The strong decays of the low-lying $\rho$-mode 1P-wave singly heavy baryons

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We have systematically calculated the strong decays of the low-lying $\rho$-mode 1P-wave $\Lambda_{c(b)}$,$\Sigma_{c(b)}$,$\Xi_{c(b)}$,$\Omega_{c(b)}$ baryons using the chiral quark model within the $j$-j coupling scheme. For the controversial states, our results indicate: (i) For the singly charmed heavy baryons, the newly observed $\Lambda_{c}(2910)^+ $ is a good candidate of the $J^P = 5/2^+ $ state $\Lambda_c |J^P = 5/2^+,2_{1/2}^+ \rangle$. (ii) For the singly bottom heavy baryons, the $\Xi_b(6227)^-$ favors the $J^P = 5/2^- $ state $\Xi_b |J^P = 5/2^-,2_{3/2}^- \rangle$. (iii) The other missing $\rho$-mode 1P-wave excitations in $\Lambda_b$, $\Sigma_{c(b)}$, 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 $\rho$-mode 1P-wave $\Xi_{c(b)}$ and $\Omega_{c(b)}$ baryons have a relatively narrow decay width of a few MeV or a few tens of MeV, and have a good potential to be observed in forthcoming experiments.

PACS numbers:

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 [1, 2], which is a simpler model in hadron physics. Thus, the singly heavy baryons provide a good plot to better understand the non-perturbative nature of the quantum chromodynamics (QCD).

Over the last 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 single charm quark, the excitations listed by the Particle Data Group (PDG) [3] include $\Lambda_c(2595)^{+}$, $\Lambda_c(2625)^{+}$, $\Lambda_c(2765)^{+}$ or $\Sigma_c(2765)^{+}$, $\Lambda_c(2860)^{+}$, $\Lambda_c(2880)^{+}$, $\Lambda_c(2940)^{+}$, $\Sigma_c(2800)^{+}$, $\Xi_c(2790)^{+}$, $\Xi_c(2815)^{+}$, $\Xi_c(2923)^{+}$, $\Xi_c(2930)^{+}$, $\Xi_c(2970)^{+}$, $\Xi_c(3055)^{+}$, $\Xi_c(3080)^{+}$, $\Xi_c(3123)^{+}$, $\Omega_c(3000)^{+}$, $\Omega_c(3050)^{+}$, $\Omega_c(3065)^{+}$, $\Omega_c(3090)^{+}$, $\Omega_c(3120)^{+}$. A few of states are not listed out since the evidence for their existence is poor and need further experimental investigation, such as $\Xi_c(2939)^{+}$ and $\Xi_c(2965)^{+}$. Very recently, a possibly new excited $\Lambda_c$, namely $\Lambda_c(2910)^+$, was reported by the Belle Collaboration via investigating the $B^0 \rightarrow \Sigma_c(2455)\pi\bar{p}$ decay process [5]. The mass and width were measured to be $M = 2913.8 \pm 5.6 \pm 3.8$ MeV and $\Gamma = 51.8 \pm 20.0 \pm 18.8$ MeV, respectively. While, for the states containing single bottom quark, our knowledge is slightly less. The observed excitations listed by PDG are $\Lambda_b(5912)^0$, $\Lambda_b(5920)^0$, $\Lambda_b(6070)^0$, $\Lambda_b(6146)^0$, $\Lambda_b(6152)^0$, $\Sigma_b(6097)^+$, $\Xi_b(6100)^{+}$, $\Xi_b(6227)^{-0}$, $\Omega_b(6316)^{-}$, $\Omega_b(6330)^{-}$, $\Omega_b(6340)^{-}$ and $\Omega_b(6350)^{-}$ [3]. Recently, two new excited $\Xi_b$ states $\Xi_b(6327)^0$ and $\Xi_b(6333)^0$ were reported by the LHCb collaboration in the $\Lambda^0_b K^-\pi^+$ mass spectrum [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: $\rho$-mode and $\lambda$-mode excitations in theory (see Fig. 1). The $\rho$-mode excitation appears within the light diquark, while the $\lambda$-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 [7], one finds that the $\rho$-mode excitation energy should be pronouncedly larger than that of the $\lambda$-mode. This indicates that the $\lambda$-mode excitations should be more easily formed than $\rho$-mode excitations. Therefore, it is natural to think that most of the low-lying observed single heavy baryons probably are good candidates of the $\lambda$-mode excitations. Meanwhile, based on the mass spectrum and strong decay analyses [7–37], the literatures also indicate newly observed states $\Xi_c(2923, 2939, 2965)$ [22, 26, 38], $\Omega_c(3000, 3050, 3065, 3090, 3120)^0$ [18, 39–42], $\Sigma_c(6097)$ and $\Xi_c(6227)$ [17, 25, 28, 43–50], $\Omega_b(6316, 6330, 6340, 6350)^-$ [51–53] may be explained with the 1P-wave $\lambda$-mode excitations; $\Lambda_c(2910)$ may be the 2P-wave $\lambda$-mode excitation [54] and $\Lambda_c(2940)$ is a candidate of the 2P- or 1D-wave $\lambda$-mode excitation [8, 11, 12, 15]. However, it should be mentioned that there are other explanations of those observed structures, such as 2S-wave excitations [9, 15, 31, 55–57], 1P-wave $\rho$-mode excitations [22, 45] and unconventional interpretations [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 $\rho$-mode excitations [22, 45] cannot be excluded completely. Additionally, according to the quark model predictions [7, 22, 66, 69] the mass of the $\rho$-mode states is about $(70 - 150)$ MeV higher than that of $\lambda$-mode states. We collect some theoretical predictions of the spectrum for the 1P-wave $\rho$-mode singly heavy baryons in Table 1. From the table, it is seen that some ob-

