THE EUROPEAN
PHYSICAL JOURNAL C

The newly observed $\Lambda_b(6072)^0$ structure and its ρ-mode nonstrange partners

Wei Liang[1,2,3], **Qi-Fang Lü**[1,2,3,a]

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

Abstract Inspired by the newly observed $\Lambda_b(6072)$ structure, we investigate its strong decay behaviors under various assignments within the $^3P_0$ model. Compared with the mass and total decay width, our results suggest that the $\Lambda_b(6072)$ can be regarded as the lowest ρ-mode excitation in Λ_b family. Then, the strong decays of ρ-mode nonstrange partners for the $\Lambda_b(6072)$ are calculated. It is found that the $J^P = 5/2^-$ Λ_b and Λ_c states are relatively narrow, and mainly decay into the $\Sigma_b^{(*)}\pi$ and $\Sigma_c^{(*)}\pi$ final states, respectively. These two states have good potentials to be observed in future experiments, which may help us to distinguish the three-quark model and diquark model.

1 Introduction

Recently, the CMS Collaboration observed an evidence for a broad excess of events in the $\Lambda_b^0\pi^+\pi^-$ mass spectrum in the region of $6040 \sim 6100$ MeV [1]. Subsequently, the LHCb Collaboration also found a new baryon resonance $\Lambda_b(6072)^0$ in the same final states. The measured mass and decay width are [2]:

$$m[\Lambda_b(6072)^0] = 6072.3 \pm 2.9 \ \pm 0.6 \pm 0.2 \text{ MeV}, \quad (1)$$

$$\Gamma[\Lambda_b(6072)^0] = 72 \pm 11 \ \pm 2 \text{ MeV}, \quad (2)$$

which is consistent with the structure reported by the CMS Collaboration.

In recent years, a series of important progresses on the $\Lambda_{c(b)}$ and $\Sigma_{c(b)}$ families have been made experimentally. In 2017, a new charmed baryon $\Lambda_c(2860)$ was reported by the LHCb Collaboration in the D^0p final state, and the

masses and decay widths of the $\Lambda_c(2880)$ and $\Lambda_c(2940)$ were measured [3]. In 2018, the LHCb Collaboration found an excited bottom baryon $\Sigma_b(6097)$ in the $\Lambda_b^0\pi^\pm$ invariant mass spectrum [4]. In 2019, the LHCb Collaboration reported the observation of $\Lambda_b(6146)$ and $\Lambda_b(6152)$ in the $\Lambda_b^0\pi^+\pi^-$ decay mode [5], which were confirmed by the CMS Collaboration subsequently [1]. These discoveries have attracted wide attentions of theorists, and plenty of works have been done to investigate the inner structures of observed $\Lambda_{c(b)}$ and $\Sigma_{c(b)}$ resonances [6–40]. In the traditional quark model, for the low-lying λ-mode Λ_c states, the $\Lambda_c(2595)$ and $\Lambda_c(2625)$ resonances can be assigned as the $\Lambda_c(1P)$ doublet, the $\Lambda_c(2860)$ and $\Lambda_c(2880)$ resonances can be categorized into the $\Lambda_c(1D)$ doublet, and the $\Lambda_c(2765)$ can be regarded as the $\Lambda_c(2S)$ singlet [21–30]. Similarly, for the low-lying λ-mode Λ_b states, the $\Lambda_b(5912)$ and $\Lambda_b(5920)$ have been assigned as the $\Lambda_b(1P)$ doublet, and the two structures $\Lambda_b(6146)$ and $\Lambda_b(6152)$ can be clarified into the $\Lambda_b(1D)$ doublet [9–11,27–32]. It can be seen that the spectra of the low-lying λ-mode Λ_c and Λ_b states have been established well except for the $\Lambda_b(2S)$ state. For the Σ_c and Σ_b states, the similar patterns should also exist, and two P-wave candidates $\Sigma_c(2800)$ and $\Sigma_b(6097)$ have been observed experimentally [4,41]. Contrary to the abundant λ-mode states, no ρ-mode heavy baryon has been confirmed both theoretically and experimentally.

Considering the mass and width of $\Lambda_b(6072)$, the LHCb Collaboration suggested that it can be assigned as the first radial excitation of the Λ_b baryon, the λ-mode $\Lambda_b(2S)$ state. Although the predicted mass of λ-mode $\Lambda_b(2S)$ state is consistent with the experimental observation [28–32], the predicted total decay width is actually smaller than $72 \pm 11 \ \pm 2$ MeV in the literature [9,10,15]. Meanwhile, recent works suggested that it may be a Roper-like resonance [42] or a overlap of two $\Sigma_b(1P)$ states [43]. Before making

[a] e-mail: lvqifang@hunnu.edu.cn (corresponding author)

a final conclusion, it is necessary to examine all possible interpretations carefully.

Based on the small predicted $\Lambda_b^0 \pi\pi$ decay widths of $\Sigma_b(1P)$ states [44] and no signal with 6072 MeV in $\Lambda_b^0 \pi^{\pm}$ decay modes [4], the LHCb Collaboration suggested that the interpretation of this newly observed structure as an excited $\Sigma_b(1P)$ resonance is disfavoured. However, for the $\Lambda_b^0 \pi\pi$ decay mode, only the $\Sigma_b(1P) \to \Lambda_b^0 (\pi\pi)_{I=1} \to \Lambda_b^0 \pi\pi$ decay chain was calculated [44], and other decay chains, such as $\Sigma_b(1P) \to \Sigma_b^{(*)} \pi \to \Lambda_b^0 \pi\pi$, should also exist. Indeed, the decay chains via virtual heavy baryons play essential roles in the three-body decays of excited heavy baryons [42,45–47]. From Refs. [9,15–17,27], there are five $\Sigma_b(1P)$ states and several of them have rather small $\Lambda_b^0 \pi^{\pm}$ branching ratios. It is possible for a $\Sigma_b(1P)$ state to be not observed in the $\Lambda_b^0 \pi^{\pm}$ final states experimentally. Hence, the observed structure with 6072 MeV as $\Sigma_b(1P)$ assignments need further investigations.

In the three-quark model, the excitations of the heavy baryons can be divided into two parts, the ρ-mode and λ-mode. In the diquark model, the two light quarks are usually treated as a cluster without excitation, and only the λ-mode excitation exists. It can be seen that the diquark model freezes the degree of freedom between two light quarks and have less states than that of the three-quark model. In the relativized quark model, the predicted lowest ρ-mode Λ_b state lies about 6100 MeV [31], which is consistent with the experimental data. It is crucial to discuss the possibility of newly observed $\Lambda_b(6072)$ as a ρ-mode $\tilde{\Lambda}_b(1P)$ state. Moreover, it is a good opportunity to investigate these low-lying ρ-mode excitations in the nonstrange singly heavy baryon systems.

