\rangle_\rho$	$\Xi_c\|J^P=\frac{5}{2}^-,2\rangle_\rho$
Decay width	$M=2951$	$M=2980$	$M=2987$	$M=3016$	$M=3076$
$\Gamma[\Xi_c\pi]$	48.6	0.0	10.7	10.8	37.1
$\Gamma[\Lambda_c K]$	64.2	0.0	5.1	5.5	20.7
$\Gamma[\Xi_c'\pi]$	0.0	33.5	0.3	10.2	5.5
$\Gamma[\Sigma_c K]$	0.0	102.9	0.0	1.9	2.9
$\Gamma[\Xi_c^*\pi]$	0.0	1.9	16.1	17.9	3.5
$\Gamma[\Sigma_c^* K]$	...	...	...	11.5	0.6
$\Gamma[\Xi_c(2790)\pi]$	0.0	0.0	0.0	0.0	0.1
$\Gamma[\Xi_c(2815)\pi]$	0.0	0.0	0.0	0.0	0.1
Γ_{Total}	112.8	138.3	32.2	57.8	70.5

	$\Xi_b\|J^P=\frac{1}{2}^-,0\rangle_\rho$	$\Xi_b\|J^P=\frac{1}{2}^-,1\rangle_\rho$	$\Xi_b\|J^P=\frac{3}{2}^-,1\rangle_\rho$	$\Xi_b\|J^P=\frac{3}{2}^-,2\rangle_\rho$	$\Xi_b\|J^P=\frac{5}{2}^-,2\rangle_\rho$
Decay width	$M=6214$	$M=6226$	$M=6222$	$M=6234$	$M=6247$
$\Gamma[\Xi_b\pi]$	50.6	0.0	5.5	5.1	13.1
$\Gamma[\Lambda_b K]$	76.0	0.0	1.5	1.5	4.4
$\Gamma[\Xi_b'\pi]$	0.0	25.0	0.1	1.5	0.6
$\Gamma[\Sigma_b K]$	0.0	0.0	0.0	0.0	0.0
$\Gamma[\Xi_b^*\pi]$	0.0	0.8	11.2	13.7	0.6
$\Gamma[\Sigma_b^* K]$	0.0	0.0	0.0	0.0	0.0
Γ_{Total}	126.6	25.8	18.3	21.9	18.7

For the other $J^P=1/2^-$ state $\Xi_c|J^P=\frac{1}{2}^-,1\rangle_\rho$, its width is predicted to be around $\Gamma\simeq 138$ MeV. This state mainly decays into $\Xi_c'\pi$ and $\Sigma_c K$. Their branching fractions are

$$\frac{\Gamma[\Xi_c|J^P=\frac{1}{2}^-,1\rangle_\rho\to\Xi_c'\pi]}{\Gamma_{\mathrm{Total}}}\sim 24\%, \tag{32}$$

$$\frac{\Gamma[\Xi_c|J^P=\frac{1}{2}^-,1\rangle_\rho\to\Sigma_c K]}{\Gamma_{\mathrm{Total}}}\sim 74\%. \tag{33}$$

The $J^P=3/2^-$ state $\Xi_c|J^P=\frac{3}{2}^-,1\rangle_\rho$ has a narrow width of $\Gamma\sim 32$ MeV, and dominantly decays into the $\Xi_c\pi$, $\Lambda_c K$ and $\Xi_c^*\pi$ channels. The branching fractions are predicted to be

$$\frac{\Gamma[\Xi_c|J^P=\frac{3}{2}^-,1\rangle_\rho\to\Xi_c\pi]}{\Gamma_{\mathrm{Total}}}\sim 33\%, \tag{34}$$

$$\frac{\Gamma[\Xi_c|J^P=\frac{3}{2}^-,1\rangle_\rho\to\Lambda_c K]}{\Gamma_{\mathrm{Total}}}\sim 16\%, \tag{35}$$

$$\frac{\Gamma[\Xi_c|J^P=\frac{3}{2}^-,1\rangle_\rho\to\Xi_c^*\pi]}{\Gamma_{\mathrm{Total}}}\sim 50\%. \tag{36}$$

This state has a large potential to be observed in the $\Xi_c\pi$, $\Lambda_c K$, and $\Xi_c^*\pi$ channels.

