Canonical interpretation of the newly observed $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ via strong decay behaviors

Wei Liang, Qi-Fang Lü^{✉,*} and Xian-Hui Zhong[†]

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

(Received 6 August 2019; published 13 September 2019)

Stimulated by the newly observed $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ resonances, we investigate the strong decays of the low-lying singly bottom baryons within the quark pair creation model. Considering their masses and decay modes, we tentatively assign these states as the λ -mode $\Lambda_b(2S)$, $\Lambda_b(1D)$, $\Sigma_b(2S)$, and $\Sigma_b(1P)$ states and then estimate their strong decay widths. Compared with the experimental total widths and decay modes measured by the LHCb Collaboration, the $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ can be reasonably clarified into the $J^P = 5/2^+$ and $J^P = 3/2^+$ $\Lambda_b(1D)$ states, respectively, while other canonical assignments are disfavored. Other low-lying bottom states are also presented, where various narrow states may have good potential to be observed in future LHCb experiments.

DOI: [10.1103/PhysRevD.100.054013](https://doi.org/10.1103/PhysRevD.100.054013)

I. INTRODUCTION

Very recently, the LHCb Collaboration reported the discovery of two new singly bottom baryons $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ in the $\Lambda_b^0 \pi^+ \pi^-$ invariant mass distribution [1]. Their measured masses and widths are listed as follows:

$$m[\Lambda_b(6146)^0] = 6146.17 \pm 0.33 \pm 0.22 \pm 0.16 \text{ MeV}, \quad (1)$$

$$\Gamma[\Lambda_b(6146)^0] = 2.9 \pm 1.3 \pm 0.3 \text{ MeV}, \quad (2)$$

$$m[\Lambda_b(6152)^0] = 6152.51 \pm 0.26 \pm 0.22 \pm 0.16 \text{ MeV}, \quad (3)$$

$$\Gamma[\Lambda_b(6152)^0] = 2.1 \pm 0.8 \pm 0.3 \text{ MeV}, \quad (4)$$

where the mass gap between these two states is only about 6 MeV. Compared with the masses predicted by the constituent quark model [2–6], the LHCb Collaboration suggested that these two states can be assigned as the $1D$ doublet of the Λ_b^0 states [1].

*Corresponding author.
lvqifang@hunnu.edu.cn

†Corresponding author.
zhongxh@hunnu.edu.cn

Published by the American Physical Society under the terms of the [Creative Commons Attribution 4.0 International](https://creativecommons.org/licenses/by/4.0/) license. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI. Funded by SCOAP³.

A singly bottom baryon without a strange quark is composed of one bottom quark and two light quarks. These bottom baryons can be categorized into the Λ_b and Σ_b families, which belong to the antisymmetric flavor configuration $\bar{3}_F$ and symmetric flavor configuration 6_F , respectively. From the Review of Particle Physics [7], there exist six Λ_b and Σ_b baryons: $\Lambda_b(5620)$, $\Lambda_b(5912)$, $\Lambda_b(5920)$, $\Sigma_b(5811)$, $\Sigma_b^*(5830)$, and $\Sigma_b(6097)$. The $\Lambda_b(5620)$, $\Sigma_b(5811)$, and $\Sigma_b^*(5830)$ are the S -wave ground states undoubtedly. The $\Lambda_b(5912)$ and $\Lambda_b(5920)$ can be well established as the two λ -mode P -wave Λ_b states by various theoretical studies [2–6,8–12]. Under the canonical interpretation, the mass and strong decay behaviors indicate that $\Sigma_b(6097)$ can be categorized into the λ -mode P -wave Σ_b states in the literature [13–18]. Because of the lack of more experimental information, the spectra of these low-lying bottom baryons have not been established so far [19–23].