In this work, we tentatively assign the newly observed resonance $\Lambda_b(6072)$ as the λ-mode $\Lambda_b(2S)$, λ-mode $\Sigma_b(1P)$, and ρ-mode $\tilde{\Lambda}_b(1P)$ states, respectively, and calculate their strong decay behaviors. Our results indicate that the λ-mode $\Lambda_b(2S)$ and $\Sigma_b(1P)$ assignments are disfavored, while the $\Lambda_b(6072)$ as the lowest ρ-mode Λ_b state is supported. With this interpretation, the $\Lambda_b(6072)$ may be the first observed ρ-mode excitation in singly heavy baryons. Then, the strong decays of the ρ-mode $\tilde{\Lambda}_c(1P)$, $\tilde{\Sigma}_b(1P)$ and $\tilde{\Sigma}_c(1P)$ states are calculated, and some of them have relatively narrow total decay widths. We hope these theoretical predictions on $\tilde{\Lambda}_{b(c)}(1P)$ and $\tilde{\Sigma}_{b(c)}(1P)$ states can provide valuable information for searching more ρ-mode excitations in future experiments.

The paper is organized as follows. In Sect. 2, we introduce the $^3P_0$ model and notations briefly. In Sect. 3, the strong decays of the newly observed $\Lambda_b(6072)$ state under various assignments are investigated. The strong decay behaviors of the ρ-mode $\tilde{\Lambda}_c(1P)$, $\tilde{\Sigma}_b(1P)$ and $\tilde{\Sigma}_c(1P)$ states are presented in Sect. 4. A summary is given in the last section.

2 Model and notations

In this issue, we adopt the $^3P_0$ model to study the strong decay behaviors of the singly heavy baryons. For a certain decay process, this model supposes that a quark–antiquark pair with the quantum number $J^{PC} = 0^{++}$ is created from the vacuum and falls apart into the final states [48]. The transition operator T for a decay process $A \to BC$ can be expressed as

$$T = -3\gamma \sum_m \langle 1m1-m|00 \rangle \int d^3\boldsymbol{p}_4 d^3\boldsymbol{p}_5 \delta^3(\boldsymbol{p}_4 + \boldsymbol{p}_5)$$
$$\times \mathcal{Y}_1^m \left(\frac{\boldsymbol{p}_4 - \boldsymbol{p}_5}{2} \right) \chi_{1,-m}^{45} \phi_0^{45} \omega_0^{45} b_{4i}^{\dagger}(\boldsymbol{p}_4) d_{4j}^{\dagger}(\boldsymbol{p}_5). \quad (3)$$

Here, the overall constant γ reflects the $q_4\bar{q}_5$ pair-production strength, and $\boldsymbol{p}_4$ and $\boldsymbol{p}_5$ are the momenta of the created quark–antiquark pair. The solid harmonic polynomial $\mathcal{Y}_1^m(\boldsymbol{p}) \equiv |p| Y_1^m(\theta_p, \phi_p)$ is the P-wave distribution of the created quark pair in the momentum representation. The ϕ_0^{45}, ω_0^{45} and $\chi_{1,-m}^{45}$ are the flavor, color, and spin parts of the quark pair $q_4\bar{q}_5$.

The transition matrix element for this model can be given by

$$\langle BC|T|A \rangle = \delta^3(\boldsymbol{P}_A - \boldsymbol{P}_B - \boldsymbol{P}_C) \mathcal{M}^{M_{J_A} M_{J_B} M_{J_C}}, \quad (4)$$

where the $\mathcal{M}^{M_{J_A} M_{J_B} M_{J_C}}$ corresponds to the helicity amplitude of the decay process $A \to B + C$. With the $\mathcal{M}^{M_{J_A} M_{J_B} M_{J_C}}$, one can calculate the partial width of this process directly

$$\Gamma = \pi^2 \frac{p}{M_A^2} \frac{1}{2J_A + 1} \sum_{M_{J_A}, M_{J_B}, M_{J_C}} |\mathcal{M}^{M_{J_A} M_{J_B} M_{J_C}}|^2, \quad (5)$$

where $p = |\boldsymbol{p}|$ is the momentum of the final hadrons. More details of the $^3P_0$ model and the explicit formula can be found in Refs. [49–52].

As mentioned above, there are two independent excitations in these baryon systems. The excitation between two light quarks is named as the ρ-mode, while the λ-mode stands for the excitation between the heavy quark and light quark subsystem. Then, the P-wave baryons can be divided into two groups, the ρ-mode states with $l_\rho = 1$ and $l_\lambda = 0$, and the λ-mode states with $l_\rho = 0$ and $l_\lambda = 1$. Here, we adopt a series of quantum numbers n_ρ, l_ρ, n_λ, l_λ, L, S_ρ, j, and J^P to denote a theoretical state. The n_ρ and l_ρ are the radial and orbital quantum numbers between the two light quarks, respectively. Similarly, the n_λ and l_λ correspond to the radial and orbital quantum numbers between the heavy quark and light quark subsystem, respectively. The S_ρ stands for the total spin of the two light quarks. The j represents total angular momentum of the L and S_ρ, where L is the total orbital angular momentum. J^P is the spin-parity of a heavy baryon.

Table 1 Notations, quantum numbers and masses of the initial baryons. The masses are taken from the relativized quark model [31]. The Q stands for a charm or bottom quark, and the $\sim$ is used for the ρ-mode states. The units are in MeV

State	n_ρ	l_ρ	n_λ	l_λ	L	S_ρ	j	J^P	Charmed	Bottom
$\Lambda_Q(2S)$	0	0	1	0	0	0	0	$\frac{1}{2}^+$	2775	6045
$\tilde{\Lambda}_{Q0}(\frac{1}{2}^-)$	0	1	0	0	1	1	0	$\frac{1}{2}^-$	2780	6100
$\tilde{\Lambda}_{Q1}(\frac{1}{2}^-)$	0	1	0	0	1	1	1	$\frac{1}{2}^-$	2830	6165
$\tilde{\Lambda}_{Q1}(\frac{3}{2}^-)$	0	1	0	0	1	1	1	$\frac{3}{2}^-$	2840	6185
$\tilde{\Lambda}_{Q2}(\frac{3}{2}^-)$	0	1	0	0	1	1	2	$\frac{3}{2}^-$	2885	6190
$\tilde{\Lambda}_{Q2}(\frac{5}{2}^-)$	0	1	0	0	1	1	2	$\frac{5}{2}^-$	2900	6205
$\Sigma_{Q0}(\frac{1}{2}^-)$	0	0	0	1	1	1	0	$\frac{1}{2}^-$	2765	6070
$\Sigma_{Q1}(\frac{1}{2}^-)$	0	0	0	1	1	1	1	$\frac{1}{2}^-$	2770	6070
$\Sigma_{Q1}(\frac{3}{2}^-)$	0	0	0	1	1	1	1	$\frac{3}{2}^-$	2770	6070
$\Sigma_{Q2}(\frac{3}{2}^-)$	0	0	0	1	1	1	2	$\frac{3}{2}^-$	2805	6085
$\Sigma_{Q2}(\frac{5}{2}^-)$	0	0	0	1	1	1	2	$\frac{5}{2}^-$	2815	6090
$\tilde{\Sigma}_{Q1}(\frac{1}{2}^-)$	0	1	0	0	1	0	1	$\frac{1}{2}^-$	2840	6170
$\tilde{\Sigma}_{Q1}(\frac{3}{2}^-)$	0	1	0	0	1	0	1	$\frac{3}{2}^-$	2865	6180