The other $J^P=3/2^-$ state $\Xi_c|J^P=\frac{3}{2}^-,2\rangle_\rho$ is slightly broader than $\Xi_c|J^P=\frac{3}{2}^-,1\rangle_\rho$ and has a width of $\Gamma\sim 58$ MeV. Except for the $\Xi_c\pi$, $\Lambda_c K$, and $\Xi_c^*\pi$ channels, this state also has large decay rates into $\Xi_c'\pi$ and $\Sigma_c^* K$. The branching fractions for the $\Xi_c^*\pi$ and $\Sigma_c^* K$ channels can reach up to

$$\frac{\Gamma[\Xi_c|J^P=\frac{3}{2}^-,2\rangle_\rho\to\Xi_c^*\pi]}{\Gamma_{\mathrm{Total}}}\sim 31\%, \tag{37}$$

$$\frac{\Gamma[\Xi_c|J^P=\frac{3}{2}^-,2\rangle_\rho\to\Sigma_c^* K]}{\Gamma_{\mathrm{Total}}}\sim 20\%. \tag{38}$$

The $\Xi_c|J^P=\frac{3}{2}^-,2\rangle_\rho$ may be observed in the $\Xi_c\pi\pi/\Lambda_c\pi K$ final states via the decay chains $\Xi_c|J^P=\frac{3}{2}^-,2\rangle_\rho\to\Xi_c^*\pi/\Sigma_c^* K\to\Xi_c\pi\pi/\Lambda_c\pi K$.

The decay of $\Xi_c|J^P=\frac{5}{2}^-,2\rangle_\rho$ is governed by $\Xi_c\pi$ and $\Lambda_c K$ with branching fractions

$$\frac{\Gamma[\Xi_c|J^P=\frac{5}{2}^-,2\rangle_\rho\to\Xi_c\pi]}{\Gamma_{\mathrm{Total}}}\sim 53\%, \tag{39}$$

$$\frac{\Gamma[\Xi_c|J^P=\frac{5}{2}^-,2\rangle_\rho\to\Lambda_c K]}{\Gamma_{\mathrm{Total}}}\sim 29\%. \tag{40}$$

In the Ξ_b family, the $\Xi_b|J^P=\frac{1}{2}^-,0\rangle_\rho$ has a moderate width of $\Gamma\simeq 127$ MeV and mainly decays via $\Xi_b\pi$ and $\Lambda_b K$. Their predicted branching fractions are

$$\frac{\Gamma[\Xi_b|J^P=\frac{1}{2}^-,0\rangle_\rho\to\Xi_b\pi]}{\Gamma_{\text{Total}}}\sim 40\%, \quad (41)$$

$$\frac{\Gamma[\Xi_b|J^P=\frac{1}{2}^-,0\rangle_\rho\to\Lambda_b K]}{\Gamma_{\text{Total}}}\sim 60\%. \quad (42)$$

The other four ρ-mode $1P$ states $\Xi_b|J^P=\frac{1}{2}^-,1\rangle_\rho$, $\Xi_b|J^P=\frac{3}{2}^-,1\rangle_\rho$, $\Xi_b|J^P=\frac{3}{2}^-,2\rangle_\rho$, and $\Xi_b|J^P=\frac{5}{2}^-,2\rangle_\rho$ have a comparable width of $\Gamma\sim 20$ MeV. While we notice that the main decay channels have big differences among those four states, the $\Xi_b|J^P=\frac{1}{2}^-,1\rangle_\rho$ is mostly saturated by the decay channel $\Xi_b'\pi$, and the branching fraction for the $\Xi_b'\pi$ channel can reach up to

$$\frac{\Gamma[\Xi_b|J^P=\frac{1}{2}^-,1\rangle_\rho\to\Xi_b'\pi]}{\Gamma_{\text{Total}}}\sim 97\%. \quad (43)$$