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served states in experiments are in the predicted mass region of the 1P-wave $\rho$-mode states $[7, 20, 22]$. 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 $\rho$-mode states. However, there are only a few discussions of the strong decays of the 1P-wave $\rho$-mode singly heavy baryons $[22, 45]$.

In the present work, we conduct a systematic discussion of the strong decays of the low-lying 1P-wave $\rho$-mode $\Lambda_c(b)\Sigma_c(b)$, $\Xi_c(b)$, $\Omega_c(b)$ 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 $\Xi_c(6227)^-$ may be assignments of the 1P-wave $\rho$-mode resonances, and collect our possible explanations in Table II. We hope the predicted strong decay properties of the missing 1P-wave $\rho$-mode singly heavy baryons be helpful for future experimental exploring.

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

| state | $n_p, l_p, L, S_p, j, J^P$ | CQM $[7]$ | RQM $[66]$ | AQM $[20]$ | Mass Formula $[22]$ | strong decay channels |
|-------|-----------------|---------|---------|---------|-----------------|-----------------|
| $\Sigma_c(1P) = \frac{1}{2}^-, 1^-$ | 0 1 1 0 1 $\frac{3}{2}^-$ | 2909 | 2840 | 2848 | $\Sigma_c, \pi, \Sigma_c, \pi$ |
| $\Lambda_c(1P) = \frac{3}{2}^-, 1^-$ | 0 1 1 1 0 $\frac{3}{2}^-$ | 2910 | 2865 | 2860 | $\Sigma_c, \pi, \Sigma_c, \pi$ |
| $\Xi_c(1P) = \frac{3}{2}^-, 2^-$ | 0 1 1 1 2 $\frac{3}{2}^-$ | 2956 | 2885 | 2830 | $\Sigma_c, \pi, \Sigma_c, \pi$ |
| $\Omega_c(1P) = \frac{3}{2}^-, 2^-$ | 0 1 1 1 2 $\frac{3}{2}^-$ | 2960 | 2900 | 2872 | $\Xi_c, \pi, \Omega_c, \Xi_c, \pi, \Omega_c, K, \Omega_c, K, \Omega_c, (2790)\pi, \Omega_c, (2815)\pi$ |
| $\Sigma_c(1P) = \frac{3}{2}^-, 1^-$ | 0 1 1 0 1 $\frac{3}{2}^-$ | 3060 | 3096 | $\Xi_c, \pi, \Omega_c, K, \Xi_c, \pi, \Xi_c, K$ |
| $\Lambda_c(1P) = \frac{3}{2}^-, 1^-$ | 0 1 1 1 0 $\frac{3}{2}^-$ | 2951 | 2980 | $\Xi_c, \pi, \Xi_c, \pi, \Sigma_c, K, \Xi_c, \pi, \Lambda_c, K, \Xi_c, (2790)\pi, \Xi_c, (2815)\pi$ |
| $\Xi_c(1P) = \frac{3}{2}^-, 2^-$ | 0 1 1 1 2 $\frac{3}{2}^-$ | 3016 | 3076 | $\Xi_c, \pi, \Xi_c, \pi, \Omega_c, K, \Xi_c, \pi, \Omega_c, K, \Xi_c, (2790)\pi, \Xi_c, (2815)\pi$ |

TABLE I: The masses(MeV) of the 1P-wave $\rho$-mode single heavy baryons obtained from the quark model. ($S_p$ 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 $S_p$; $J$ is the total angular momentum; $P$ is the parity; $n_p$ and $l_p$ represent the nodal quantum number and orbital angular momentum, respectively.)
our results

\[ \Lambda_c(2910)^+ [54] \]
\[ \Sigma_c(2455)^{0 (+)} \pi^+ \]
51.8 ± 20.0 ± 18.8

2P-wave with \( J^P = 1/2^+ \)

\[ \Xi_c(6227)^- \]
\[ \Lambda_c \Sigma_c \pi \]
18 ± 6

1P-wave \( \Xi_c^0 \) with \( J^P = 3/2^- \) [17, 28, 32, 44, 50]
1P-wave \( \Xi_c^0 \) with \( J^P = 5/2^- \) [17, 28]
1P-wave or 2S-wave with \( J^P = 3/2 \) [35]
pentaquark molecular state with \( J^P = 1/2^+ \) [65, 67, 68]
\( \Sigma_c \kappa \) molecular state with \( J^P = 1/2^- \) [61]

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

Finally, a summary is given in section 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 (a, 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 \( \bar{\Xi}_f \) and antisymmetric antitriplet \( \bar{3}_f \). In the singly charmed (bottom) baryons, there are two families, \( \Lambda_f \) and \( \Xi_f \) (\( \Lambda_b \) and \( \Xi_b \)) belonging to \( \bar{3}_f \), while there are three families, \( \Sigma_f \), \( \Sigma_f' \), and \( \Omega_f \) (\( \Sigma_b \), \( \Sigma_b' \), and \( \Omega_b \)) belonging to \( \bar{\Xi}_f \) [70].