Table 2 Strong decays of the $\Lambda_b(6072)$ as $\Lambda_b(2S)$ state in MeV

Decay mode	$\Lambda_Q(2S)$
$\Sigma_b\pi$	3.93
$\Sigma_b^*\pi$	5.34
Total width	9.27
Experiment	$72 \pm 11 \pm 2$

Fig. 1 The decay behaviors for $\Lambda_b(2S)$ state versus its initial mass. The black line corresponds to the total decay width. The red dotted and blue dashed lines stand for the partial decay widths of $\Sigma_b\pi$ and $\Sigma_b^*\pi$, respectively

The notations of initial states and predicted masses within the relativized quark model are listed in Table 1. For the $\Lambda_b(6072)$ or $\Sigma_b(6072)$ resonance, we adopt its experimental mass under various assignments. For other ρ-mode baryons, we employ the theoretical masses to calculate their strong decays. All the parameters adopted here are the same as our previous works, which have been widely used for the strong decays of singly heavy baryon systems [8,9,52–54].

3 Strong decays of the $\Lambda_b(6072)$ or $\Sigma_b(6072)$

3.1 $\Lambda_b(2S)$

As mentioned in the introduction, LHCb Collaboration suggested that the $\Lambda_b(6072)$ may be regarded as $\Lambda_b(2S)$ state. The predicted masses of the $\Lambda_b(2S)$ state within quark models are also consistent with the experimental data. The strong decays of this assignment are calculated and listed in Table 2. The predicted width is about 9 MeV, which is significantly smaller than the experimental observation. Thus, our calculations do not support the $\Lambda_b(6072)$ as $\Lambda_b(2S)$ state.

Other theoretical works also predicted smaller total decay widths of the $\Lambda_b(2S)$ state, which varies in the range of $2 \sim 36$ MeV [9,10,15]. These calculations indicate that the $\Lambda_b(2S)$ should be a narrow state. Also, the decay behaviors for $\Lambda_b(2S)$ state versus its initial mass is presented in Fig. 1. It can be seen that both $\Sigma_b\pi$ and $\Sigma_b^*\pi$ decay modes are important, which can be tested by future experiments.

3.2 $\Sigma_b(1P)$

In the traditional quark model, there are five λ-mode $\Sigma_b(1P)$ states, and their masses are predicted to be around $6070 \sim 6090$ MeV in relativized quark model. It is possible to regard the newly observed structure as the $\Sigma_b(1P)$ states. The strong

Table 3 Decay widths of the $\Sigma_b(6072)$ as $\Sigma_b(1P)$ states in MeV

Decay mode	$\Sigma_{b0}(\frac{1}{2}^-)$	$\Sigma_{b1}(\frac{1}{2}^-)$	$\Sigma_{b1}(\frac{3}{2}^-)$	$\Sigma_{b2}(\frac{3}{2}^-)$	$\Sigma_{b2}(\frac{5}{2}^-)$
$\Lambda_b\pi$	263.54	$\cdots$	$\cdots$	8.65	8.65
$\Sigma_b\pi$	$\cdots$	208.93	0.22	0.40	0.18
$\Sigma_b^*\pi$	$\cdots$	0.23	180.35	0.21	0.33
Total width	263.54	209.16	180.57	9.26	9.16
Experiment	$72 \pm 11 \pm 2$				

decay behaviors of $\Sigma_b(1P)$ assignments are presented in Table 3. It should be mentioned that the $^3P_0$ model is actually a spectator model, where the quarks in the initial state carry their color, flavor, spin, and momenta into the final states. The only change of degrees of freedom arises from the created quark pair. Based on this spectator assumption, the $\Sigma_b^{(*)}\pi$ channels for the $j = 0$ $\Sigma_b(1P)$ state is not allowed. It is shown that all the pure $\Sigma_b(1P)$ assignments are disfavored.

However, the physical resonance may correspond to the mixing of the quark model states. The mixing scheme of P-wave states can be expressed as

$$\begin{pmatrix} |1P\ 1/2^-\rangle_1 \\ |1P\ 1/2^-\rangle_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} |1/2^-, j=0\rangle \\ |1/2^-, j=1\rangle \end{pmatrix},$$

$$\begin{pmatrix} |1P\ 3/2^-\rangle_1 \\ |1P\ 3/2^-\rangle_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} |3/2^-, j=1\rangle \\ |3/2^-, j=2\rangle \end{pmatrix}.$$

Due to the finite mass of bottom quark, a small mixing angle is allowed which breaks the heavy quark symmetry explicitly. The total decay widths of various assignments versus the mixing angle θ in the range of $-30° \sim 30°$ are plotted in Fig. 2. It can be seen that when the mixing angle θ goes close to $\pm30°$, the predicted width of $\Sigma_b(6072)$ is consistent with the experimental data. This mixing angle seems larger than that of previous works on the singly bottom baryons [9,53]. With this mixing angle, the calculated total width of $\Sigma_b(6072)$ is about 52 MeV and the predicted branching ratios of dominating channels are

$$Br(\Lambda_b\pi, \Sigma_b^*\pi) = 12.4\%, 86.4\%, \tag{6}$$

which indicates that the branching ratio of $\Lambda_b\pi$ final state is also significant. However, the LHCb Collaboration did not observe the $\Sigma_b(6072)$ signal in $\Lambda_b\pi$ mass spectrum [4]. Moreover, there already exists a good candidate $\Sigma_b(6097)$ for the $|1P\ 3/2^-\rangle_2$ state in the literatures [4,9,14–19]. Given the large mixing angle and significant branching ratio of $\Lambda_b\pi$ channel, the newly observed structure as $\Sigma_b(1P)$ assignments are disfavored.