The $J^P=3/2^-$ states $\Xi_b|J^P=\frac{3}{2}^-,1\rangle_\rho$ and $\Xi_b|J^P=\frac{3}{2}^-,2\rangle_\rho$ dominantly decay into the $\Xi_b\pi$ and $\Xi_b^*\pi$ channels. The branching fractions are predicted to be

$$\frac{\Gamma[\Xi_b|J^P=\frac{3}{2}^-,1(2)\rangle_\rho\to\Xi_b\pi]}{\Gamma_{\text{Total}}}\sim 30\%(23\%), \quad (44)$$

$$\frac{\Gamma[\Xi_b|J^P=\frac{3}{2}^-,1(2)\rangle_\rho\to\Xi_b^*\pi]}{\Gamma_{\text{Total}}}\sim 61\%(63\%). \quad (45)$$

For the $\Xi_b|J^P=\frac{5}{2}^-,2\rangle_\rho$ state, the dominant decay mode is $\Xi_b\pi$ with a branching fraction of

$$\frac{\Gamma[\Xi_b|J^P=\frac{5}{2}^-,2\rangle_\rho\to\Xi_b\pi]}{\Gamma_{\text{Total}}}\sim 70\%. \quad (46)$$

Meanwhile, the $\Xi_b|J^P=\frac{5}{2}^-,2\rangle_\rho$ state has a sizable decay rate into $\Lambda_b K$, and the branching fraction is about

$$\frac{\Gamma[\Xi_b|J^P=\frac{5}{2}^-,2\rangle_\rho\to\Lambda_b K]}{\Gamma_{\text{Total}}}\sim 24\%. \quad (47)$$

Our theoretical results indicate that the decay properties of the $\Xi_b|J^P=\frac{5}{2}^-,2\rangle_\rho$ state is in good agreement with the newly observed $\Xi_b(6227)^-$ in both the $\Lambda_b^- K$ and the $\Xi_b^0\pi^-$ invariant mass spectra at LHCb Ref. [74]. Fixing the mass at the physical mass $M=6228$ MeV, the total decay width of $\Xi_b|J^P=\frac{5}{2}^-,2\rangle_\rho$ is about $\Gamma_{\text{Total}}\sim 15$ MeV (see Table V), which is close to the lower limit of the measured width $\Gamma_{\text{Expt}}\simeq 19.9\pm 2.6$ MeV. Furthermore, the dominant decay channels are $\Xi_b\pi$ and $\Lambda_b K$, which is consistent with the nature of $\Xi_b(6227)^-$.

TABLE V. The partial decay widths (MeV) of $\Xi_b(6227)^-$ assigned as ρ-mode $1P$ Ξ_b state $\Xi_b|J^P=\frac{5}{2}^-,2\rangle_\rho$.

Decay width	$\Xi_b\|J^P=\frac{5}{2}^-,2\rangle_\rho$ $\Xi_b(6227)^-$
$\Gamma[\Xi_b\pi]$	10.7
$\Gamma[\Lambda_b K]$	3.0
$\Gamma[\Xi_b'\pi]$	0.4
$\Gamma[\Xi_b^*\pi]$	0.4
Γ_{Total}	14.5
Γ_{Expt}.	19.9 ± 2.6

Similarly, the predicted masses of the ρ-mode $1P$ Ξ_c and Ξ_b excitations certainly have a large uncertainty, which may bring uncertainties to the theoretical results. To investigate this effect, we plot the two-body strong decay widths of the ρ-mode $1P$ Ξ_c and Ξ_b excitations as a function of the mass in Fig. 4. As a whole, most of the ρ-mode $1P$ Ξ_c and Ξ_b states may have good potential to be observed in experiments due to their relatively narrow widths.

D. Ξ_c' and Ξ_b' baryons

In the Ξ_c' and Ξ_b' families, there are two each ρ-mode $1P$-wave excitations: $|J^P=\frac{1}{2}^-,1\rangle_\rho$ and $|J^P=\frac{3}{2}^-,1\rangle_\rho$. According to the theoretical predictions by various methods, the masses of the ρ-mode $1P$ Ξ_c' and Ξ_b' baryons are about $M\sim 3.0$ and $M\sim 6.3$ GeV, respectively. Fixing their masses at the predictions in Ref. [22], we collect their strong decay properties in Table VI.