Although the LHCb Collaboration suggested that these two states seem to be the $\Lambda_b(1D)$ doublet, other interpretations are possible. In fact, because these two states are observed in the $\Lambda_b^0 \pi^+ \pi^-$ final states, they probably correspond to the neutral excited Σ_b states [1]. Hence, the newly observed two states have the potential to be the $\Sigma_b(6146)^0$ and $\Sigma_b(6152)^0$ resonances, and we also need to examine this $I = 1$ case. Moreover, the constituent quark model may have significant uncertainties on the mass spectrum and just perform the mass pattern of these canonical baryon states. Considering the mass uncertainties predicted by the quark model, we find that these two resonances lie in the mass region of the predicted λ -mode $\Lambda_b(2S)$, $\Lambda_b(1D)$, $\Sigma_b(2S)$, and $\Sigma_b(1P)$ states. To clarify their nature, the strong decays of these assignments should be examined carefully.

The studies on these low-lying bottom baryons can help us to understand the nature of these two newly observed resonances and establish the bottom baryon spectrum. Before this discovery by the LHCb Collaboration, the strong decays of the low-lying bottom baryons have been investigated by several works. However, due to the lack of experimental information, the choices of parameters may be ambiguous, and the predictions of these different works do not agree with each other. Hence, it is essential to investigate the strong decays of these low-lying bottom baryons within the unified model and coincident parameters. In this issue, we calculate the strong decay behaviors of these states within the 3P_0 model systematically. Our results shows that the $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ can be assigned as the $\Lambda_b(1D)$ doublet reasonably, while other canonical assignments are disfavored. The predictions of other low-lying bottom states may provide helpful information for future experimental searches.

This paper is organized as follows. The 3P_0 model and notations are introduced in Sec. II. The strong decays of the low-lying bottom baryons are estimated in Sec. III. A short summary is presented in the last section.

II. 3P_0 MODEL

In this calculation, the 3P_0 quark pair creation model is adopted to investigate the Okubo-Zweig-Iizuka-allowed two-body strong decays of the excited Λ_b and Σ_b states. The 3P_0 model has been widely employed to estimate the strong decay behaviors of conventional hadrons and achieved with considerable successes [24–42]. In this model, the initial hadrons can decay into two final states via a quark-antiquark pair with the vacuum quantum number $J^{PC} = 0^{++}$ [24]. For the baryons, the transition operator T of the decay $A \rightarrow BC$ can be written as [30,33]

$$T = -3\gamma \sum_m \langle 1m1 - m | 00 \rangle \int d^3p_4 d^3p_5 \delta^3(\mathbf{p}_4 + \mathbf{p}_5) \times \mathcal{Y}_1^m \left(\frac{\mathbf{p}_4 - \mathbf{p}_5}{2} \right) \chi_{1,-m}^{45} \phi_0^{45} \omega_0^{45} b_{4i}^\dagger(\mathbf{p}_4) d_{4j}^\dagger(\mathbf{p}_5), \quad (5)$$

where γ is a dimensionless constant reflecting the $q_4\bar{q}_5$ pair-production strength and $\mathbf{p}_4$ and $\mathbf{p}_5$ are the momenta of the created quark q_4 and antiquark $\bar{q}_5$, respectively. The solid harmonic polynomial $\mathcal{Y}_1^m(\mathbf{p}) \equiv |p| Y_1^m(\theta_p, \phi_p)$ stands for the P -wave momentum-space distribution of the created quark pair. $\phi_0^{45} = (u\bar{u} + d\bar{d} + s\bar{s})/\sqrt{3}$, $\omega_0^{45} = \delta_{ij}$, and $\chi_{1,-m}^{45}$ are the flavor singlet, color singlet, and spin triplet wave functions of the $q_4\bar{q}_5$, respectively. The $b_{4i}^\dagger(\mathbf{p}_4) d_{4j}^\dagger(\mathbf{p}_5)$ corresponds to the creation operators of the created quark and antiquark, where i and j are the color indices.