3.3 $\tilde{\Lambda}_b(1P)$

According to the quark model, there are five ρ-mode $\tilde{\Lambda}_b(1P)$ states, and the predicted masses within relativized quark
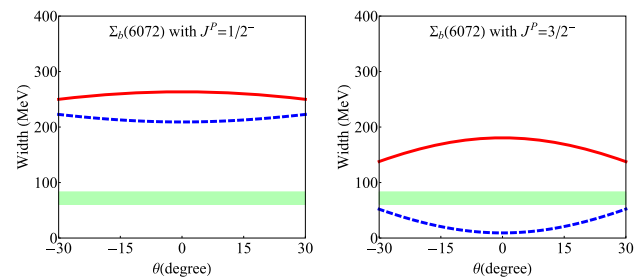

Fig. 2 The total decay widths versus the mixing angle θ. The red solid and blue dashed lines correspond to the $|1P\ J^P\rangle_1$ and $|1P\ J^P\rangle_2$ states, respectively, where the J^P equals to $1/2^-$ or $3/2^-$. The green bands are the experimental total decay widths

model vary from 6100 to 6205 MeV. Considering the uncertainties of quark model, it is possible to treat the $\Lambda_b(6072)$ as the lowest one of $\tilde{\Lambda}_b(1P)$ states. Meanwhile, the masses for the ρ-mode $\tilde{\Lambda}_b(1P)$ states can be estimated with the help of the λ-mode resonances. In the three-quark model with harmonic oscillator approximation [7], the masses between ρ-mode and λ-mode P-wave excitations can be expressed as

$$\frac{\bar{m}[\tilde{\Lambda}_b(1P)] - m[\Lambda_b(1S)]}{\bar{m}[\Lambda_b(1P)] - m[\Lambda_b(1S)]} = \sqrt{\frac{3m_b}{2m_q + m_b}}, \tag{7}$$

where the $\bar{m}[\tilde{\Lambda}_b(1P)]$ and $\bar{m}[\Lambda_b(1P)]$ are the average masses of $\tilde{\Lambda}_b(1P)$ and $\Lambda_b(1P)$ states, respectively. With the masses of $\Lambda_b(5912)$ and $\Lambda_b(5920)$, one can obtain

$$\begin{aligned} \bar{m}[\Lambda_b(1P)] \\ = \frac{2m[\Lambda_b(5912)] + 4m[\Lambda_b(5920)]}{6} = 5917.35 \text{ MeV}. \end{aligned} \tag{8}$$

The $m_b = 4977$ MeV and $m_q = 220$ MeV are the masses of bottom and light quarks, respectively [9,53]. Then, the estimated $\bar{m}[\tilde{\Lambda}_b(1P)]$ equals to 6114 MeV, which is consistent with the predicted average mass from relativized quark model [31]. When the mass splitting is considered, the lowest $\tilde{\Lambda}_b(1P)$ state should lie around 6072 MeV. Moreover, this estimation is not sensitive to the parameters of quark masses because the bottom quark is much heavier than the light quark and the ratio approximately equals to $\sqrt{3}$.

Table 4 Strong decays of the $\Lambda_b(6072)$ as $\tilde{\Lambda}_b(1P)$ states in MeV

Decay mode	$\tilde{\Lambda}_{b0}(\frac{1}{2}^-)$	$\tilde{\Lambda}_{b1}(\frac{1}{2}^-)$	$\tilde{\Lambda}_{b1}(\frac{3}{2}^-)$	$\tilde{\Lambda}_{b2}(\frac{3}{2}^-)$	$\tilde{\Lambda}_{b2}(\frac{5}{2}^-)$
$\Sigma_b\pi$	$\cdots$	521.81	1.38	2.47	1.10
$\Sigma_b^*\pi$	$\cdots$	1.47	458.33	1.30	2.03
Total width	$\cdots$	523.28	459.71	3.77	3.13
Experiment	$72 \pm 11 \pm 2$				
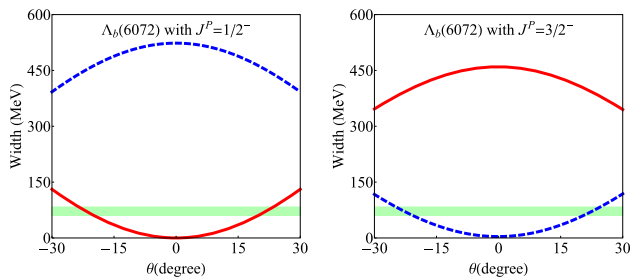
Fig. 3 The total decay widths versus the mixing angle θ. The red solid and blue dashed lines correspond to the $|1P\,J^P\rangle_1$ and $|1P\,J^P\rangle_2$ states, respectively, where the J^P equals to $1/2^-$ or $3/2^-$. The green bands are the experimental total decay widths

Here, the strong decays of the $\tilde{\Lambda}_b(1P)$ assignments are calculated and shown in Table 4. For the pure $j = 0$ state, the strong decays are not allowed based on the spectator assumption in the $^3P_0$ model. The predicted widths of two $j = 1$ states are extremely large, while the two $j = 2$ assignments show smaller total decay widths. Our results indicate that the $\Lambda_b(6072)$ as pure $\tilde{\Lambda}_b(1P)$ states can be excluded.

The mixing of the states with same J^P is taken into account. The mixing scheme is similar to the $\Sigma_b(1P)$ states, and the results are shown in Fig. 3. Obviously, the $\Lambda_b(6072)$ state can be regarded as the $J^P = 1/2^- \; \tilde{\Lambda}_b(1P)$ state with large $j = 0$ component. Meanwhile, the strong decays also support it as the $J^P = 3/2^- \; \tilde{\Lambda}_b(1P)$ state with large $j = 2$ component. From Table 1, the predicted masses of $\tilde{\Lambda}_{b0}(\frac{1}{2}^-)$ and $\tilde{\Lambda}_{b2}(\frac{3}{2}^-)$ states are 6100 and 6190 MeV, respectively. Given these predicted masses, the $|1P\,1/2^-\rangle_1$ assignment is favored, while the $|1P\,3/2^-\rangle_2$ assignment can be excluded.

When the mixing angle is $22°$, the strong decay width of $|1P\,1/2^-\rangle_1$ state is about 73 MeV, which is consistent with the experimental data. The branching ratios are predicted to be