All of the four states may be moderate states with a comparable width of $\Gamma\sim 100$ MeV. While their main decay channels have some differences, the $\Xi_c'|J^P=\frac{1}{2}^-,1\rangle_\rho$ is governed by $\Sigma_c K$, and the corresponding branching fraction is predicted to be

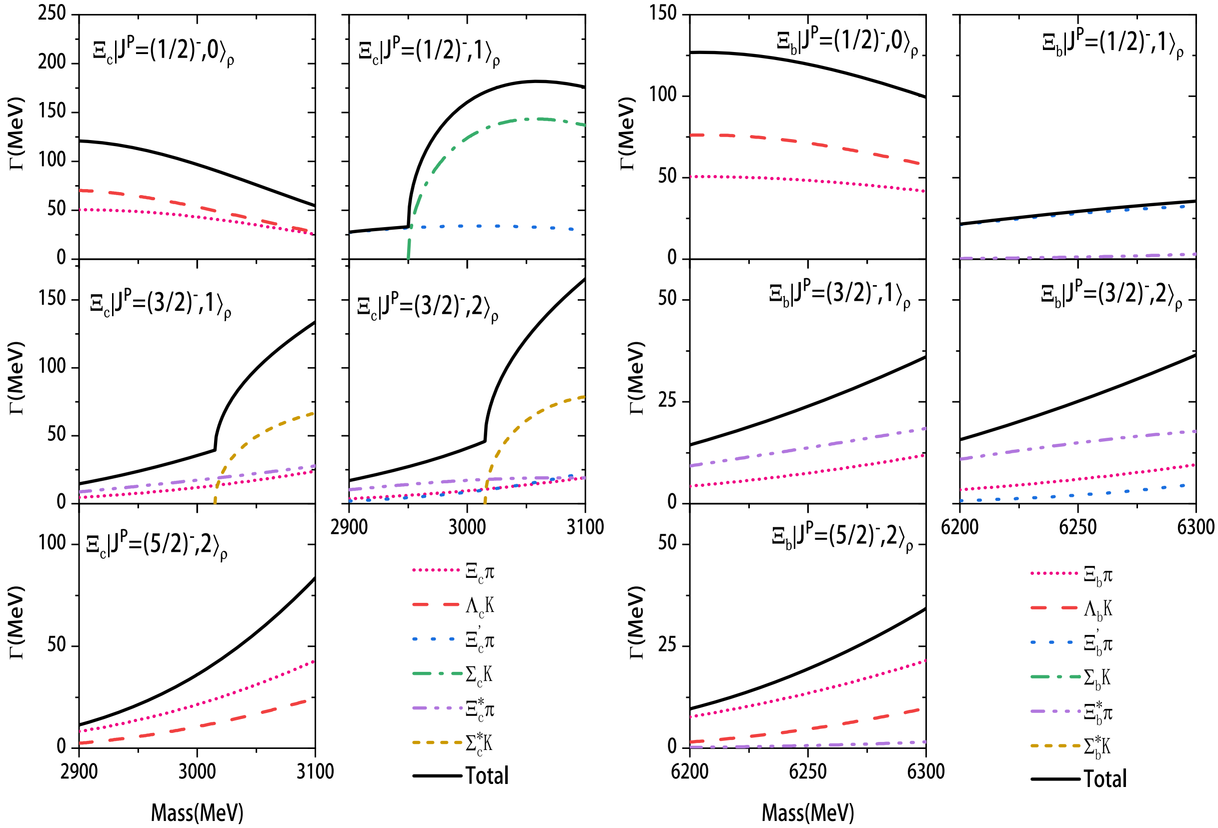
$$\frac{\Gamma[\Xi_c'|J^P=\frac{1}{2}^-,1\rangle_\rho\to\Sigma_c K]}{\Gamma_{\text{Total}}}\sim 71\%. \quad (48)$$

