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Interpretation of the newly observed $\Lambda_b(6146)$ and $\Lambda_b(6152)$ states in a chiral quark model

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The strong decays of the low-lying λ-mode $\Lambda_b(1D, 2S)$ and $\Sigma_b(2S)$ states are studied in a chiral quark model. We find that (i) the newly observed $\Lambda_b(6146/6152)$ resonances in the $\Lambda_b\pi^+\pi^-$ spectrum by the LHCb Collaboration might be explained with the λ-mode $\Lambda_b(1D)$ states in the quark model. It should be emphasized that whether the structure in the $\Lambda_b\pi^+\pi^-$ spectrum corresponds to two states or one state should be further clarified with more observations in future experiments. (ii) The $\Lambda_b(2S)$ $|J^P = \frac{1}{2}^+, 0\rangle$ state mainly decays into $\Sigma_b^*\pi$ channel, which may be an ideal channel for searching for this $\Lambda_b(2S)$ state in future experiments. (iii) The $\Sigma_b(2S)$ $|J^P = \frac{1}{2}^+, 1\rangle$ and $|J^P = \frac{3}{2}^+, 1\rangle$ dominantly decay into $\Lambda_b\pi$ with $\Gamma \simeq 3.82$ MeV and $\Gamma \simeq 4.72$ MeV, respectively.

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I. INTRODUCTION

Understanding the heavy baryon spectrum and searching for the missing heavy baryons and new exotic states are interesting topics in hadronic physics [1–5]. The LHC facility provides good opportunities for us to establish the heavy baryon spectra. In 2017, five extremely narrow Ω_c states, $\Omega_c(3000)$, $\Omega_c(3050)$, $\Omega_c(3066)$, $\Omega_c(3090)$, and $\Omega_c(3119)$, were observed in the $\Xi_c^+K^-$ channel by the LHCb Collaboration [6]. Most of them may be interpreted as the P-wave excited states of Ω_c [7–15]. In 2018, the LHCb Collaboration announced the observation of a new bottom baryon $\Xi_b(6227)^-$ in both Λ_bK^- and $\Xi_b^0\pi^-$ decay modes [16] and found two new resonances $\Sigma_b(6097)^\pm$ in the $\Lambda_b\pi^\pm$ channels [17]. Both the $\Sigma_b(6097)^\pm$ and $\Xi_b(6227)^-$ states favor P-wave states with spin-parity $J^P = 3/2^-$ or $J^P = 5/2^-$ [18–23]. Recently, the LHCb Collaboration announced the observation of two new bottom baryons $\Lambda_b(6146)$ and $\Lambda_b(6152)$ in the $\Lambda_b\pi^+\pi^-$ decay mode [24]. The measured masses and widths of the $\Lambda_b(6146)$ and $\Lambda_b(6152)$ are presented as follows:

$$m[\Lambda_b(6146)] = 6146.17 \pm 0.33 \pm 0.22 \pm 0.16\ \text{MeV}, \quad (1)$$

$$\Gamma[\Lambda_b(6146)] = 2.9 \pm 1.3 \pm 0.3\ \text{MeV}, \quad (2)$$

$$m[\Lambda_b(6152)] = 6152.51 \pm 0.26 \pm 0.22 \pm 0.16\ \text{MeV}, \quad (3)$$

$$\Gamma[\Lambda_b(6152)] = 2.1 \pm 0.8 \pm 0.3\ \text{MeV}. \quad (4)$$

Considering their masses and small splitting, the LHCb Collaboration suggested that both of them may be clarified into the doublet of $\Lambda_b(1D)$ states in the quark model. It should be noticed that current experimental information does not exclude the two new resonances as the $I = 0$ Σ_b states, which has to be considered in the following discussions.

The Λ_b or Σ_b baryon contains a heavy bottom quark and two light u/d quarks. Such a structure is illustrated in Fig. 1, the degree of freedom between two light quarks (q_1 and q_2), is labeled with Jacobi coordinate $\boldsymbol{\rho}$, and the excitations between two light quarks are usually called "ρ-mode" excitations, while the degree between the center of mass of two light quarks and the heavy quark (Q_3) is labeled with Jacobi coordinate $\boldsymbol{\lambda}$, and the excitations between the center of mass of two light quarks and the heavy quark are usually called "λ-mode" excitations. The ρ-mode oscillator frequency ω_ρ can be related to the λ-mode oscillator frequency

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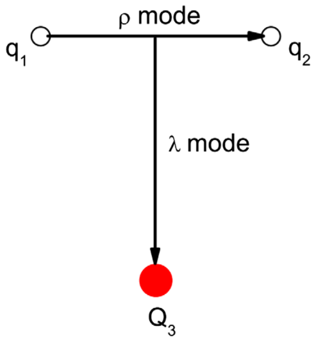