$$Br(\Sigma_b\pi, \Sigma_b^*\pi) = 99.7\%, 0.3\%, \qquad (9)$$

which indicates that the $\Sigma_b\pi$ is the predominant decay channel and the three-body decay can occur via the $\Lambda(6072) \to \Sigma_b\pi \to \Lambda_b\pi\pi$ process. Also, we plot the decay widths as functions of the initial masses for the $\tilde{\Lambda}_b(1P)$ states in Fig. 4. For the $|1P\,1/2^-\rangle_2$ and $\tilde{\Lambda}_{b1}(\frac{3}{2}^-)$ states, it is difficult to find them experimentally due to the large total decay
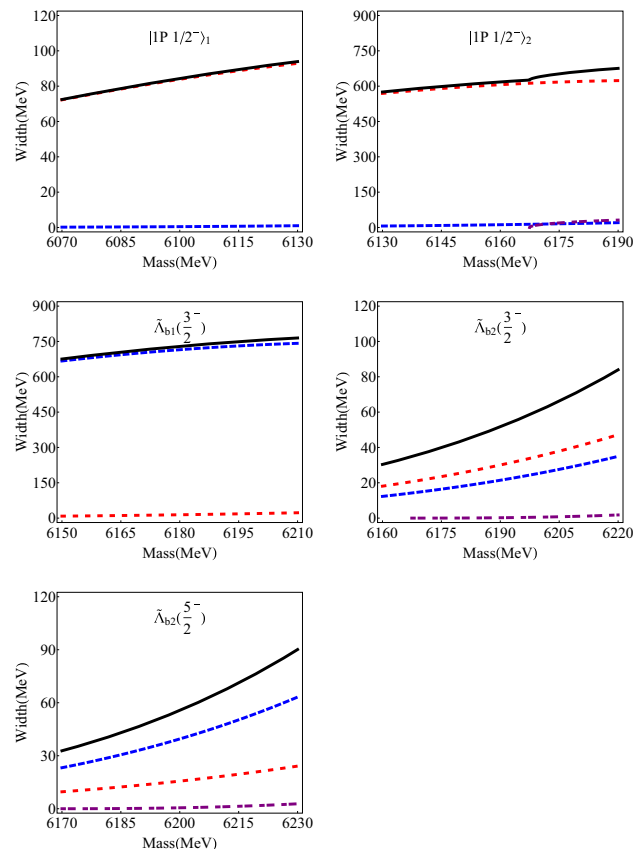
Fig. 4 The decay behaviors for the $\tilde{\Lambda}_b(1P)$ states versus their initial masses. The black lines correspond to the total decay widths. The red dotted, blue dashed, purple dot-dashed lines stand for the partial decay widths of $\Sigma_b\pi$, $\Sigma_b^*\pi$, and $\Lambda_b\eta$ channels, respectively. The $\Lambda_b\eta$ mode for $|1P\,1/2^-\rangle_2$ state arises due to the allowed phase space and mixing scheme

widths. However, for the $\tilde{\Lambda}_{b2}(\frac{3}{2}^-)$ and $\tilde{\Lambda}_{b2}(\frac{5}{2}^-)$ states, their total widths are relatively narrow, which have good potentials to be observed by future experiments. Also, when the initial masses for the $j = 2$ states increase, the total decay widths become larger and the dominating channels remain.

It should be mentioned that the $\tilde{\Lambda}_{b2}(\frac{5}{2}^-)$ state is a crucial point for distinguishing the three-quark model and diquark model. In the three-quark model, the lowest $J^P = 5/2^- \; \Lambda_b$ state belongs to the ρ-mode P-wave excitation. However, the ρ-mode excitations are frozen in the diquark model, and the lowest $J^P = 5/2^-$ state is the F-wave $\Lambda_{b2}(\frac{5}{2}^-)$. The predi-

cated masses of $\Lambda_{b2}(\frac{5}{2}^-)$ in diquark model lie in the region of $6346 \sim 6408$ MeV [29,30,32], which is significantly larger than that of $\tilde{\Lambda}_{b2}(\frac{5}{2}^-)$ state in the three-quark model [28,31]. The future experimental searches can help us to distinguish these two types of models.

4 Strong decays of nonstrange partners

4.1 $\tilde{\Lambda}_c(1P)$

In the constituent quark model, there are five ρ-mode $\tilde{\Lambda}_c(1P)$ states, and their predicted masses in relativized quark model are about $2780 \sim 2900$ MeV. Similarly, one can estimate the average mass of ρ-mode $\tilde{\Lambda}_c(1P)$ states with the help of the λ-mode excitations. The average mass $\bar{m}[\tilde{\Lambda}_c(1P)]$ equals to 2793 MeV, which is consistent with the result of relativized quark model [31]. Within these masses, their strong decays are calculated and listed in Table 5. For the pure $j = 0$ state, the strong decays are not allowed based on the specta-tor assumption in the $^3P_0$ model. For the two $j = 1$ states, their total decay width are predicted to be several hundred MeV, and the main decay modes for $\tilde{\Lambda}_{c1}(\frac{1}{2}^-)$ and $\tilde{\Lambda}_{c1}(\frac{3}{2}^-)$ states are $\Sigma_c\pi$ and $\Sigma_c^*\pi$, respectively. Due to the large decay widths, these two states can hardly be observed experimen-tally. For the two $j = 2$ states, the total decay widths for the $J^P = 3/2^-$ and $5/2^-$ states are about 70 and 68 MeV, respectively. The main decay channels are $\Sigma_c\pi$ and $\Sigma_c^*\pi$, and the branching ratios are

$$Br(\Sigma_c\pi, \Sigma_c^*\pi) = 70.1\%, 28.4\%, \qquad J^P = 3/2^-, \qquad (10)$$

$$Br(\Sigma_c\pi, \Sigma_c^*\pi) = 38.9\%, 58.0\%, \qquad J^P = 5/2^-. \qquad (11)$$

In Ref. [30], the authors claimed that the lowest $J^P = 5/2^-$ Λ_c state is a nice criterion to test the three-quark model and diquark model for charmed baryons. Our results indicate that the $\tilde{\Lambda}_{c2}(\frac{5}{2}^-)$ state is not a broad state and can be searched in the $\Sigma_c\pi$ and $\Sigma_c^*\pi$ final states.

Also, we plot the decay widths as functions of the initial masses for the $\tilde{\Lambda}_c(1P)$ states in Fig. 5. In constituent quark model, the features of these ρ-mode states may be mainly generated by the interactions from two light quarks. From Table 1, the mass gaps among five ρ-mode Λ_b and Λ_c states are 105 and 120 MeV, respectively, which suggests that ρ-
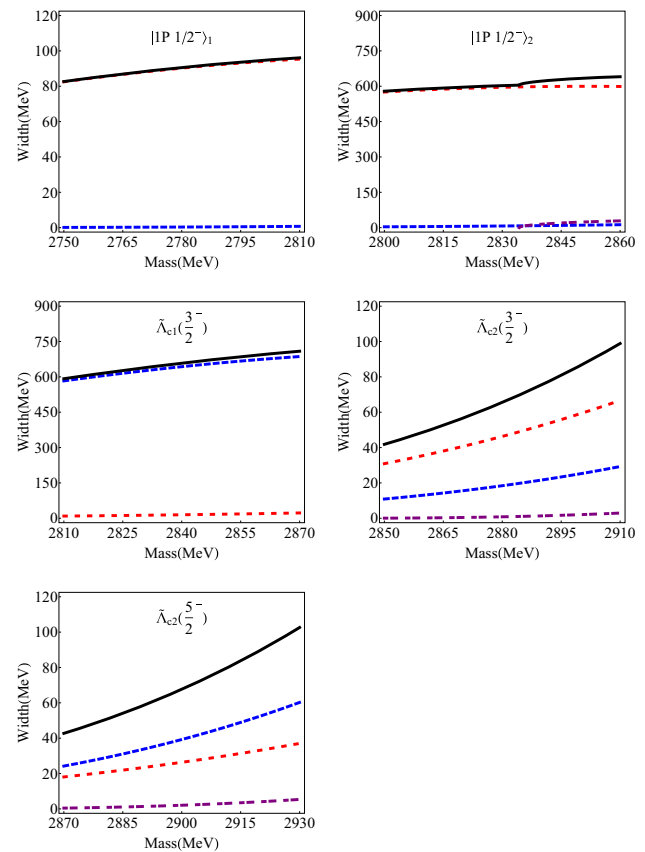