Thus, the $\Xi_c'|J^P=\frac{1}{2}^-,1\rangle_\rho$ may be observed in the $\Lambda_c\pi K$ final state via the decay chain $\Xi_c'|J^P=\frac{1}{2}^-,1\rangle_\rho\to\Sigma_c K\to\Lambda_c\pi K$ in future experiments. Meanwhile, this state has sizable decay decay rates into $\Xi_c'\pi$ and $\Xi_c^*\pi$ with branching fractions

$$\frac{\Gamma[\Xi_c'|J^P=\frac{1}{2}^-,1\rangle_\rho\to\Xi_c'\pi]}{\Gamma_{\text{Total}}}\sim 16\%, \quad (49)$$

$$\frac{\Gamma[\Xi_c'|J^P=\frac{1}{2}^-,1\rangle_\rho\to\Xi_c^*\pi]}{\Gamma_{\text{Total}}}\sim 12\%. \quad (50)$$

For the $\Xi_c'|J^P=\frac{3}{2}^-,1\rangle_\rho$, it mainly decays into $\Sigma_c^* K$ with a branching fraction



(a)$1P_\rho$-wave Ξ_c states (b)$1P_\rho$-wave Ξ_b states

FIG. 4. Partial and total strong decay width of the ρ-mode $1P$ states in the Ξ_c and Ξ_b families as functions of their masses. Some decay channels are not shown in the figure for their small partial decay widths.

$$\frac{\Gamma[\Xi_c'|J^P=\frac{3}{2}^-,1\rangle_\rho\to\Sigma_c^*K]}{\Gamma_{\text{Total}}}\sim 58\%. \tag{51}$$

Yet the other channels $\Xi_c'\pi$, $\Xi_c^*\pi$, and Σ_cK are not obviously neglectable as well. The branching fraction for the $\Xi_c^*\pi$ channel can reach up to

$$\frac{\Gamma[\Xi_c'|J^P=\frac{3}{2}^-,1\rangle_\rho\to\Xi_c^*\pi]}{\Gamma_{\text{Total}}}\sim 21\%. \tag{52}$$

TABLE VI. Partial and total strong decay widths of the ρ-mode $1P$ states in the Ξ_c' and Ξ_b' families. The unit of the width and mass is MeV. The masses for the unestablished ρ-mode $1P$ Ξ_c' and Ξ_b' states are taken from the predictions in Ref. [22].

	Decay modes				
States	$\Xi_c'\pi$	$\Xi_c^*\pi$	Σ_cK	Σ_c^*K	Total
$\Xi_c'\lvert J^P=\frac{1}{2}^-,1\rangle_\rho(3060)$	16.3	11.7	71.7	1.1	100.8
$\Xi_c'\lvert J^P=\frac{3}{2}^-,1\rangle_\rho(3096)$	16.4	25.8	10.4	72.8	125.4
	Decay modes				
States	$\Xi_b'\pi$	$\Xi_b^*\pi$	Σ_bK	Σ_b^*K	Total
$\Xi_b'\lvert J^P=\frac{1}{2}^-,1\rangle_\rho(6356)$	16.9	13.4	69.6	0.6	100.4
$\Xi_b'\lvert J^P=\frac{3}{2}^-,1\rangle_\rho(6364)$	8.3	24.3	1.5	65.1	99.1

For the two ρ-mode $1P$ states in the Ξ_b' family, the dominant decay channel of $\Xi_b'|J^P=\frac{1}{2}^-,1\rangle_\rho$ is Σ_bK, while that of $\Xi_b'|J^P=\frac{3}{2}^-,1\rangle_\rho$ is Σ_b^*K. The predicted branching fractions are