FIG. 1. The λ- or ρ-mode excitations of the Λ_b or Σ_b baryon. ρ and λ are the Jacobi coordinates defined as $\boldsymbol{\rho}=\frac{1}{\sqrt{2}}(\mathbf{r}_1-\mathbf{r}_2)$ and $\boldsymbol{\lambda}=\frac{1}{\sqrt{6}}(\mathbf{r}_1+\mathbf{r}_2-2\mathbf{r}_3)$. q_1 and q_2 stand for the light u/d quarks,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

ω_λ by $\omega_\rho=\sqrt{3m'/(2m+m')}\omega_\lambda$ [25]. For a singly-heavy baryon system, the heavy quark mass m' is much larger than the light quark mass m, then we easily have $\omega_\lambda<\omega_\rho$. Thus, we expect that in the heavy quark sector, the low-lying internal excitations favor excitations of the so-called λ-mode where the orbital/radial excitation lies between the light quarks and the heavy quark in a Jacobi coordinate. There are many predictions of the Λ_b and Σ_b baryon spectra in various models [26–42]. The low-lying Λ_b and Σ_b states predicted in the quark models are listed in Table I. From this table, it is found that in the Λ_b and Σ_b families, only the ground states Λ_b, Σ_b, and Σ_b^*, and two low-lying orbitally excited states $\Lambda_b(5912)1/2^-$ and $\Lambda_b(5920)3/2^-$ have been established in experiments [1]. Two newly observed resonances $\Lambda_b(6146)$ and $\Lambda_b(6152)$ lie in the mass region of the λ-mode $\Lambda_b(1D,2S)$ states and the neutral excited $\Sigma_b(2S)$ states.

TABLE I. Mass spectra of the low-lying λ-mode excited Λ_b and Σ_b baryons from various quark models [26–30] compared with the data from the Particle Data Group [1]. The units are in MeV.

	Λ_b					
State $\vert J^P,j\rangle$	[28]	[30]	[27]	[26]	[29]	PDG[1]
$\vert J^P=\frac{1}{2}^+,0\rangle$ $(1S)$	5620	5618	5612	5585	5619	5620
$\vert J^P=\frac{1}{2}^-,1\rangle$ $(1P)$	5930	5938	5939	5912	5911	5912
$\vert J^P=\frac{3}{2}^-,1\rangle$ $(1P)$	5942	5939	5941	5920	5920	5920
$\vert J^P=\frac{1}{2}^+,0\rangle$ $(2S)$	6089	6153	6107	6045	$\cdots$	
$\vert J^P=\frac{3}{2}^+,2\rangle$ $(1D)$	6190	6211	6181	6145	6147	
$\vert J^P=\frac{5}{2}^+,2\rangle$ $(1D)$	6196	6212	6183	6165	6153	

	Σ_b				
State $\vert J^P,j\rangle$	[28]	[30]	[27]	[26]	PDG [1]
$\vert J^P=\frac{1}{2}^+,1\rangle$ $(1S)$	5808	5823	5833	5795	5811
$\vert J^P=\frac{3}{2}^+,1\rangle$ $(1S)$	5834	5845	5858	5805	5832
$\vert J^P=\frac{1}{2}^-,0\rangle$ $(1P)$	6101	6127	6099	6070	
$\vert J^P=\frac{1}{2}^-,1\rangle$ $(1P)$	6095	6135	6106	6070	
$\vert J^P=\frac{3}{2}^-,1\rangle$ $(1P)$	6096	6132	6101	6070	
$\vert J^P=\frac{3}{2}^-,2\rangle$ $(1P)$	6087	6141	6105	6085	
$\vert J^P=\frac{5}{2}^-,2\rangle$ $(1P)$	6084	6144	6172	6090	
$\vert J^P=\frac{1}{2}^+,1\rangle$ $(2S)$	6213	6343	6294	6200	
$\vert J^P=\frac{3}{2}^+,1\rangle$ $(2S)$	6226		6308	6250	

Recently, to identify the $\Lambda_b(6146)$ and $\Lambda_b(6152)$ resonances in the quark model, their strong decay behaviors were studied with the ${}^3P_0$ model in Ref. [43]. The results indicate that the $\Lambda_b(6146)$ and $\Lambda_b(6152)$ resonances can be assigned as the λ-mode $\Lambda_b(1D)$ doublet with $J^P=5/2^+$ and $J^P=3/2^+$, respectively. In our previous works [21,25], the strong decays of the P-wave singly bottom baryon states $\Sigma_b(1P)$ were studied within the chiral quark model. It is found that $\Sigma_b(6097)$ may favor the light spin $j=2$ states with spin-parity numbers $J^P=3/2^-$ or $J^P=5/2^-$. If $\Sigma_b(6097)$ corresponds to the $|J^P=\frac{3}{2}^-,2\rangle$ or $|J^P=\frac{5}{2}^-,2\rangle$ state, the typical mass of the $\Sigma_b(1P)$ states should be around 6090 MeV since the mass splitting between them is within 10 MeV according to quark model predictions [28]. Thus, one should exclude the $\Sigma_b(6146)$ and $\Sigma_b(6152)$ resonances as the $\Sigma_b(1P)$ states because the masses of $\Sigma_b(6146)$ and $\Sigma_b(6152)$ are obviously larger than the quark model predictions.