The spatial wave function of a singly heavy baryon is adopted the harmonic oscillator form in the constituent quark model [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

\[ H = \frac{P_{c.m.}^2}{2M} + \frac{1}{2m_{\rho}} p^2 + \frac{1}{2m_{\lambda}} \lambda^2 + \frac{3}{2} K (\rho^2 + \lambda^2). \]  

(1)

Here, the constituent quarks are confined in an oscillator potential with the potential parameter \( K \) independent on the flavor quantum number. \( \rho \) and \( \lambda \) are Jacobi coordinates as shown in Fig. 1 and \( R_{c.m.} \) is the center-of-mass coordinate. The momenta \( P_{\rho}, P_{\lambda}, P_{c.m.} \) are defined as

\[ P_{\rho} = m_{\rho} \rho, \quad P_{\lambda} = m_{\lambda} \lambda, \quad P_{c.m.} = M R_{c.m.}, \]  

(2)

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

\[ \psi_{l,m}^{\rho,\lambda}(\sigma) = R_{m,l}(\sigma) Y_{l,m}(\sigma) \]  

(3)

where \( \sigma = \rho, \lambda \). Thus, in the spatial wave functions of a singly heavy baryon, there are two oscillator parameters, i.e. the potential strengths \( \alpha_\rho \) and \( \alpha_\lambda \). The parameters \( \alpha_\rho \) and \( \alpha_\lambda \) satisfy the following relation:

\[ \alpha_\lambda^2 = \sqrt{\frac{3m'}{2m + m'} \alpha_\rho^2}. \]  

(4)

The spatial wave function is a product of the \( \rho \)-oscillator and \( \lambda \)-oscillator states. With the standard notation, the principle quantum numbers of the \( \rho \)-mode and \( \lambda \)-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

\[ E = (N_{\rho} + \frac{3}{2} \omega_\rho) + (N_{\lambda} + \frac{3}{2} \omega_\lambda) \]  

(5)

with the \( \rho \)-mode and \( \lambda \)-mode frequencies

\[ \omega_\rho = (3K/m_{\rho})^{1/2}, \quad \omega_\lambda = (3K/m_{\lambda})^{1/2}. \]  

(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 [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

\[ H_m = \sum_j \frac{1}{m} \bar{\psi}_j \gamma^\mu \gamma_5 \psi_j \gamma^\mu \phi_m. \]  

(7)
where $\psi_j$ stands for the $j$-th quark field in a baryon. $f_m$ is the pseudoscalar meson decay constant and $\phi_m$ is the pseudoscalar meson octet

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

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

$$
H_m^{nr} = \sum_j \left\{ \frac{\omega_m}{E_f + M_j} \sigma_j \cdot P_f + \frac{\omega_m}{E_i + M_i} \sigma_j \cdot P_i \right\}
$$

$$
= -\sigma_j \cdot q + \frac{\omega_m}{2\mu_q} \sigma_j \cdot P_i \right\} I_j \phi_m,
$$

where the $\sigma_j$ and $\mu_q$ stand for the Pauli spin vector and the reduced mass of the $j$-th quark in the initial and final baryons, respectively. $\omega_m = e^{\phi_{q,\ell}}$ denotes (emitting)absorbing a meson. $P_i = p_i - (m_j/M_i)P_{c.m.}$ is the internal momentum of the $j$-th quark in the baryon rest frame. $\omega_m$ and $q$ 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

$$
\Gamma_m = \left( \frac{\delta}{f_m} \right)^2 \frac{(E_f + M_{jL})|q|^2}{4\pi M_j} \frac{1}{2J_f + 1} \sum_{J_i, I_{jL}} |M_{J_i, J_f}|^2,
$$

where $M_{J_i, J_f}$ is the transition amplitude, $J_i$ and $J_f$ stand for the third components of the total angular momenta of the initial and final baryons, respectively. Accounting for the strength of the quark-meson coupling, $\delta$ is a global parameter which has been determined in previous study of the strong decays of the charmed baryons and heavy-light mesons. Here, 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 [20]