Fig. 5 The decay behaviors for the $\tilde{\Lambda}_c(1P)$ states versus their initial masses. The black lines correspond to the total decay widths. The red dotted, blue dashed, purple dot-dashed lines stand for the partial decay widths of $\Sigma_c\pi$, $\Sigma_c^*\pi$, and $\Lambda_c\eta$ channels, respectively. The $\Lambda_c\eta$ mode for $|1P\ 1/2^-\rangle_2$ state arises due to the allowed phase space and mixing scheme
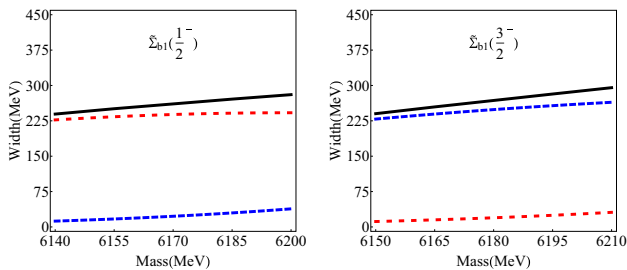
mode Λ_b and Λ_c states may have similar characteristics. Thus, we take the same mixing angle as Λ_b states to show the mass dependence of five ρ-mode Λ_c states. It can be seen that the total decay widths increases with the rise of initial masses, but the branching ratios are almost unchanged. By assuming various observed Λ_c baryons as the $\tilde{\Lambda}_c$ states, the authors discussed their strong decay behaviors [25], where the calculated branching ratios are consistent with ours. With mixing mechanism, the $|1P\ 1/2^-\rangle_1$ state in the charm sector is predicted to be relatively narrow, which can be searched in the $\Sigma_c\pi$ final state in future.

Table 5 Strong decays of the $\tilde{\Lambda}_c(1P)$ states with the predicted masses in MeV

Decay mode	$\tilde{\Lambda}_{c0}(\frac{1}{2}^-)$	$\tilde{\Lambda}_{c1}(\frac{1}{2}^-)$	$\tilde{\Lambda}_{c1}(\frac{3}{2}^-)$	$\tilde{\Lambda}_{c2}(\frac{3}{2}^-)$	$\tilde{\Lambda}_{c2}(\frac{5}{2}^-)$
$\Sigma_c\pi$	$\cdots$	692.79	14.84	49.35	26.35
$\Sigma_c^*\pi$	$\cdots$	8.15	643.21	19.97	39.25
$\Lambda_c\eta$	$\cdots$	$\cdots$	$\cdots$	1.07	2.06
Total width	$\cdots$	700.94	658.05	70.39	67.66

Table 6 Strong decays of the $\tilde{\Sigma}_b(1P)$ states with the predicted masses in MeV

Decay mode	$\tilde{\Sigma}_{b1}(\frac{1}{2}^-)$	$\tilde{\Sigma}_{b1}(\frac{3}{2}^-)$
$\Sigma_b\pi$	238.43	19.44
$\Sigma_b^*\pi$	22.64	248.84
Total width	261.07	268.28

Table 7 Strong decays of the $\tilde{\Sigma}_c(1P)$ states with the predicted masses in MeV

Decay mode	$\tilde{\Sigma}_{c1}(\frac{1}{2}^-)$	$\tilde{\Sigma}_{c1}(\frac{3}{2}^-)$
$\Sigma_c\pi$	231.95	28.30
$\Sigma_c^*\pi$	13.43	234.76
Total width	245.38	263.06

Fig. 6 The total decay widths for the $\tilde{\Sigma}_b(1P)$ states versus their initial masses. The black lines correspond to the total decay widths. The red dotted and blue dashed lines stand for the partial decay widths of $\Sigma_b\pi$ and $\Sigma_b^*\pi$ channels, respectively

Fig. 7 The total decay widths for the $\tilde{\Sigma}_c(1P)$ states versus their initial masses. The black lines correspond to the total decay widths. The red dotted and blue dashed lines stand for the partial decay widths of $\Sigma_c\pi$ and $\Sigma_c^*\pi$ channels, respectively

4.2 $\tilde{\Sigma}_b(1P)$

From Table 1, two ρ-mode $\tilde{\Sigma}_b(1P)$ states exist in the conventional quark model, and their masses are predicted to be 6170 MeV and 6180 MeV in the relativized quark model. With the calculated masses, their strong decays are estimated and listed in Table 6. The total decay widths for these two states are about 260 MeV, which are rather large. The main decay modes are $\Sigma_b\pi$ and $\Sigma_b^*\pi$ for the $J^P = 1/2^-$ and $3/2^-$ states, respectively. The branching ratios for these two states are

$$Br(\Sigma_b\pi, \Sigma_b^*\pi) = 91.3\%, 8.7\%, \qquad J^P = 1/2^-, \qquad (12)$$
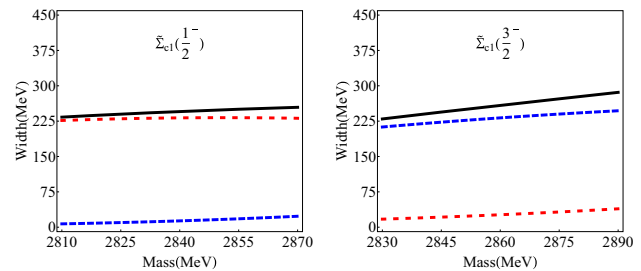$$Br(\Sigma_b\pi, \Sigma_b^*\pi) = 7.2\%, 92.8\%, \qquad J^P = 3/2^-. \qquad (13)$$

The total decay widths for the $\tilde{\Sigma}_b(1P)$ states versus their initial masses are plotted in Fig. 6. With the initial masses increase, the total decay widths also become larger, and the branching ratios are almost unchanged. In Ref. [17], by assuming the $\Sigma_b(6097)$ as the $\tilde{\Sigma}_b(1P)$ states, the authors estimated the strong decays, and the calculated total decay widths are about 168-235 MeV. Since large masses are adopted for the initial $\tilde{\Sigma}_b(1P)$ states in present work, the predicted decay widths are also larger than the previous work [17]. More theoretical efforts on masses and decays are needed to understand these two $\tilde{\Sigma}_b(1P)$ states.