Taking the masses predicted from quark models, we have studied the decays of the D-wave singly heavy baryons within the chiral quark model in Ref. [44]. Since the newly observed $\Lambda_b(6146)$ and $\Lambda_b(6152)$ resonances may favor the D-wave Λ_b states, to confirm this assignment we revisit the strong decays of the D-wave Λ_b states by adopting the measured masses in present work. Moreover, the $2S$-wave Λ_b and Σ_b states were not investigated in the framework of chiral quark model. Hence, in this work, as a supplement of Refs. [25,44], we employ the chiral quark model to study the strong decays with emission of one light pseudoscalar meson for the low-lying $\Lambda_b(1D)$, $\Lambda_b(2S)$, and $\Sigma_b(2S)$ states. Combining the masses, total widths, and decay modes, our results indicate that the $\Lambda_b(6146)$ and $\Lambda_b(6152)$ states may be explained with the λ-mode $\Lambda_b(1D)$ states in the quark model. It should be mentioned that there are some studies about the strong decay properties of the Λ_b and Σ_b states [12,45–52]. Most of the discussions focus on the low-lying S- and P-wave states. For the strong decay properties of higher D-wave Λ_b and Σ_b states, only a few studies are found in the literature [29,43,51,52].

This paper is organized as follows. The spectrum and notations are presented in Sec. II. The chiral quark model are briefly introduced in Sec. III. The strong decays of the low-lying $\Lambda_b(1D,2S)$ and $\Sigma_b(2S)$ states are estimated in Sec. IV. A short summary is presented in the last section.

II. SPECTROSCOPY

The heavy baryon containing a heavy quark violates the SU(4) symmetry. However, the SU(3) symmetry between the other two light quarks (u, d, or s) is approximately kept. According to the symmetry, the heavy baryons containing a single heavy quark belong to two different SU(3) flavor representations: the symmetric sextet $\mathbf{6}_F$ and antisymmetric antitriplet $\bar{\mathbf{3}}_F$. For the bottom baryons, Λ_b and Ξ_b, belonging to $\bar{\mathbf{3}}_F$, the antisymmetric flavor wave functions are given by [25]

$$\phi^b_{\bar{\mathbf{3}}} = \begin{cases} \frac{1}{\sqrt{2}}(ud - du)b & \text{for } \Lambda^0_b, \\ \frac{1}{\sqrt{2}}(us - su)b & \text{for } \Xi^0_b, \\ \frac{1}{\sqrt{2}}(ds - sd)b & \text{for } \Xi^-_b. \end{cases} \tag{5}$$

For the bottom baryons, Σ_b, Ξ'_b, and Ω_b, belonging to $\mathbf{6}_F$, the symmetric flavor wave functions are given by [25]

$$\phi^b_{\mathbf{6}} = \begin{cases} uub & \text{for } \Sigma^+_b, \\ \frac{1}{\sqrt{2}}(ud + du)b & \text{for} \Sigma^0_b, \\ ddb & \text{for } \Sigma^-_b, \\ \frac{1}{\sqrt{2}}(us + su)b & \text{for } \Xi'^0_b, \\ \frac{1}{\sqrt{2}}(ds + sd)b & \text{for } \Xi'^-_b, \\ ssb & \text{for } \Omega^-_b. \end{cases} \tag{6}$$

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

$$\mathcal{H} = \frac{P^2_{\text{c.m.}}}{2M} + \frac{1}{2m_\rho}\mathbf{p}^2_\rho + \frac{1}{2m_\lambda}\mathbf{p}^2_\lambda + \frac{3}{2}K(\rho^2 + \lambda^2). \tag{7}$$

The constituent quarks are confined in an oscillator potential with the potential parameter K independent of the flavor quantum number. The Jacobi coordinates $\boldsymbol{\rho}$ and $\boldsymbol{\lambda}$ and center-of-mass (c.m.) coordinate $\mathbf{R}_{\text{c.m.}}$ can be related to the coordinate $\mathbf{r}_j$ of the jth quark by

$$\boldsymbol{\rho} = \frac{1}{\sqrt{2}}(\mathbf{r}_1 - \mathbf{r}_2), \tag{8}$$

$$\boldsymbol{\lambda} = \frac{1}{\sqrt{6}}(\mathbf{r}_1 + \mathbf{r}_2 - 2\mathbf{r}_3), \tag{9}$$

$$\mathbf{R}_{\text{c.m.}} = \frac{m(\mathbf{r}_1 + \mathbf{r}_2) + m'\mathbf{r}_3}{2m + m'}, \tag{10}$$

and the momenta $\mathbf{p}_\rho$, $\mathbf{p}_\lambda$, and $\mathbf{P}_{\text{c.m.}}$ are defined by

$$\mathbf{p}_\rho = m_\rho\dot{\boldsymbol{\rho}}, \qquad \mathbf{p}_\lambda = m_\lambda\dot{\boldsymbol{\lambda}}, \qquad \mathbf{P}_{\text{c.m.}} = M\dot{\mathbf{R}}_{\text{c.m.}}, \tag{11}$$

with

$$M = 2m + m', \qquad m_\rho = m, \qquad m_\lambda = \frac{3mm'}{2m + m'}. \tag{12}$$