$$
|\ell J_f \rangle = |(l_i \ell_i \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'_f \ell'
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 $\rho$-mode $\Lambda_c$ excitations are about $M \approx (2780 - 3000) \text{ MeV}$, and their OZI-allowed two body strong decay channels are $\Sigma \pi$ and $\Sigma^* \pi$. However, we notice that the mass of $\Lambda_c|J^P = 1/2^-, 0\rangle_p$ is above the threshold of $\Sigma \pi$ and $\Sigma^* \pi$, 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 $\rho$-mode $\Lambda_c$ states are sensitive to the masses. With the mass in the region of $M \approx (2780 - 3000) \text{ MeV}$, the states $\Lambda_c|J^P = 1/2^-, 1\rangle_p$, $\Lambda_c|J^P = 3/2^-, 1\rangle_p$, and $\Lambda_c|J^P = 3/2^-, 2\rangle_p$ are predicted to be moderate states with a width of $\Gamma \approx (50 - 150) \text{ MeV}$. It should be pointed out that the mainly decay channel of $\Lambda_c|J^P = 1/2^-, 1\rangle_p$ is $\Sigma \pi$, while that of $\Lambda_c|J^P = 3/2^-, 1\rangle_p$ is $\Sigma^* \pi$. For the $\Lambda_c|J^P = 3/2^-, 2\rangle_p$ state, if its mass is less than $M < 2958 \text{ MeV}$, its dominant decay channel is $\Sigma^* \pi$. Otherwise its dominant decay channel is $\Sigma \pi$. As to the $\Lambda_c|J^P = 5/2^-, 2\rangle_p$ state, it is likely to be a narrow state with a width of $\Gamma \approx (10 - 50) \text{ MeV}$ when the mass varies in the region of what we considered in the present work. The mainly decay channel is $\Sigma \pi$, while the $\Sigma^* \pi$ partial decay width is considerable as well.

Combining the natures of the newly observed state $\Lambda_c(2910)^+$ at Belle [54], we find that this new state may be an assignment of the narrow state $\Lambda_c|J^P = 5/2^-, 2\rangle_p$. Fixing the mass of $\Lambda_c|J^P = 5/2^-, 2\rangle_p$ at $M = 2914 \text{ MeV}$, the predicted total decay width

$$\Gamma_{\text{Total}} = 22 \text{ MeV},$$

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

$$\frac{\Gamma[\Lambda_c|J^P = 5/2^-, 2\rangle_p \to \Sigma \pi]}{\Gamma_{\text{Total}}} \approx 63\%.$$  

Meanwhile, the decay rate of $\Lambda_c|J^P = 5/2^-, 2\rangle_p$ into $\Sigma^* \pi$ is considerable, and the predicted branching fraction is

$$\frac{\Gamma[\Lambda_c|J^P = 5/2^-, 2\rangle_p \to \Sigma^* \pi]}{\Gamma_{\text{Total}}} \approx 37\%.$$  

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 $\Lambda_c|J^P = 1/2^-, 2\rangle_p$ and $\Lambda_c|J^P = 3/2^-, 1\rangle_p$ since there are large uncertainties in the observed width of $\Lambda_c(2910)^+$.

In the $\Lambda_b$ family, according to the predicted masses collected in Table I, the masses of the five $\rho$-mode $1P$ $\Lambda_b$ excitations are in the region of $M \approx (6100 - 6300) \text{ MeV}$. Similarly, although the mass of the $\Lambda_b|J^P = 1/2^-, 0\rangle_p$ is above the threshold of $\Sigma \pi$ and $\Sigma^* \pi$, 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 $\rho$-mode $1P$ $\Lambda_b$ states as a function of the mass.
TABLE III: Partial decay widths (MeV) and branching fractions for the ρ-mode 1P-wave states in the Σc and Σb families. The numbers in parentheses stand for the corresponding masses (MeV).

| State | Width (MeV) | Branching Fraction (%) |
|-------|-------------|------------------------|
| Σc | 1J = 1/2, 1 | 2909 | 100 | 66 | 74% |
| Σc | 1J = 1/2, 1 | 2910 | 51 | 34 | 73% |

The masses of the ρ-mode 1P-wave Σc and Σb excitations are predicted to be $M_c = (2840 - 2910) \text{ MeV}$ and $M_b = (6170 - 6250) \text{ MeV}$, 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 $\Gamma \sim (150 - 200) \text{ MeV}$.

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

$$\frac{\Gamma(\Sigma_c |J^P = 1/2^-, 1\rangle_\rho \rightarrow \Sigma_c \pi)}{\Gamma_{\text{Total}}} \sim 66\%,$$

$$\frac{\Gamma(\Sigma_c |J^P = 3/2^-, 1\rangle_\rho \rightarrow \Sigma_c \pi)}{\Gamma_{\text{Total}}} \sim 70\%,$$

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

In the Σb family, the $J^P = 1/2^+$ state $\Sigma_b |J^P = 1/2^+, 1\rangle_\rho$ mainly decays into $\Sigma_b \pi$ and $\Sigma_b^\ast \pi$. Their branching fractions are

$$\frac{\Gamma(\Sigma_b |J^P = 1/2^+, 1\rangle_\rho \rightarrow \Sigma_b \pi)}{\Gamma_{\text{Total}}} \sim 53\%,$$

$$\frac{\Gamma(\Sigma_b |J^P = 1/2^+, 1\rangle_\rho \rightarrow \Sigma_b^\ast \pi)}{\Gamma_{\text{Total}}} \sim 47\%.$$

The $J^P = 3/2^+$ state $\Sigma_b |J^P = 3/2^+, 1\rangle_\rho$ is governed by $\Sigma_b \pi$, and branching fraction is predicted to be

$$\frac{\Gamma(\Sigma_b |J^P = 3/2^+, 1\rangle_\rho \rightarrow \Sigma_b \pi)}{\Gamma_{\text{Total}}} \sim 73\%.$$
Considering the uncertainty of the mass predictions of the \( \rho \)-mode 1\( P \)-wave \( \Sigma \) and \( \Sigma_b \) 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. \( \Xi \) and \( \Xi_b \) baryons