For the relevant hadrons, the definition of the mock states should be adopted. Taking the initial baryon A as an example, the total wave function can be expressed as [43]

$$|A(n_A^{2S_A+1} L_A J_A M_{J_A})(\mathbf{P}_A)\rangle \equiv \sqrt{2E_A} \sum_{M_{L_A}, M_{S_A}} \langle L_A M_{L_A} S_A M_{S_A} | J_A M_{J_A} \rangle \int d^3p_1 d^3p_2 d^3p_3 \times \delta^3(\mathbf{p}_1 + \mathbf{p}_2 + \mathbf{p}_3 - \mathbf{P}_A) \psi_{n_A L_A M_{L_A}}(\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3) \chi_{S_A M_{S_A}}^{123} \phi_A^{123} \omega_A^{123} \times |q_1(\mathbf{p}_1) q_2(\mathbf{p}_2) q_3(\mathbf{p}_3)\rangle, \quad (6)$$

which satisfies the normalization condition

$$\langle A(\mathbf{P}_A) | A(\mathbf{P}'_A) \rangle = 2E_A \delta^3(\mathbf{P}_A - \mathbf{P}'_A). \quad (7)$$

Here, the $\mathbf{P}_A$, $\mathbf{p}_1$, $\mathbf{p}_2$, and $\mathbf{p}_3$ are the momenta of the A , q_1 , q_2 , and q_3 , respectively. E_A is the total energy of the baryon A . $\chi_{S_A M_{S_A}}^{123}$, ϕ_A^{123} , ω_A^{123} , and $\psi_{n_A L_A M_{L_A}}(\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3)$ are the spin, flavor, color, and space wave functions of the baryon A , respectively. The definitions of the mock states B and C are similar to that of initial state A and can be found in Ref. [30].

For the decay of the singly bottom baryon A , there are three possible rearrangements:

$$A(q_1, q_2, b_3) + P(q_4, \bar{q}_5) \rightarrow B(q_2, q_4, b_3) + C(q_1, \bar{q}_5), \quad (8)$$

$$A(q_1, q_2, b_3) + P(q_4, \bar{q}_5) \rightarrow B(q_1, q_4, b_3) + C(q_2, \bar{q}_5), \quad (9)$$

$$A(q_1, q_2, b_3) + P(q_4, \bar{q}_5) \rightarrow B(q_1, q_2, q_4) + C(b_3, \bar{q}_5), \quad (10)$$

where the q_i and b_3 denote the light quark and bottom quark, respectively. These three ways of recoupling are also shown in Fig. 1. It can be seen that the first and second cases stand for the heavy baryon plus the light meson decay modes, while the last one corresponds to the light baryon plus the heavy-light meson final states. In our present calculations, the light baryon plus the heavy-light meson decay mode do not exist due to the phase space constraint.

The S matrix is defined as

$$\langle f | S | i \rangle = I - i2\pi\delta(E_f - E_i) \mathcal{M}^{M_{J_A} M_{J_B} M_{J_C}}, \quad (11)$$

where the $\mathcal{M}^{M_{J_A} M_{J_B} M_{J_C}}$ corresponds to the helicity amplitude of the decay process $A \rightarrow B + C$. Given the $A(q_1, q_2, b_3) + P(q_4, \bar{q}_5) \rightarrow B(q_1, q_4, b_3) + C(q_2, \bar{q}_5)$ shown in Fig. 1(b), the helicity amplitude $\mathcal{M}^{M_{J_A} M_{J_B} M_{J_C}}$ can be expressed as [30,32]

FIG. 1. The baryon decay process $A \rightarrow B + C$ in the 3P_0 model.