The wave function of an oscillator is given by

$$\psi^{n_\sigma}_{l_\sigma m}(\sigma) = R_{n_\sigma l_\sigma}(\sigma)Y_{l_\sigma m}(\sigma), \tag{13}$$

where $\sigma = \rho, \lambda$. The spatial wave function is a product of the ρ-oscillator and the λ-oscillator wave functions. There are two parameters, i.e., the potential strengths α_ρ and α_λ in the oscillator wave functions. The parameters α_ρ and α_λ satisfy the following relation [53]:

$$\alpha^2_\lambda = \sqrt{\frac{3m'}{2m + m'}}\alpha^2_\rho. \tag{14}$$

With the standard notation, the principal quantum numbers of the ρ-mode oscillator and λ-mode oscillator are $N_\rho = (2n_\rho + l_\rho)$ and $N_\lambda = (2n_\lambda + l_\lambda)$, respectively. For the ρ and λ mode excitations, their corresponding energies E_ρ and E_λ are given by

$$E_\rho = \left(N_\rho + \frac{3}{2}\right)\omega_\rho, \qquad E_\lambda = \left(N_\lambda + \frac{3}{2}\right)\omega_\lambda, \tag{15}$$

with the frequencies

$$\omega_\rho = (3K/m_\rho)^{1/2}, \qquad \omega_\lambda = (3K/m_\lambda)^{1/2}. \tag{16}$$

According to the above equations, one has $\omega_\rho = \sqrt{3m'/(2m + m')}\omega_\lambda > \omega_\lambda$. Taking $N_\rho = N_\lambda$, one finds that the ρ-mode excited energy $E_\rho = (N_\rho + \frac{3}{2})\omega_\rho$ is much larger than the λ-mode excited energy $E_\lambda = (N_\lambda + \frac{3}{2})\omega_\lambda$. It indicates that the λ-mode excitations should be easily formed than the ρ-mode excitations in experiments. Thus, in present work, we only study the λ-mode excitations.

It should be pointed out that the quark model states that we obtain for the baryons containing a single heavy quark respect the dictates of the heavy quark effective theory [27,30,54,55]. For a singly heavy baryon, the interactions which depend on the heavy quark spin $\mathbf{s}_Q$ are strongly suppressed by heavy quark mass [26]. In the heavy quark limit, these interactions will disappear. Thus, the heavy quark spin $\mathbf{s}_Q$ in a singly heavy baryon is conserved approximately. On the other hand, the total angular momentum $\mathbf{j}$ carried by the light quarks is conserved as well. In the heavy-quark symmetry limit, since the angular momentum $\mathbf{j}$ of light quarks is conserved, one may first obtain $\mathbf{j}$ by coupling the total spin $\mathbf{s}_\rho$ of light quarks to their total orbital angular momentum $\mathbf{L}$, i.e., $\mathbf{j} = \mathbf{L} + \mathbf{s}_\rho$; then one obtains the total angular momentum

TABLE II. The classifications of the low-lying λ-mode $1P$- and $2S$-wave states belonging to $\mathbf{6}_F$ in the $j-j$ coupling scheme.

$\lvert J^P, j\rangle$	J^P	j	n_ρ	ℓ_ρ	n_λ	ℓ_λ	L	s_ρ	s_Q
$\lvert J^P=\frac{1}{2}^-,0\rangle$ $(1P)$	$\frac{1}{2}^-$	0	0	0	0	1	1	1	$\frac{1}{2}$
$\lvert J^P=\frac{1}{2}^-,1\rangle$ $(1P)$	$\frac{3}{2}^-$	1	0	0	0	1	1	1	$\frac{1}{2}$
$\lvert J^P=\frac{3}{2}^-,1\rangle$ $(1P)$	$\frac{1}{2}^-$	1	0	0	0	1	1	1	$\frac{1}{2}$
$\lvert J^P=\frac{3}{2}^-,2\rangle$ $(1P)$	$\frac{3}{2}^-$	2	0	0	0	1	1	1	$\frac{1}{2}$
$\lvert J^P=\frac{5}{2}^-,2\rangle$ $(1P)$	$\frac{5}{2}^-$	2	0	0	0	1	1	1	$\frac{1}{2}$
$\lvert J^P=\frac{1}{2}^+,1\rangle$ $(2S)$	$\frac{1}{2}^+$	1	0	0	1	0	0	1	$\frac{1}{2}$
$\lvert J^P=\frac{3}{2}^+,1\rangle$ $(2S)$	$\frac{3}{2}^+$	1	0	0	1	0	0	1	$\frac{1}{2}$

TABLE III. The classifications of the low-lying λ-mode $1P$-, $1D$-, and $2S$-wave states belonging to $\bar{\mathbf{3}}_F$ in the $j-j$ coupling scheme.