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

In the \( \Xi \) family, the \( J^P = 1/2^- \) state \( \Xi_c |J^P = \frac{1}{2}^-, 0\rangle_\rho \) has a moderate width of \( \Gamma \sim 113 \) MeV, and dominantly decays into \( \Xi_\rho \pi \) and \( \Lambda_c K \) with predicted branching fractions

\[
\frac{\Gamma(\Xi_c |J^P = \frac{1}{2}^-, 0\rangle_\rho \rightarrow \Xi_\rho \pi)}{\Gamma_{\text{Total}}} \sim 43%, \quad (30)
\]

\[
\frac{\Gamma(\Xi_c |J^P = \frac{1}{2}^-, 0\rangle_\rho \rightarrow \Lambda_c K)}{\Gamma_{\text{Total}}} \sim 57%. \quad (31)
\]

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

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 \( \Gamma \sim 138 \) MeV. This state mainly decays into \( \Xi_\rho \pi \) and \( \Sigma \). Their branching fractions are

\[
\frac{\Gamma(\Xi_c |J^P = \frac{1}{2}^-, 1\rangle_\rho \rightarrow \Xi_\rho \pi)}{\Gamma_{\text{Total}}} \sim 24%, \quad (32)
\]

\[
\frac{\Gamma(\Xi_c |J^P = \frac{1}{2}^-, 1\rangle_\rho \rightarrow \Sigma \pi)}{\Gamma_{\text{Total}}} \sim 74%. \quad (33)
\]

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 \( \Xi_\rho \pi \), \( \Lambda_c K \) and \( \Xi_\rho \pi \) channels. The branching fractions are predicted to be

\[
\frac{\Gamma(\Xi_c |J^P = \frac{3}{2}^-, 1\rangle_\rho \rightarrow \Xi_\rho \pi)}{\Gamma_{\text{Total}}} \sim 33%, \quad (34)
\]

\[
\frac{\Gamma(\Xi_c |J^P = \frac{3}{2}^-, 1\rangle_\rho \rightarrow \Lambda_c K)}{\Gamma_{\text{Total}}} \sim 16%, \quad (35)
\]

\[
\frac{\Gamma(\Xi_c |J^P = \frac{3}{2}^-, 1\rangle_\rho \rightarrow \Xi_\rho \pi)}{\Gamma_{\text{Total}}} \sim 50%. \quad (36)
\]

This state have a large potential to be observed in the \( \Xi_\rho \pi \), \( \Lambda_c K \) and \( \Xi_\rho \pi \) 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 the \( \Xi_c \pi \), \( \Lambda_c K \) and \( \Xi_\rho \pi \) channels, this state also has large decay rates into \( \Xi_\rho \pi \) and \( \Sigma \). The branching fractions for the \( \Xi_\rho \pi \) and \( \Sigma \) channels can reach up to

\[
\frac{\Gamma(\Xi_c |J^P = \frac{3}{2}^-, 2\rangle_\rho \rightarrow \Xi_\rho \pi)}{\Gamma_{\text{Total}}} \sim 31%, \quad (37)
\]

\[
\frac{\Gamma(\Xi_c |J^P = \frac{3}{2}^-, 2\rangle_\rho \rightarrow \Sigma \pi)}{\Gamma_{\text{Total}}} \sim 20%. \quad (38)
\]

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 \( \Xi_c |J^P = \frac{3}{2}^-, 2\rangle_\rho \rightarrow \Xi_\rho \pi \pi K \rightarrow \Xi_c \pi \pi \Lambda_c \pi K \).

The decay of \( \Xi_c |J^P = \frac{3}{2}^-, 2\rangle_\rho \) is governed by \( \Xi_\rho \pi \) and \( \Lambda_c K \) with branching fractions

\[
\frac{\Gamma(\Xi_c |J^P = \frac{3}{2}^-, 2\rangle_\rho \rightarrow \Xi_\rho \pi)}{\Gamma_{\text{Total}}} \sim 53%, \quad (39)
\]

\[
\frac{\Gamma(\Xi_c |J^P = \frac{3}{2}^-, 2\rangle_\rho \rightarrow \Lambda_c K)}{\Gamma_{\text{Total}}} \sim 29%. \quad (40)
\]

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

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

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

The other four \( \rho \)-mode 1\( P \) 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 difference 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

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

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

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

\[
\frac{\Gamma(\Xi_b |J^P = \frac{3}{2}^-, 2\rangle_\rho \rightarrow \Xi_b \pi)}{\Gamma_{\text{Total}}} \sim 61\% (63%). \quad (45)
\]
TABLE IV: The strong decay properties of the $\rho$-mode $1P$-wave states in the $\Xi_c$ and $\Xi_b$ families. $\Gamma_{\text{Total}}$ stands for the total decay width. The unit of the width and mass is MeV. The masses for the unestablished $\rho$-mode $1P\,\Xi_c$ and $\Xi_b$ states are taken from the predictions in Ref. [22].