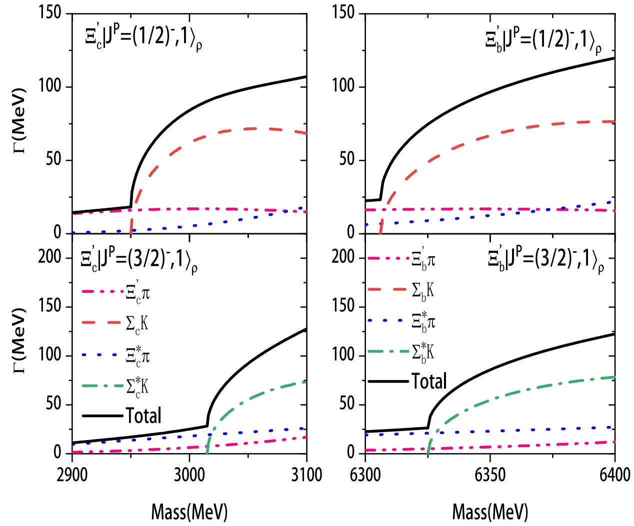
$$\frac{\Gamma[\Xi_b'|J^P=\frac{1}{2}^-,1\rangle_\rho\to\Sigma_bK]}{\Gamma_{\text{Total}}}\sim 69\%, \tag{53}$$

$$\frac{\Gamma[\Xi_b'|J^P=\frac{3}{2}^-,1\rangle_\rho\to\Sigma_b^*K]}{\Gamma_{\text{Total}}}\sim 66\%. \tag{54}$$

In addition, the $\Xi_b'|J^P=\frac{3}{2}^-,1\rangle_\rho$ has a large decay rate into $\Xi_b^*\pi$ with the branching fraction

$$\frac{\Gamma[\Xi_b'|J^P=\frac{3}{2}^-,1\rangle_\rho\to\Xi_b^*\pi]}{\Gamma_{\text{Total}}}\sim 25\%. \tag{55}$$

We also plot the partial decay widths of the ρ-mode $1P$ Ξ_c' and Ξ_b' baryons as a function of the mass in Fig. 5. The two-body strong decays of the ρ-mode $1P$ state in the Ξ_c'



(a)1P_ρ-wave Ξ_c' states (b)1P_ρ-wave Ξ_b' states

FIG. 5. Partial and total strong decay widths of the ρ-mode 1P states in the Ξ_c' and Ξ_b' families as functions of their masses.

family are similar to that in the Ξ_b' family. Roughly speaking, they only contain different heavy quarks: In the Ξ_c' family the heavy quark is the c quark, while in the Ξ_b' family the heavy quark changes to the b quark.

E. Ω_c and Ω_b baryons

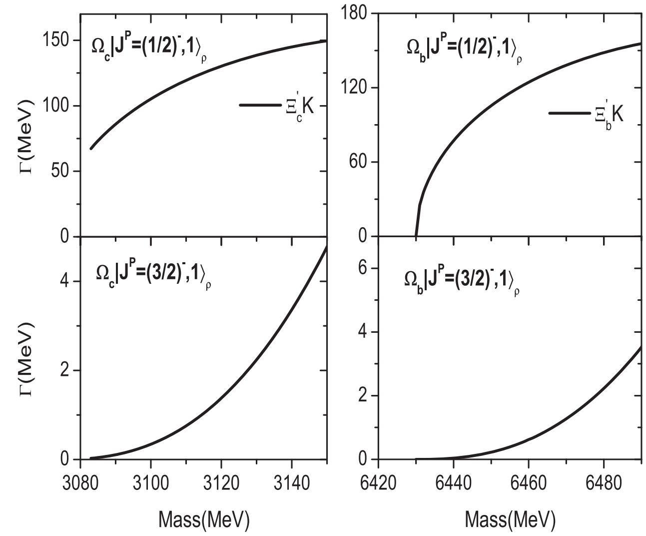
In the Ω_c and Ω_b families, there are also two ρ-mode 1P-wave states, $|J^P=\frac{1}{2}^-,1\rangle$ and $|J^P=\frac{3}{2}^-,1\rangle$. The masses of these ρ-mode 1P-wave Ω_c and Ω_b states are, respectively, about $M\sim 3.1$ and $M\sim 6.4$ GeV within various quark model predictions. Similarly, we first fix their masses at the predictions in Ref. [7] and collect the decay properties in Table VII.