4.3 $\tilde{\Sigma}_c(1P)$

The predicted masses of the $\tilde{\Sigma}_{c1}(\frac{1}{2}^-)$ and $\tilde{\Sigma}_{c1}(\frac{3}{2}^-)$ states in the relativized quark model are 2840 and 2865 MeV, respec-

tively. Their calculated decay widths are presented in Table 7. It is shown that the total decay widths are quite large and the main decay modes are $\Sigma_c\pi$ and $\Sigma_c^*\pi$ for the $J^P = 1/2^-$ and $3/2^-$ states, respectively. Moreover, the total decay widths for the $\tilde{\Sigma}_c(1P)$ states versus their initial masses are plotted in Fig. 7 for reference. These results are similar with the $\tilde{\Sigma}_b(1P)$ states, which preserves the heavy quark symmetry well. In Ref. [49], the authors calculated the strong decays of the $\tilde{\Sigma}_c(1P)$ states with a mass of 2882 MeV, and the calculated total decay width are also large. However, the predicted branching ratios in present work are quite different with theirs, and more theoretical works are demanded to clarify this problem.

5 Summary

In this work, we study the strong decay behaviors of the newly observed resonance $\Lambda_b(6072)$ by the LHCb Collaboration. Given its mass and decay modes, this resonance can be tentatively assigned as the $\Lambda_b(2S)$, $\Sigma_b(1P)$ and $\tilde{\Lambda}_b(1P)$ states. The strong decay behaviors are investigated within the $^3P_0$ model, and our results suggest that the $\Lambda_b(6072)$ can be regarded as the lowest ρ-mode excitation in Λ_b family.

Then, the strong decays for the nonstrange partners of $\Lambda_b(6072)$ resonance are calculated. The predicted total decay widths of the $J^P = 5/2^-$ Λ_b and Λ_c states are relatively small, and the main decay channels are the $\Sigma_b^{(*)}\pi$ and $\Sigma_c^{(*)}\pi$, respectively. These two states have good potentials to be observed in future experiments, which may help us to distinguish the three-quark model and diquark model.

Until now, there exist abundant λ-mode states in the heavy baryon systems, while no ρ-mode excitation has been confirmed both theoretically and experimentally. Under our assignment, the $\Lambda_b(6072)$ should correspond to the ρ-mode excitation for the singly heavy baryons. We hope these theoretical predictions on $\tilde{\Lambda}_{b(c)}(1P)$ and $\tilde{\Sigma}_{b(c)}(1P)$ states can provide valuable information for searching more ρ-mode excitations in future experiments.

Data Availability Statement This manuscript has no associated data or the data will not be deposited. [Authors' comment: This work is theoretical, and the results have been presented in our paper. Hence, there is no more data to be deposited elsewhere.]

References

1. A.M. Sirunyan et al. (CMS Collaboration), Study of excited Λ_b^0 states decaying to $\Lambda_b^0\pi^+\pi^-$ in proton–proton collisions at $\sqrt{s} = 13$ TeV. Phys. Lett. B**803**, 135345 (2020)
2. R. Aaij et al. (LHCb Collaboration), Observation of a new baryon state in the $\Lambda_b^0\pi^+\pi^-$ mass spectrum. JHEP **6**, 136 (2020)
3. R. Aaij et al. (LHCb Collaboration), Study of the $D^0 p$ amplitude in $\Lambda_b^0 \to D^0 p\pi^-$ decays. JHEP **1705**, 030 (2017)
4. R. Aaij et al. (LHCb Collaboration), Observation of two resonances in the $\Lambda_b^0\pi^\pm$ systems and precise measurement of $\Sigma_b^\pm$ and $\Sigma_b^{*\pm}$ properties. Phys. Rev. Lett. **122**, 012001 (2019)
5. R. Aaij et al. (LHCb Collaboration), Observation of new resonances in the $\Lambda_b^0\pi^+\pi^-$ system. Phys. Rev. Lett. **123**, 152001 (2019)
6. H.Y. Cheng, C.K. Chua, Strong decays of charmed baryons in heavy hadron chiral perturbation theory: an update. Phys. Rev. D **92**, 074014 (2015)
7. X. Zhong, Q. Zhao, Charmed baryon strong decays in a chiral quark model. Phys. Rev. D **77**, 074008 (2008)
8. Q.F. Lü, L.Y. Xiao, Z.Y. Wang, X.H. Zhong, Strong decay of $\Lambda_c(2940)$ as a $2P$ state in the Λ_c family. Eur. Phys. J. C **78**, 599 (2018)
9. W. Liang, Q.F. Lü, X.H. Zhong, Canonical interpretation of the newly observed $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ via strong decay behaviors. Phys. Rev. D **100**, 054013 (2019)
10. K.L. Wang, Q.F. Lü, X.H. Zhong, Interpretation of the newly observed $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ states in a chiral quark model. Phys. Rev. D **100**, 114035 (2019)
11. B. Chen, S.Q. Luo, X. Liu, T. Matsuki, Interpretation of the observed $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ states as $1D$ bottom baryons. Phys. Rev. D **100**, 094032 (2019)
12. S.Q. Luo, B. Chen, Z.W. Liu, X. Liu, Resolving the low mass puzzle of $\Lambda_c(2940)^+$. Eur. Phys. J. C **80**, 301 (2020)
13. K. Azizi, Y. Sarac, H. Sundu, The $\Lambda_b(6146)^0$ state newly observed by LHCb. Phys. Rev. D **101**, 074026 (2020)
14. E.L. Cui, H.M. Yang, H.X. Chen, A. Hosaka, Identifying the $\Xi_b(6227)$ and $\Sigma_b(6097)$ as P-wave bottom baryons of $J^P = 3/2^-$. Phys. Rev. D **99**, 094021 (2019)
15. B. Chen, X. Liu, Assigning the newly reported $\Sigma_b(6097)$ as a P-wave excited state and predicting its partners. Phys. Rev. D **98**, 074032 (2018)
16. K.L. Wang, Q.F. Lü, X.H. Zhong, Interpretation of the newly observed $\Sigma_b(6097)^\pm$ and $\Xi_b(6227)^-$ states as the P-wave bottom baryons. Phys. Rev. D **99**, 014011 (2019)
17. P. Yang, J.J. Guo, A.L. Zhang, Identification of the newly observed $\Sigma_b(6097)^\pm$ baryons from their strong decays. Phys. Rev. D **99**, 034018 (2019)
18. T.M. Aliev, K. Azizi, Y. Sarac, H. Sundu, Determination of the quantum numbers of $\Sigma_b(6097)^\pm$ via their strong decays. Phys. Rev. D **99**, 094003 (2019)
19. D.J. Jia, W.N. Liu, A. Hosaka, Regge behaviors in orbitally excited spectroscopy of charmed and bottom baryons. Phys. Rev. D **101**, 034016 (2020)
20. H.M. Yang, H.X. Chen, E.L. Cui, A. Hosaka, Q. Mao, Decay properties of P-wave bottom baryons within light-cone sum rules. Eur. Phys. J. C **80**, 80 (2020)
21. B. Chen, X. Liu, A.L. Zhang, Newly observed $\Lambda_c(2860)^+$ at LHCb and its D-wave partners $\Lambda_c(2880)^+$, $\Xi_c(3055)^+$ and $\Xi_c(3080)^+$. Phys. Rev. D **95**, 074022 (2017)
22. T. Yoshida, E. Hiyama, A. Hosaka, M. Oka, K. Sadato, Spectrum of heavy baryons in the quark model. Phys. Rev. D **92**, 114029 (2015)
23. Z.G. Wang, The $\Lambda_c(2860)$, $\Lambda_c(2880)$, $\Xi_c(3055)$ and $\Xi_c(3080)$ as D-wave baryon states in QCD. Nucl. Phys. B **926**, 467 (2018)
24. Y.X. Yao, K.L. Wang, X.H. Zhong, Strong and radiative decays of the low-lying D-wave singly heavy baryons. Phys. Rev. D **98**, 076015 (2018)
25. J.J. Guo, P. Yang, A.L. Zhang, Strong decays of observed Λ_c baryons in the $^3P_0$ model. Phys. Rev. D **100**, 014001 (2019)
26. H.Y. Cheng, C.W. Chiang, Quantum numbers of Ω_c states and other charmed baryons. Phys. Rev. D **95**, 094018 (2017)
27. K.L. Wang, Y.X. Yao, X.H. Zhong, Q. Zhao, Strong and radiative decays of the low-lying S- and P-wave singly heavy baryons. Phys. Rev. D **96**, 116016 (2017)
28. W. Roberts, M. Pervin, Heavy baryons in a quark model. Int. J. Mod. Phys. A **23**, 2817 (2008)
29. D. Ebert, R.N. Faustov, V.O. Galkin, Spectroscopy and Regge trajectories of heavy baryons in the relativistic quark–diquark picture. Phys. Rev. D **84**, 014025 (2011)
30. B. Chen, K.W. Wei, A.L. Zhang, Assignments of Λ_Q and Ξ_Q baryons in the heavy quark–light diquark picture. Eur. Phys. J. A **51**, 82 (2015)
31. S. Capstick, N. Isgur, Baryons in a relativized quark model with chromodynamics. Phys. Rev. D **34**, 2809 (1986)
32. D. Ebert, R.N. Faustov, V.O. Galkin, Masses of excited heavy baryons in the relativistic quark model. Phys. Lett. B **659**, 612 (2008)
33. H. Garcilazo, J. Vijande, A. Valcarce, Faddeev study of heavy baryon spectroscopy. J. Phys. G **34**, 961 (2007)