$\lvert J^P, j\rangle$	J^P	j	n_ρ	ℓ_ρ	n_λ	ℓ_λ	L	s_ρ	s_Q
$\lvert J^P=\frac{1}{2}^-,1\rangle$ $(1P)$	$\frac{1}{2}^-$	0	0	0	0	1	1	1	$\frac{1}{2}$
$\lvert J^P=\frac{3}{2}^-,1\rangle$ $(1P)$	$\frac{3}{2}^-$	1	0	0	0	1	1	0	$\frac{1}{2}$
$\lvert J^P=\frac{1}{2}^+,0\rangle$ $(2S)$	$\frac{1}{2}^+$	0	0	0	1	0	0	0	$\frac{1}{2}$
$\lvert J^P=\frac{3}{2}^+,2\rangle$ $(1D)$	$\frac{3}{2}^+$	2	0	0	0	2	2	0	$\frac{1}{2}$
$\lvert J^P=\frac{5}{2}^+,2\rangle$ $(1D)$	$\frac{5}{2}^+$	2	0	0	0	2	2	0	$\frac{1}{2}$

$\mathbf{J}$ by coupling $\mathbf{j}$ to the heavy quark spin $\mathbf{s}_Q$, i.e., $\mathbf{J}=\mathbf{j}+\mathbf{s}_Q$. Consequently, the singly heavy baryons may more favor the $j-j$ coupling scheme [27], i.e.,

$$|J^P, j\rangle = |\{[(\ell_\rho \ell_\lambda)_L s_\rho]_j s_Q\}_{J^P}\rangle, \tag{17}$$

where ℓ_ρ and ℓ_λ correspond to the quantum numbers of the orbital angular momenta of ρ- and λ-mode excitations, respectively; s_ρ is the quantum number of the total spin of the two light quarks. Two states whose quantum numbers $J=j\pm 1/2$ $(j\neq 0)$ will be degenerate. They form a heavy quark spin doublet. The Σ_b $1P$- and $2S$-wave states belonging to $\mathbf{6}_F$ and the Λ_b $1P$-, $2S$-, and $1D$-wave states belonging to $\bar{\mathbf{3}}_F$ in the $j-j$ coupling scheme and their corresponding quantum numbers have been collected in Tables II and III. The newly observed resonances $\Sigma_b(6097)^\pm$ and $\Xi_b(6227)^-$ at LHCb [16,17] may favor the light spin $j=2$ states belonging to $\mathbf{6}_F$ with spin-parity numbers $J^P=3/2^-$ or $J^P=5/2^-$ in the $j-j$ coupling scheme [21].

III. STRONG DECAY

In this work, strong decays of the singly heavy baryons with emission of one light pseudoscalar meson, i.e., π, K, and η are studied within chiral quark model [56]. In this model, the light pseudoscalar mesons are treated as pointlike Goldstone boson. This model has been successfully applied to study the strong decays of heavy-light mesons and strange and singly heavy baryons [15,44,45,53,57–63]. The effective quark-pseudoscalar-meson interactions at low energies can be described by the simple chiral Lagrangian,

$$H_m = \sum_j \frac{1}{f_m} \bar{\psi}_j \gamma_\mu^j \gamma_5^j \psi_j \partial^\mu \phi_m, \tag{18}$$

where ψ_j represents the jth quark field in the hadron, ϕ_m is the pseudoscalar meson field, and f_m is the pseudoscalar meson decay constant.

To match the nonrelativistic harmonic oscillator wave functions in this work, one should adopt the quark-pseudoscalar-meson interactions in the nonrelativistic form [53]

$$H_m^{nr} = \sum_j [\mathcal{G}\boldsymbol{\sigma}_j\cdot\mathbf{q} + h\boldsymbol{\sigma}_j\cdot\mathbf{p}_j] I_j e^{-i\mathbf{q}\cdot\mathbf{r}_j}, \tag{19}$$

with $\mathcal{G}\equiv -(1+\frac{\omega_m}{E_f+M_f})$ and $h\equiv\frac{\omega_m}{2\mu_q}$. In the above equation, ω_m and $\mathbf{q}$ are the energy and three momenta of the emitted light meson, respectively; μ_q stand for a reduced mass given by $1/\mu_q = 1/m_j + 1/m_j'$ with m_j and m_j' for the masses of the jth quark in the initial and final hadrons, respectively; $\boldsymbol{\sigma}_j$ and $\mathbf{p}_j$ are the Pauli spin vector and internal momentum operator for the jth quark of the initial hadron; and I_j is the isospin operator associated with the pseudoscalar meson.