In the Ω_c family, both the two ρ-mode 1P states mainly decay into $\Xi_c'K$. However, the $J^P=1/2^-$ state $\Omega_c|J^P=\frac{1}{2}^-,1\rangle_\rho$ may be a moderate state with a width of $\Gamma\sim 119$ MeV, while the $J^P=3/2^-$ state $\Omega_c|J^P=\frac{3}{2}^-,1\rangle_\rho$ is most likely to be a very narrow state with a width of $\Gamma\sim 0.9$ MeV.

TABLE VII. Partial and total strong decay widths of the ρ-mode 1P states in the Ω_c and Ω_b families. The unit of the width and mass is MeV. The masses for the unestablished ρ-mode 1P Ω_c and Ω_b states are taken from the predictions in Ref. [7].

	$\Omega_c\|J^P=\frac{1}{2}^-,1\rangle_\rho$	$\Omega_c\|J^P=\frac{3}{2}^-,1\rangle_\rho$
States	$M=3110$	$M=3112$
$\Gamma[\Xi_c'K]$	119.4	0.9

	$\Omega_b\|J^P=\frac{1}{2}^-,1\rangle_\rho$	$\Omega_b\|J^P=\frac{3}{2}^-,1\rangle_\rho$
States	$M=6437$	$M=6438$
$\Gamma[\Xi_b'K]$	65.2	0.02



(a) 1P_ρ-wave Ω_c states (b) 1P_ρ-wave Ω_b states

FIG. 6. Partial and total strong decay width of the ρ-mode 1P states in the Ω_c and Ω_b families as functions of their mass.

For the two ρ-mode 1P Ω_b states, their decays are governed by $\Xi_b'K$. The $J^P=1/2^-$ state $\Omega_b|J^P=\frac{1}{2}^-,1\rangle_\rho$ has a width of $\Gamma\sim 65$ MeV and may be observed in the $\Xi_b\pi K$ final state via the decay chain $\Omega_b|J^P=\frac{1}{2}^-,1\rangle_\rho\to\Xi_b'K\to\Xi_b\pi K$. The $J^P=3/2^-$ state $\Omega_b|J^P=\frac{3}{2}^-,1\rangle_\rho$ may be a particularly narrow state with a width of $\Gamma<0.1$ MeV. Thus, the state $\Omega_b|J^P=\frac{3}{2}^-,1\rangle_\rho$ may have a large potential to be observed in the $\Xi_b\pi K$ final state via the decay chain $\Omega_b|J^P=\frac{3}{2}^-,1\rangle_\rho\to\Xi_b'K\to\Xi_b\pi K$ at LHCb.

In addition, we analyze the decay properties of the ρ-mode 1P Ω_c and Ω_b baryons as a function of the mass in Fig. 6. It should be pointed out that the total width of the $J^P=3/2^-$ state $\Omega_{c(b)}|J^P=\frac{3}{2}^-,1\rangle_\rho$ is $\Gamma<5$ MeV within the mass varying in the region of what we considered, which indicates the state $\Omega_{c(b)}|J^P=\frac{3}{2}^-,1\rangle_\rho$ has a good potential to be observed in future experiments.

IV. SUMMARY

In the present work, we systematically studied the two-body strong decays of the low-lying ρ-mode 1P-wave singly heavy baryons in a chiral quark model within the j-j coupling scheme. On the one hand, we attempt to confirm the possibility of the controversial singly heavy baryons taken as ρ-mode excitations. On the other hand, we hope to provide the theories' foundation for the experiment exploring of the missing ρ-mode 1P singly heavy baryons. Our main results are summarized as follows.