| Decay width | $\Xi_c\,|J^p = \frac{1}{2}^-, 0\rangle_\rho$ | $\Xi_c\,|J^p = \frac{1}{2}^-, 1\rangle_\rho$ | $\Xi_c\,|J^p = \frac{1}{2}^-, 2\rangle_\rho$ | $\Xi_b\,|J^p = \frac{1}{2}^-, 0\rangle_\rho$ | $\Xi_b\,|J^p = \frac{1}{2}^-, 1\rangle_\rho$ | $\Xi_b\,|J^p = \frac{1}{2}^-, 2\rangle_\rho$ |
|-------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| $\Gamma(\Xi_c,\pi)$ | 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 |
| $\Gamma(\Xi_b,(2790)\pi)$ | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 |
| $\Gamma(\Xi_b,(2815)\pi)$ | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 |
| $\Gamma_{\text{Total}}$ | 112.8 | 138.3 | 32.2 | 57.8 | 70.5 |

| Decay width | $\Xi_c\,|J^p = \frac{1}{2}^-, 0\rangle_\rho$ | $\Xi_c\,|J^p = \frac{1}{2}^-, 1\rangle_\rho$ | $\Xi_c\,|J^p = \frac{1}{2}^-, 2\rangle_\rho$ | $\Xi_b\,|J^p = \frac{1}{2}^-, 0\rangle_\rho$ | $\Xi_b\,|J^p = \frac{1}{2}^-, 1\rangle_\rho$ | $\Xi_b\,|J^p = \frac{1}{2}^-, 2\rangle_\rho$ |
|-------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| $\Gamma(\Xi_c,\pi)$ | 50.6 | 0.0 | 5.5 | 5.1 | 13.1 |
| $\Gamma(\Lambda_c K)$ | 76.0 | 0.0 | 1.5 | 1.5 | 4.4 |
| $\Gamma(\Xi_c,\pi)$ | 0.0 | 25.0 | 0.1 | 1.5 | 0.6 |
| $\Gamma(\Sigma_c K)$ | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| $\Gamma(\Xi_c,\pi)$ | 0.0 | 0.8 | 11.2 | 13.7 | 0.6 |
| $\Gamma(\Sigma_c K)$ | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| $\Gamma_{\text{Total}}$ | 126.6 | 25.8 | 18.3 | 21.9 | 18.7 |

FIG. 4: Partial and total strong decay width of the $\rho$-mode $1P$ states in the $\Xi_c$ and $\Xi_b$ families as functions of their masses. Some decay channels are not shown in the figure for their small partial decay widths.
TABLE V: The partial decay widths (MeV) of $\Xi_b(6227)^-$ assigned as $p$-mode $1P$ $\Xi_b$ state $\Xi_b |J^P = \frac{3}{2}^-, 2\rangle_p$.

| Decay width $\Xi_b |J^P = \frac{3}{2}^-, 2\rangle_p$ | $\Xi_b(6227)^-$ |
|-----------------------------------------------|-------------------------------|
| $\Gamma(\Xi_b\pi)$                          | 10.7                          |
| $\Gamma(\Lambda_bK)$                        | 3.0                           |
| $\Gamma(\Xi_b\pi)$                         | 0.4                           |
| $\Gamma_{\text{Total}}$                    | 14.5                          |
| $\Gamma_{\text{Exp.}}$                     | 19.9 ± 2.6                    |

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

$$\frac{\Gamma(\Xi_b |J^P = \frac{5}{2}^-, 2\rangle_p \rightarrow \Xi_b\pi)}{\Gamma_{\text{Total}}} \sim 70\%.$$  (46)

Meanwhile, the $\Xi_b |J^P = \frac{5}{2}^-, 2\rangle_p$ state has a sizeable decay rate into $\Lambda_bK$, and the branching fraction is about

$$\frac{\Gamma(\Xi_b |J^P = \frac{5}{2}^-, 2\rangle_p \rightarrow \Lambda_bK)}{\Gamma_{\text{Total}}} \sim 24\%.$$  (47)

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

Similarly, the predicted masses of the $p$-mode $1P$ $\Xi_c$ and $\Xi_b$ 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 $p$-mode $1P$ $\Xi_c$, and $\Xi_b$ excitations as a function of the mass in Fig. 4. As a whole, most of the $p$-mode $1P$ $\Xi_c$, and $\Xi_b$ states may have good potential to be observed in experiments due to their relatively narrow widths.

D. $\Xi'_c$ and $\Xi'_b$ baryons

In the $\Xi'_c$ and $\Xi'_b$ families, there are each two $p$-mode $1P$-wave excitations: $|J^P = \frac{1}{2}^-, 1\rangle_p$ and $|J^P = \frac{3}{2}^-, 1\rangle_p$. According to the theoretical predictions by various methods, the masses of the $p$-mode $1P$ $\Xi'_c$ and $\Xi'_b$ 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 difference. The $\Xi'_c |J^P = \frac{1}{2}^-, 1\rangle_p$ is governed by $\Sigma, K$, and the corresponding branching fraction is predicted to be

$$\frac{\Gamma(\Xi'_c |J^P = \frac{1}{2}^-, 1\rangle_p \rightarrow \Sigma K)}{\Gamma_{\text{Total}}} \sim 71\%.$$  (48)