For a light pseudoscalar meson emission in a strong decay process, the partial decay width can be calculated with [53]

$$\Gamma_m = \left(\frac{\delta}{f_m}\right)^2 \frac{(E_f+M_f)|\mathbf{q}|}{4\pi M_i(2J_i+1)} \sum_{J_{fz},J_{iz}} |\mathcal{M}_{J_{fz},J_{iz}}|^2, \tag{20}$$

where $\mathcal{M}_{J_{fz},J_{iz}}$ corresponds to the strong amplitudes. The quantum numbers J_{iz} and J_{fz} stand for the third components of the total angular momenta of the initial and final heavy baryons, respectively. M_i is the mass of the initial heavy baryon. E_f and M_f are the energy and mass of the final heavy baryon. δ as a global parameter accounts for the strength of the quark-meson couplings. It has been determined in our previous work of the strong decays of the charmed baryons and heavy-light mesons [53,58]. Here, we fix its value the same as that in Refs. [53,58], i.e., $\delta=0.557$.

In the calculation, the standard quark model parameters are adopted. Namely, we set $m_u=m_d=330$ MeV and $m_b=5000$ MeV for the constituent quark masses. The harmonic oscillator parameter α_ρ in the wave function $\psi_{lm}^n = R_{nl}Y_{lm}$ for $uu/ud/dd$ diquark systems is taken as $\alpha_\rho=400$ MeV. The decay constant for π meson is taken as $f_\pi=132$ MeV. The masses of the well-established hadrons used in the calculations are taken from the

Particle Data Group [1], and the masses of the undiscovered initial states adopt from the predictions in Refs. [26,28].

IV. RESULTS AND DISCUSSIONS

A. $\Lambda_b(1D)$

In the Λ_b family, there are two λ-mode $1D$-wave excitations $|J^P = \frac{3}{2}^+, 2\rangle$ and $|J^P = \frac{5}{2}^+, 2\rangle$ according to the classification of quark models. The masses for the λ-mode $1D$-wave Λ_b excitations are predicted to be ~6.1–6.2 GeV (see Table I). The measured masses of the $\Lambda_b(6146)$ and $\Lambda_b(6152)$ indicate that they may be good candidates of the λ-mode $1D$-wave excitations.

Our calculations are presented in Table IV. The $\Lambda_b(6146)$ resonance is most likely to be the $J^P = 5/2^+$ $|J^P = \frac{5}{2}^+, 2\rangle$ state. Assigning the $\Lambda_b(6146)$ as $|J^P = \frac{5}{2}^+, 2\rangle$, one can find that it has a narrow width of ~5 MeV and dominantly decays into $\Sigma_b^*\pi$. The partial widths into $\Sigma_b\pi$ and $\Sigma_b^*\pi$ channels are predicted to be

$$\Gamma[\Lambda_b(6146) \to \Sigma_b\pi] \simeq 0.64 \text{ MeV}, \tag{21}$$

$$\Gamma[\Lambda_b(6146) \to \Sigma_b^*\pi] \simeq 4.26 \text{ MeV}. \tag{22}$$

Both the decay width and decay mode are consistent with the observations of $\Lambda_b(6146)$ considering the model uncertainties. Our chiral quark model predictions are consistent with the results of the $^3P_0$ model [43,52]. To further confirm the nature of the $\Lambda_b(6146)$ resonance, the partial width ratio between $\Sigma_b\pi$ and $\Sigma_b^*\pi$ channels,

$$\frac{\Gamma(\Sigma_b\pi)}{\Gamma(\Sigma_b^*\pi)} \simeq 0.15, \tag{23}$$

is worth to observing in future experiments.

On the other hand, the $\Lambda_b(6152)$ resonance most likely corresponds to the λ-mode $1D$-wave Λ_b excitation $|J^P = \frac{3}{2}^+, 2\rangle$. If we assign the $\Lambda_b(6152)$ resonance as $|J^P = \frac{3}{2}^+, 2\rangle$, it has a narrow width of ~6 MeV and dominantly decays into $\Sigma_b\pi$ and $\Sigma_b^*\pi$. We predicted partial widths

$$\Gamma[\Lambda_b(6152) \to \Sigma_b\pi] \simeq 4.67 \text{ MeV}, \tag{24}$$

$$\Gamma[\Lambda_b(6152) \to \Sigma_b^*\pi] \simeq 1.41 \text{ MeV}, \tag{25}$$

which are in agreement with the recent $^3P_0$ model predictions [43]. In Ref. [52], the authors suggested $\Lambda_b(6146)$ may be the $|J^P = \frac{3}{2}^+, 2\rangle$ state according to their mass prediction, with this assignment the strong decay properties of $\Lambda_b(6146)$ predicted by them agree with our results. As the $|J^P = \frac{3}{2}^+, 2\rangle$ assignment, the partial width ratio of $\Lambda_b(6152)$ between $\Sigma_b\pi$ and $\Sigma_b^*\pi$ channels is predicted to be

$$\frac{\Gamma(\Sigma_b\pi)}{\Gamma(\Sigma_b^*\pi)} \simeq 3.3. \tag{26}$$

This ratio might be crucial to test the nature of $\Lambda_b(6152)$, which is suggested to be measured in future experiments.