For the ρ-mode 1P Λ_c and Λ_b baryons, the OZI-allowed two-body strong decays of the $J^P=1/2^-$ state

$\Lambda_{c(b)}|J^P=\frac{1}{2}^-,0\rangle_\rho$ are forbidden since we adopt the simple harmonic oscillator wave functions. Hence, the $\Lambda_{c(b)}|J^P=\frac{1}{2}^-,0\rangle_\rho$ should be a very narrow state. The three ρ-mode states $\Lambda_{c(b)}|J^P=\frac{1}{2}^-,1\rangle_\rho$, $\Lambda_{c(b)}|J^P=\frac{3}{2}^-,1\rangle_\rho$, and $\Lambda_{c(b)}|J^P=\frac{3}{2}^-,2\rangle_\rho$ have a broad width of $\Gamma\sim(100\text{–}200)$ MeV. It can be a big challenge for experimenters to observe them in the future. While the $J^P=5/2^-$ state $\Lambda_{c(b)}|J^P=\frac{5}{2}^-,2\rangle_\rho$ may be a narrow state and the decay width is about dozens of MeV, the $\Lambda_c|J^P=\frac{5}{2}^-,2\rangle_\rho$ has a good potential to be observed in the $\Lambda_c\pi\pi$ final state via the decay chain $\Lambda_c|J^P=\frac{5}{2}^-,2\rangle_\rho\to\Sigma_c\pi\to\Lambda_c\pi\pi$, and the $\Lambda_b|J^P=\frac{5}{2}^-,2\rangle_\rho$ may be observed in the $\Lambda_b\pi\pi$ final state via the decay chain $\Lambda_b|J^P=\frac{5}{2}^-,2\rangle_\rho\to\Sigma_b\pi/\Sigma_b^*\pi\to\Lambda_b\pi\pi$. The newly observed state $\Lambda_c(2910)^+$ can be explained as the $J^P=5/2^-$ state $\Lambda_c|J^P=\frac{5}{2}^-,2\rangle_\rho$.

The ρ-mode $1P$ $\Sigma_{c(b)}$ and $\Xi'_{c(b)}$ states are predicted to be broad states with a decay width of around $\Gamma\sim(150\text{–}200)$ and $\Gamma\sim100$ MeV, respectively. It should be mentioned that if the mass of the $J^P=3/2^-$ state $\Xi'_{c(b)}|J^P=\frac{3}{2}^-,1\rangle_\rho$ is close to the mass threshold of the $\Sigma^*_{c(b)}K$, this state may be a narrow state with dozens of MeV. Hence, the $\Xi'_{c(b)}|J^P=\frac{3}{2}^-,1\rangle_\rho$ may be observed via its mainly decay channel $\Xi_{c(b)}\pi$.

For the ρ-mode $1P$ Ξ_c and Ξ_b baryons, the states $\Xi_b|J^P=\frac{1}{2}^-,1\rangle_\rho$, $\Xi_{c(b)}|J^P=\frac{3}{2}^-,2\rangle_\rho$, $\Xi_{c(b)}|J^P=\frac{3}{2}^-,2\rangle_\rho$, and $\Xi_{c(b)}|J^P=\frac{5}{2}^-,2\rangle_\rho$ may be narrow states with a total decay width around dozens of MeV, and have a good potential to be observed in experiments, especially the Ξ_b states, whose decay widths are relatively narrower. The ideal channels for exploring these missing ρ-mode $1P$ Ξ_c states may be $\Xi_c\pi$, $\Xi_c^*\pi$, and Λ_cK, while that for the Ξ_b states may be $\Xi_b\pi$, $\Xi'_b\pi$, and $\Xi^*_b\pi$. Furthermore, our results indicate that the decay properties of the $\Xi_b|J^P=\frac{5}{2}^-,2\rangle_\rho$ state is in good agreement with the newly observed state $\Xi_b(6227)^-$, which mainly decays into $\Xi_b\pi$ and Λ_bK.

As to the ρ-mode $1P$ Ω_c and Ω_b baryons, the $\Omega_{c(b)}|J^P=\frac{3}{2}^-,1\rangle$ state also has a good potential to be observed in experiments due to its particularly narrow width of a few MeV. To look for these states, the $\Xi'_{c(b)}K$ is worth observing in future experiments.

ACKNOWLEDGMENTS

This work is supported by the National Natural Science Foundation of China under Grants No. 12005013, No. 11947048, No. 12175065, No. U1832173, and No. 11775078.

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