$$\begin{aligned}
\delta^3(\mathbf{p}_B + \mathbf{p}_C - \mathbf{p}_A) \mathcal{M}^{M_{J_A} M_{J_B} M_{J_C}} = & -\gamma \sqrt{8E_A E_B E_C} \sum_{M_{\rho_A}} \sum_{M_{L_A}} \sum_{M_{\rho_B}} \sum_{M_{L_B}} \sum_{M_{S_1}, M_{S_3}, M_{S_4}, m} \sum_{M_{S_2}} \langle j_A M_{j_A} S_3 M_{S_3} | J_A M_{J_A} \rangle \langle L_{\rho_A} M_{L_{\rho_A}} L_{\lambda_A} M_{L_{\lambda_A}} | L_A M_{L_A} \rangle \\
& \times \langle L_A M_{L_A} S_{12} M_{S_{12}} | j_A M_{j_A} \rangle \langle S_1 M_{S_1} S_2 M_{S_2} | S_{12} M_{S_{12}} \rangle \langle j_B M_{j_B} S_3 M_{S_3} | J_B M_{J_B} \rangle \\
& \times \langle L_{\rho_B} M_{L_{\rho_B}} L_{\lambda_B} M_{L_{\lambda_B}} | L_B M_{L_B} \rangle \langle L_B M_{L_B} S_{14} M_{S_{14}} | j_B M_{j_B} \rangle \langle S_1 M_{S_1} S_4 M_{S_4} | S_{14} M_{S_{14}} \rangle \\
& \times \langle 1m1-m | 00 \rangle \langle S_4 M_{S_4} S_5 M_{S_5} | 1-m \rangle \langle L_C M_{L_C} S_C M_{S_C} | J_C M_{J_C} \rangle \langle S_2 M_{S_2} S_5 M_{S_5} | S_C M_{S_C} \rangle \\
& \times \langle \phi_B^{143} \phi_C^{25} | \phi_A^{123} \phi_0^{45} \rangle I_{M_{L_B} M_{L_C}}^{M_{L_A} m}(\mathbf{p}), \quad (12)
\end{aligned}$$

where $\langle \phi_B^{143} \phi_C^{25} | \phi_A^{123} \phi_0^{45} \rangle$ is the overlap of the flavor wave functions and the $I_{M_{L_B} M_{L_C}}^{M_{L_A} m}(\mathbf{p})$ is the spatial overlap of the initial and final states. Here, the $I_{M_{L_B} M_{L_C}}^{M_{L_A} m}(\mathbf{p})$ can be written as

$$\begin{aligned}
I_{M_{L_B} M_{L_C}}^{M_{L_A} m}(\mathbf{p}) = & \int d^3 p_1 d^3 p_2 d^3 p_3 d^3 p_4 d^3 p_5 \delta^3(\mathbf{p}_1 + \mathbf{p}_2 + \mathbf{p}_3 - \mathbf{p}_A) \delta^3(\mathbf{p}_4 + \mathbf{p}_5) \\
& \times \delta^3(\mathbf{p}_1 + \mathbf{p}_4 + \mathbf{p}_3 - \mathbf{p}_B) \delta^3(\mathbf{p}_2 + \mathbf{p}_5 - \mathbf{p}_C) \psi_B^*(\mathbf{p}_1, \mathbf{p}_4, \mathbf{p}_3) \psi_C^*(\mathbf{p}_2, \mathbf{p}_5) \psi_A(\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3) \mathcal{Y}_1^m\left(\frac{\mathbf{p}_4 - \mathbf{p}_5}{2}\right). \quad (13)
\end{aligned}$$

It should be noted that the $I_{M_{L_B} M_{L_C}}^{M_{L_A} m}(\mathbf{p})$ not only depends on the magnetic quantum numbers, but also relies on the radial and orbital quantum numbers of the relevant hadrons that are usually omitted for simplicity in the literature.

In this work, the simplest vertex with a spatially constant pair-production strength γ , the relativistic phase space, and the simple harmonic oscillator wave functions are used as in Ref. [24]. Then, the decay width $\Gamma(A \rightarrow BC)$ can be calculated straightforwardly:

$$\Gamma = \pi^2 \frac{P}{M_A^2} \frac{s}{2J_A + 1} \sum_{M_{J_A}, M_{J_B}, M_{J_C}} |\mathcal{M}^{M_{J_A} M_{J_B} M_{J_C}}|^2, \quad (14)$$

where $p = |\mathbf{p}| = \frac{\sqrt{[M_A^2 - (M_B + M_C)^2][M_A^2 - (M_B - M_C)^2]}}{2M_A}$ is the momentum of the final hadrons. The statistical factor $s = 1/(1 + \delta_{BC})$ is needed only if B and C are identical particles and always equals to one in the present work.