Thus, the $\Xi'_c |J^P = \frac{1}{2}^-, 1\rangle_p$ may be observed in the $\Lambda_c\pi K$ final state via the decay chain $\Xi'_c |J^P = \frac{1}{2}^-, 1\rangle_p \rightarrow \Sigma K \rightarrow \Lambda_c \pi K$ in future experiments. Meanwhile, this state has sizeable decay decay rates into $\Xi'_c \pi$ and $\Xi'_c \pi$ with branching fractions

$$\frac{\Gamma(\Xi'_c |J^P = \frac{1}{2}^-, 1\rangle_p \rightarrow \Xi'_c \pi)}{\Gamma_{\text{Total}}} \sim 16\%.$$  (49)

For the $\Xi'_c |J^P = \frac{3}{2}^-, 1\rangle_p$, it mainly decays into $\Sigma'_c K$ with a
branching fraction
\[
\Gamma(\Xi'_c | J^P = \frac{3}{2}^-, 1)_\rho \rightarrow \Sigma^*_c K) \over \Gamma_{\text{Total}} \sim 58\%. \tag{51}
\]

Yet the other channels \(\Xi'_c \pi, \Xi'_c \pi\) and \(\Sigma^*_c K\) are not obviously neglectable as well. The branching fraction for the \(\Xi'_c \pi\) channel can reach up to
\[
\Gamma(\Xi'_c | J^P = \frac{3}{2}^-, 1)_\rho \rightarrow \Xi'_c \pi) \over \Gamma_{\text{Total}} \sim 21\%. \tag{52}
\]

For the two \(\rho\)-mode \(1P\) states in the \(\Xi'_b\) family, the dominant decay channel of \(\Xi'_b | J^P = \frac{1}{2}^-, 1)_\rho\) is \(\Sigma_b K\), while that of \(\Xi'_b | J^P = \frac{3}{2}^-, 1)_\rho\) is \(\Sigma^*_b K\). The predicted branching fractions are
\[
\Gamma(\Xi'_b | J^P = \frac{1}{2}^-, 1)_\rho \rightarrow \Sigma_b K) \over \Gamma_{\text{Total}} \sim 69\%, \tag{53}
\]
\[
\Gamma(\Xi'_b | J^P = \frac{3}{2}^-, 1)_\rho \rightarrow \Sigma^*_b K) \over \Gamma_{\text{Total}} \sim 66\%. \tag{54}
\]

In addition, the \(\Xi'_b | J^P = \frac{3}{2}^-, 1)_\rho\) has a large decay rate into \(\Xi'_b \pi\) with the branching fraction
\[
\Gamma(\Xi'_b | J^P = \frac{3}{2}^-, 1)_\rho \rightarrow \Xi'_b \pi) \over \Gamma_{\text{Total}} \sim 25\%. \tag{55}
\]

We also plot the partial decay widths of the \(\rho\)-mode \(1P\) \(\Xi'_c\) and \(\Xi'_b\) baryons as a function of the mass in Fig. 5. The two-body strong decays of the \(\rho\)-mode \(1P\) state in \(\Xi'_c\) family are similar to that in \(\Xi'_b\) family. Roughly speaking, they are only containing different heavy quarks: In the \(\Xi'_c\) family the heavy quark is \(c\) quark, while in \(\Xi'_b\) family the heavy quark changes to \(b\) quark.

### E. \(\Omega_c\) and \(\Omega_b\) baryons

In the \(\Omega_c\) and \(\Omega_b\) families, there are also two \(\rho\)-mode \(1P\)-wave states, \(| J^P = \frac{1}{2}^-, 1\rangle\) and \(| J^P = \frac{3}{2}^-, 1\rangle\). The masses of these \(\rho\)-mode \(1P\)-wave \(\Omega_c\) and \(\Omega_b\) 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 \(\Omega_c\) family, both the two \(\rho\)-mode \(1P\) states mainly decay into \(\Xi'_c K\). However, the \(J^P = 1/2^-\) state \(\Omega_c | J^P = \frac{1}{2}^-, 1\rangle\) may be a moderate state with a width of \(\Gamma \sim 119\) MeV, while the \(J^P = 3/2^-\) state \(\Omega_c | J^P = \frac{3}{2}^-, 1\rangle\) is most likely to be a very narrow state with a width of \(\Gamma \sim 0.9\) MeV.

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

In addition, we analyze the decay properties of the \(\rho\)-mode \(1P\) \(\Omega_c\) and \(\Omega_b\) 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 \(\Omega_c | J^P = \frac{3}{2}^-, 1\rangle\) is \(\Gamma \sim 5\) MeV within the mass varying in the region of what we considered, which indicates the state \(\Omega_c | J^P = \frac{3}{2}^-, 1\rangle\) 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 \(\rho\)-mode \(1P\)-wave singly heavy baryons in 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 \(\rho\)-mode excitations. On the other hand, we hope to provide the theories found-

### TABLE VII: Partial and total strong decay widths of the \(\rho\)-mode \(1P\) states in the \(\Omega_c\) and \(\Omega_b\) families. The unit of the width and mass is MeV. The masses for the unestablished \(\rho\)-mode \(1P\) \(\Omega_c\) and \(\Omega_b\) states are taken from the predictions in Ref. [7].