Finally, it should be mentioned that the $\Lambda_c(2860)3/2^+$ and $\Lambda_c(2880)5/2^+$ are often assigned to $1D$ doublet in the Λ_c family [44,64,65]. This indicates that the mass of the $J^P = 3/2^+$ D-wave state should be smaller than that of the $J^P = 5/2^+$ state. Furthermore, according to the predictions in various quark models [26–30], the mass of the $J^P = 5/2^+$ state should be larger than that of the $J^P = 3/2^+$ state (see Table I). Then, if assigning $\Lambda_b(6146)$ and $\Lambda_b(6152)$ to be $J^P = 5/2^+$ and $J^P = 3/2^+$ D-wave states, respectively, one should face a serious problem of mass reverse. Whether the structure in the $\Lambda_b\pi^+\pi^-$ spectrum corresponds to two states or one state should be further clarified with more observations in future experiments.

B. $\Lambda_b(2S)$

In the Λ_b family, there is only one λ-mode $2S$-wave excitation $|J^P = \frac{1}{2}^+, 0\rangle$ according to the quark model classification. The mass for the λ-mode $2S$-wave Λ_b excitation is predicted to be ~6.1 GeV in various quark models (see Table I). According to the predicted masses in Ref. [30], the measured mass of the $\Lambda_b(6146)$ or $\Lambda_b(6152)$ indicates that it might be a good candidate of the λ-mode $2S$-wave excitation. Considering $\Lambda_b(6146)$ or $\Lambda_b(6152)$ as the $2S$-wave state, the strong decay properties are studied; our results are listed in Table V. It is found that if assigning $\Lambda_b(6146)$ to the $2S$-wave state, both the total width $\Gamma \simeq$ 2 MeV and the dominant decay mode $\Sigma_b^*\pi$ predicted in theory are consistent with the observations. However, the other resonance $\Lambda_b(6152)$ cannot be understood in the quark model. It cannot be assigned to any D-wave states in the Λ_b family, because the mass splitting between the

TABLE IV. Partial widths (MeV) of strong decays for the λ-mode $1D$-wave Λ_b baryons.

	$\lvert J^P = \frac{3}{2}^+, 2\rangle$		$\lvert J^P = \frac{5}{2}^+, 2\rangle$	
Decay mode	$\Lambda_b(6146)$	$\Lambda_b(6152)$	$\Lambda_b(6146)$	$\Lambda_b(6152)$
$\Sigma_b\pi$	4.41	4.67	0.64	0.73
$\Sigma_b^*\pi$	1.26	1.41	4.26	4.60
Sum	5.67	6.08	4.90	5.33

TABLE V. Partial widths (MeV) of strong decays for the λ-mode $2S$-wave Λ_b baryon.

	$\lvert J^P = \frac{1}{2}^+, 0\rangle$	
Decay mode	$\Sigma_b(6146)$	$\Sigma_b(6152)$
$\Sigma_b\pi$	0.34	0.32
$\Sigma_b^*\pi$	1.72	1.77
Sum	2.06	2.09

2S-wave and D-wave Λ_b states is ~50–100 MeV. The D-wave Σ_b states should be excluded as well for their typical mass is ~6.3 GeV [26,44]. As a whole, if we assign $\Lambda_b(6146)$ as the $\Lambda_b(2S)$ state, the other state $\Lambda_b(6152)$ cannot be reasonably explained according to the classification of quark models and mass splitting [30].

Since the $\Lambda_b(2S)$ $|J^P = \frac{1}{2}^+, 0\rangle$ state may not favor $\Lambda_b(6146)$, in this work, we take its mass $M = 6045$ MeV as predicted in Ref. [26], and estimate the strong decay of $\Lambda_b(2S)$ into the $\Sigma_b\pi$ and $\Sigma_b^*\pi$ channels. It is found that $\Lambda_b(2S)$ mainly decays into $\Sigma_b\pi$ and $\Sigma_b^*\pi$ modes. The predicted partial widths are

$$\begin{aligned}\Gamma[\Sigma_b\pi] &\simeq 0.21 \text{ MeV},\\ \Gamma[\Sigma_b^*\pi] &\simeq 0.39 \text{ MeV},\end{aligned}\tag{27}$$

and the corresponding total decay width reads

$$\Gamma_{\text{total}} \simeq 0.6 \text{ MeV}.\tag{28}$$

The $\Sigma_b^*\pi$ might be an ideal channel for searching for the λ-mode 2S-wave Λ_b state $|J^P = \frac{1}{2}^+, 0\rangle$ in future experiments. It should be mentioned that decay width of $\Lambda_b(2S)$ predicted with the $^3P_0$ model in Ref. [43] is about a factor of 20 larger than that obtained with the chiral quark model in present work.