In our calculation, we take the same notations of Λ_b and Σ_b baryons as those in Ref. [19]. The explicit notations of relevant excited bottom baryons together with the predicted masses [5] are listed in Table I. For the masses of initial $\Lambda_b(2S)$, $\Lambda_b(1D)$, $\Sigma_b(2S)$, and $\Sigma_b(1P)$ states, we first adopt the masses of $\Lambda_b(6146)^0[\Sigma_b(6146)^0]$ and $\Lambda_b(6152)^0[\Sigma_b(6152)^0]$ from LHCb experimental data by assuming that they are possible candidates. If the possible assignment for the $\Lambda_b(6146)^0[\Sigma_b(6146)^0]$ or $\Lambda_b(6152)^0[\Sigma_b(6152)^0]$ is finally excluded via decay width, the predicted mass of this state is employed to recalculate its strong decay behaviors. For the final ground states, the masses are taken from the Review of Particle Physics [7]. For the harmonic oscillator parameter of π meson, the effective value $R = 2.5 \text{ GeV}^{-1}$ is employed [38]. For the baryon parameters, we use $\alpha_\rho = 400 \text{ MeV}$ and

$$\alpha_\lambda = \left(\frac{3m_Q}{2m_q + m_Q} \right)^{1/4} \alpha_\rho, \quad (15)$$

where the m_Q and m_q are the heavy and light quark masses, respectively [41,44]. The $m_{u/d} = 220 \text{ MeV}$ and $m_b = 4.977 \text{ MeV}$ are introduced to explicitly consider the mass differences between the light and the bottom quark

TABLE I. Notations, quantum numbers, and the predicted masses of the relevant excited singly bottom baryons. For the spatial $2S$ excited states, the symbol $2S$ is added in the brackets. The n_ρ and L_ρ stand for the radial and orbital angular momenta between the two light quarks, respectively, while n_λ and L_λ denote the radial and angular momenta between the two light quark system and the bottom quark, respectively. L is the total orbital angular momentum, S_ρ is the total spin of the light quarks, j is the total angular momentum of L and S_ρ , J is the total angular momentum, and P corresponds to the parity of the hadron. The predicted masses of these excited states are taken from the relativistic quark model [5]. The units are in MeV.

State	n_ρ	L_ρ	n_λ	L_λ	L	S_ρ	j	J^P	Mass [5]
$\Lambda_b(2S)$	0	0	1	0	0	0	0	$\frac{1}{2}^+$	6089
$\Lambda_{b2}(\frac{3}{2}^+)$	0	0	0	2	2	0	2	$\frac{3}{2}^+$	6190
$\Lambda_{b2}(\frac{5}{2}^+)$	0	0	0	2	2	0	2	$\frac{5}{2}^+$	6196
$\Sigma_b(2S)$	0	0	1	0	0	1	1	$\frac{1}{2}^+$	6213
$\Sigma_b^*(2S)$	0	0	1	0	0	1	1	$\frac{3}{2}^+$	6226
$\Sigma_{b0}(\frac{1}{2}^-)$	0	0	0	1	1	1	0	$\frac{1}{2}^-$	6101
$\Sigma_{b1}(\frac{1}{2}^-)$	0	0	0	1	1	1	1	$\frac{1}{2}^-$	6095
$\Sigma_{b1}(\frac{3}{2}^-)$	0	0	0	1	1	1	1	$\frac{3}{2}^-$	6096
$\Sigma_{b2}(\frac{3}{2}^-)$	0	0	0	1	1	1	2	$\frac{3}{2}^-$	6087
$\Sigma_{b2}(\frac{5}{2}^-)$	0	0	0	1	1	1	2	$\frac{5}{2}^-$	6084

TABLE II. Strong decays of the ground states Σ_b and Σ_b^* to $\Lambda_b\pi$ together with experimental data in MeV.