| States                  | \(\Omega_c | J^P = \frac{1}{2}^-, 1\rangle\) | \(\Omega_c | J^P = \frac{3}{2}^-, 1\rangle\) | \(\Omega_b | J^P = \frac{1}{2}^-, 1\rangle\) | \(\Omega_b | J^P = \frac{3}{2}^-, 1\rangle\) |
|------------------------|----------------------------------|----------------------------------|----------------------------------|----------------------------------|
| \(\Gamma(\Xi'_c K)\)   | \(M = 3110\)                     | \(M = 3112\)                     | \(M = 6437\)                     | \(M = 6438\)                     |
| \(\Gamma(\Xi'_b K)\)   | \(119.4\)                        | \(0.9\)                          | \(65.2\)                         | \(0.02\)                         |

FIG. 6: Partial and total strong decay width of the \(\rho\)-mode \(1P\) states in the \(\Omega_c\) and \(\Omega_b\) families as functions of their mass.
dation for the experiment exploring of the missing $\rho$-mode $1P$ singly heavy baryons. Our main results are summarized as follows.

For the $\rho$-mode $1P$ $\Lambda_c$ and $\Lambda_b$ baryons, the OZI-allowed two-body strong decays of the $J^P = 1/2^-$ state $\Lambda_{c(b)}(J^P = 1/2^-, 0)_\rho$ are forbidden since we adopt the simple harmonic oscillator wave functions. Hence, the $\Lambda_{c(b)}(J^P = 1/2^-, 0)_\rho$ should be very narrow state. The three $\rho$-mode states $\Lambda_{c(b)}(J^P = 3/2^-, 1)_\rho$ and $\Lambda_{c(b)}(J^P = 3/2^-, 2)_\rho$ have a broad width of $\Gamma \sim (100-200)$ MeV. It can be a big challenge for experimenters to observe them in future. While, the $J^P = 5/2^-$ state $\Lambda_{c(b)}(J^P = 5/2^-, 2)_\rho$ may be a narrow state and the decay width is about dozens of MeV. Thus, the $\Lambda_{c(b)}(J^P = 5/2^-, 2)_\rho$ has a good potential to be observed in the $\Lambda_c\pi\pi$ final state via the decay chain $\Lambda_c(3940)^\pm \rightarrow \Sigma_c\pi \rightarrow \Lambda_c\pi\pi$, and the $\Lambda_b(3940)^\pm$ should be very narrow state. The three $\rho$-mode states $\Lambda_{c(b)}(J^P = 5/2^-, 2)_\rho$ may be observed in the $\Lambda_c\pi\pi$ final state via the decay chain $\Lambda_{c(b)}(J^P = 5/2^-, 2)_\rho \rightarrow \Sigma_{c(b)}\pi\pi$, $\Sigma'_{c(b)}\pi\pi$. The newly observed state $\Lambda_{c(b)}(2910)^\pm$ can be expressed as the $J^P = 5/2^-$ state $\Lambda_c(3940)^\pm$, $\Lambda_b(3940)^\pm$.

The $\rho$-mode $1P$ $\Sigma_{c(b)}$ and $\Xi_{c(b)}$ states are predicted to be broad states with a decay width of around $\Gamma \sim (150-200)$ and $\Gamma \sim 100$ MeV, respectively. It should be mentioned that if the mass of the $J^P = 3/2^-$ state $\Sigma_{c(b)}(J^P = 3/2^-, 1)_\rho$, is close to the mass threshold of the $\Sigma_{c(b)}(1385)^\pm$, this state may be a narrow state with dozens of MeV. Hence, the $\Xi_{c(b)}(J^P = 3/2^-, 1)_\rho$ may be observed via its major decay channel $\Xi_{c(b)}\pi$.

For the $\rho$-mode $1P$ $\Xi_c$ and $\Xi_b$ baryons, the states $\Xi_{c(b)}(J^P = 1/2^-, 1)_\rho$, $\Xi_{c(b)}(J^P = 3/2^-, 2)_\rho$ and $\Xi_{c(b)}(J^P = 5/2^-, 2)_\rho$ may be observed in the $\Xi_{c(b)}(5277)^\pm$ state with a total decay width around dozens of MeV, and have a good potential to be observed in experiments, especially the $\Xi_{c(b)}$, whose decay widths are relatively narrower. The ideal channels for exploring these missing $\rho$-mode $1P$ $\Xi_c$ states may be $\Xi_c\pi$, $\Xi_c\Xi_c$ and $\Lambda_c\Lambda_c$, while for the $\Xi_b$ states may be $\Xi_b\pi$, $\Xi_b\Xi_b$ and $\Lambda_b\Lambda_b$. Furthermore, our results indicate that the decay properties of the $\Xi_{c(b)}(J^P = 3/2^-, 2)_\rho$ state is in good agreement with the newly observed state $\Xi_{c(b)}(6277)^-$, which mainly decays into $\Xi_{c(b)}\pi$ and $\Lambda_{c(b)}K$.

As to the $\rho$-mode $1P$ $\Omega_c$ and $\Omega_b$ baryons, the $\Omega_{c(b)}(J^P = 3/2^-, 1)_\rho$ state also have good potentials to be observed in experiments due to its particularly narrow width of a few MeV. To looking for these states, the $\Xi_{c(b)}K$ is worth observing in future experiments.

Acknowledgements

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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