C. $\Sigma_b(2S)$

We also study the strong decay properties of two λ-mode 2S-wave excitations $|J^P = \frac{1}{2}^+, 1\rangle$ and $|J^P = \frac{3}{2}^+, 1\rangle$ in the Σ_b family according to the quark model classification. The masses for the λ-mode 2S-wave Σ_b excitations are predicted to be 6.2 ~ 6.3 GeV in various models (see Table I).

To study the strong decay properties of the 2S-wave Σ_b excitations, we adopt the predicted masses in Ref. [28]. Our results are listed in Table VI. One can see that $|J^P = \frac{1}{2}^+, 1\rangle$ and $|J^P = \frac{3}{2}^+, 1\rangle$ dominantly decay into the $\Lambda_b\pi$ channel. Their partial widths are predicted to be

$$\Gamma[\Sigma_b(6213) \to \Lambda_b\pi] \simeq 3.82 \text{ MeV},\tag{29}$$

$$\Gamma[\Sigma_b(6226) \to \Lambda_b\pi] \simeq 4.72 \text{ MeV}.\tag{30}$$

The $\Lambda_b\pi$ might be an ideal channel to look for these radial excitations in future experiments. One should be pointed out that the decay widths of the 2S wave Σ_b states predicted in present work with the chiral quark model are about an order of magnitude smaller than those of the $^3P_0$ model in Ref. [43].

Finally, it should be mentioned that we do not consider the $\Lambda_b(6146)$ and $\Lambda_b(6152)$ as the 2S Σ_b states, for the mainly decay modes and masses of $\Sigma_b(2S)$ predicted in the quark model are inconsistent with the observations.

TABLE VI. Partial widths (MeV) of strong decays for the λ-mode 2S-wave Σ_b baryons.

	$\lvert J^P = \frac{1}{2}^+, 1\rangle$	$\lvert J^P = \frac{3}{2}^+, 1\rangle$
Decay mode	$\Sigma_b(6213)$	$\Sigma_b(6226)$
$\Lambda_b\pi$	3.82	4.72
$\Sigma_b\pi$	5.32×10^{-2}	3.63×10^{-3}
$\Sigma_b^*\pi$	6.90×10^{-2}	1.07×10^{-2}
Sum	3.94	4.73

V. SUMMARY

Stimulated by the newly observed $\Lambda_b(6146/6152)$ resonances at the LHCb, in this work we study the strong decays of the low-lying λ-mode $\Lambda_b(1D)$, $\Lambda_b(2S)$ and $\Sigma_b(2S)$ states within the chiral quark model.

Our results indicate that the newly observed $\Lambda_b(6146)$ might be assigned as the $\Lambda_b(1D)$ $|J^P = \frac{5}{2}^+, 2\rangle$ state, which dominantly decays into $\Sigma_b^*\pi$ channel. The $\Lambda_b(6152)$ seems to favor the $\Lambda_b(1D)$ $|J^P = \frac{3}{2}^+, 2\rangle$ states; with this assignment, its decay behaviors are dominated by the $\Sigma_b\pi$ and $\Sigma_b^*\pi$ channels, which are consistent with the experimental observations. According to the calculations in various quark models, the mass of the $J^P = 5/2^+$ D-wave Λ_b state should be larger than that of the $J^P = 3/2^+$ D-wave Λ_b state. Thus, if we assign $\Lambda_b(6146)$ and $\Lambda_b(6152)$ to the $J^P = 5/2^+$ and $J^P = 3/2^+$ D-wave states, respectively, one should face a serious problem of mass reverse. This puzzle was also found by Chen *et al.* in their recent studies [52]. The strong decay properties of $J^P = 3/2^+$ and $J^P = 5/2^+$ D-wave Λ_b states predicted in present work with the chiral quark model are consistent with the recent predictions with the $^3P_0$ model [43,52]. Whether the structure in the $\Lambda_b\pi^+\pi^-$ spectrum corresponds to two states or one state should be further clarified with more observations, such as the mass, decay mode, and spin parities, in future experiments.

Moreover, we find that the $\Lambda_b(2S)$ $|J^P = \frac{1}{2}^+, 0\rangle$ state mainly decays into $\Sigma_b^*\pi$, and the $\Sigma_b(2S)$ $|J^P = \frac{1}{2}^+, 1\rangle$ and $|J^P = \frac{3}{2}^+, 1\rangle$ dominantly decay into $\Lambda_b\pi$ with narrow widths $\Gamma \simeq 3.82$ MeV and $\Gamma \simeq 4.72$ MeV, respectively. The decay widths of the 2S-wave $\Lambda_b(2S)$ and $\Sigma_b(2S)$ states predicted in present work with the chiral quark model are about an order of magnitude smaller than those of the $^3P_0$ model in Ref. [43]. More studies of the strong decays of the 2S-wave bottom baryon states are expected to be carried out in theory. These theoretical predictions may provide helpful information for future experimental searches.

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