34. K. Thakkar, Z. Shah, A.K. Rai, P.C. Vinodkumar, Excited state mass spectra and Regge trajectories of bottom baryons. Nucl. Phys. A **965**, 57 (2017)
35. W.H. Liang, C.W. Xiao, E. Oset, Baryon states with open beauty in the extended local hidden gauge approach. Phys. Rev. D **89**, 054023 (2014)
36. J.X. Lu, H.X. Chen, Z.H. Guo, J. Nieves, J.J. Xie, L.S. Geng, $\Lambda_c(2595)$ resonance as a dynamically generated state: the compositeness condition and the large N_c evolution. Phys. Rev. D **93**, 114028 (2016)
37. X.G. He, X.Q. Li, X. Liu, X.Q. Zeng, $\Lambda_c(2940)^+$: a possible molecular state? Eur. Phys. J. C **51**, 883 (2007)
38. Y.B. Dong, A. Faessler, T. Gutsche, V.E. Lyubovitskij, Strong two-body decays of the $\Lambda_c(2940)^+$ in a hadronic molecule picture. Phys. Rev. D **81**, 014006 (2010)
39. H.Y. Cheng, Charmed baryons circa 2015. Front. Phys. (Beijing) **10**, 101406 (2015)
40. H.X. Chen, W. Chen, X. Liu, Y.R. Liu, S.L. Zhu, A review of the open charm and open bottom systems. Rep. Prog. Phys. **80**, 076201 (2017)
41. R. Mizuk et al. (Belle Collaboration), Observation of an isotriplet of excited charmed baryons decaying to $\Lambda_c^+\pi$. Phys. Rev. Lett. **94**, 122002 (2005)
42. A. Arifi, H. Nagahiro, A. Hosaka, K. Tanida, Roper-like resonances with various flavor contents and their two-pion emission decays. Phys. Rev. D **101**, 111502 (2020)
43. L. Xiao, X. Zhong, Toward establishing the low-lying P-wave Σ_b states. Phys. Rev. D **102**, 014009 (2020)
44. C. Mu, X. Wang, X.L. Chen, X. Liu, S.L. Zhu, Dipion decays of heavy baryons. Chin. Phys. C **38**, 113101 (2014)
45. A. Arifi, H. Nagahiro, A. Hosaka, Three-body decay of $\Lambda_c^*(2595)$ and $\Lambda_c^*(2625)$ with consideration of $\Sigma_c(2455)\pi$ and $\Sigma_c^*(2520)\pi$ in intermediate states. Phys. Rev. D **95**, 114018 (2017)
46. A. Arifi, H. Nagahiro, A. Hosaka, Three-body decay of $\Lambda_c^*(2595)$ and $\Lambda_c^*(2625)$ with the inclusion of a direct two-pion coupling. Phys. Rev. D **98**, 114007 (2018)
47. Y. Kawakami, M. Harada, Singly heavy baryons with chiral partner structure in a three-flavor chiral model. Phys. Rev. D **99**, 094016 (2019)
48. L. Micu, Decay rates of meson resonances in a quark model. Nucl. Phys. B **10**, 521 (1969)
49. C. Chen, X.L. Chen, X. Liu, W.Z. Deng, S.L. Zhu, Strong decays of charmed baryons. Phys. Rev. D **75**, 094017 (2007)
50. Z. Zhao, D.D. Ye, A.L. Zhang, Nature of charmed strange baryons $\Xi_c(3055)$ and $\Xi_c(3080)$. Phys. Rev. D **94**, 114020 (2016)
51. B. Chen, K.W. Wei, X. Liu, T. Matsuki, Low-lying charmed and charmed-strange baryon states. Eur. Phys. J. C **77**, 154 (2017)
52. Q.F. Lü, X.H. Zhong, Strong decays of the higher excited Λ_Q and Σ_Q baryons. Phys. Rev. D **101**, 014017 (2020)
53. W. Liang, Q.F. Lü, Strong decays of the newly observed narrow Ω_b structures. Eur. Phys. J. C **80**, 198 (2020)
54. Q.F. Lü, Canonical interpretations of the newly observed $\Xi_c(2923)^0$, $\Xi_c(2939)^0$ and $\Xi_c(2965)^0$ resonances. arXiv:2004.02374