Mode	Σ_b^+	Σ_b^-	Σ_b^{*+}	Σ_b^{*-}
$\Lambda_b\pi$	5.08	6.11	9.71	10.99
Experiments	5.0 ± 0.5	5.3 ± 0.5	9.4 ± 0.5	10.4 ± 0.8

[2,38,45]. The overall parameter γ can be determined by the well-established $\Sigma_c(2520)^{++} \rightarrow \Lambda_c\pi^+$ process. The $\gamma = 9.83$ is obtained by reproducing the width $\Gamma[\Sigma_c(2520)^{++} \rightarrow \Lambda_c\pi^+] = 14.78$ MeV [7,41]. With these parameters, the calculated decay widths of the ground states Σ_b and Σ_b^* to $\Lambda_b\pi$ are shown in Table II, which agree with the experimental data well.

III. STRONG DECAY

A. $\Lambda_b(2S)$ state

In the conventional quark model, only one λ -mode $\Lambda_b(2S)$ state exists. From Table I, the predicted mass of the $\Lambda_b(2S)$ state within the relativistic quark model is about 6089 MeV. Considering the uncertainties of different quark models, it is possible to assign the newly observed $\Lambda_b(6146)^0$ or $\Lambda_b(6152)^0$ as the $\Lambda_b(2S)$ state. The strong decay behaviors of the $\Lambda_b(2S)$ assignments are listed in Table III. It is shown that the total decay widths of the $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ as a $\Lambda_b(2S)$ state are 28.23 and 30.28 MeV, respectively. Compared with the experimental total widths $2.9 \pm 1.3 \pm 0.3$ and $2.1 \pm 0.8 \pm 0.3$ MeV measured by LHCb Collaboration, both assignments can be excluded.

From the heavy quark flavor symmetry, the mass gap between $\Lambda_b(2S)$ and Λ_b should be similar to the charmed baryon case, that is,

$$m[\Lambda_b(2S)] - m[\Lambda_b] \approx m[\Lambda_c(2S)] - m[\Lambda_c] = 480 \text{ MeV}. \quad (16)$$

Hence, the mass of $\Lambda_b(2S)$ is about 6100 MeV, which is consistent with the quark model prediction.

TABLE III. Strong decays of the $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ as $\Lambda_b(2S)$ states in MeV.

Decay mode	$\Lambda_b(2S)$	
	$\Lambda_b(6146)^0$	$\Lambda_b(6152)^0$
$\Sigma_b^+\pi^-$	3.69	3.94
$\Sigma_b^0\pi^0$	3.75	3.99
$\Sigma_b^-\pi^+$	3.52	3.77
$\Sigma_b^{*+}\pi^-$	5.79	6.23
$\Sigma_b^{*0}\pi^0$	5.9	6.34
$\Sigma_b^{*-}\pi^+$	5.58	6.01
Total width	28.23	30.28
Experiments	$2.9 \pm 1.3 \pm 0.3$	$2.1 \pm 0.8 \pm 0.3$

The strong decays of $\Lambda_b(2S)$ with a mass of 6089 MeV are presented in Table IV. It can be seen that $\Lambda_b(2S)$ state is relatively narrow due to the small phase space. The partial decay width ratios of the $\Lambda_b(2S)$ state are predicted to be

$$\Gamma[\Sigma_b\pi] : \Gamma[\Sigma_b^*\pi] = 0.70, \quad (17)$$

which is independent with the overall parameter γ in the 3P_0 model. For the total decay width of $\Lambda_b(2S)$, our result is about 3 times smaller than that of Ref. [13]. However, our predicted branching ratios agree with the results of Ref [13], which can provide useful information to search for the $\Lambda_b(2S)$ in future experiments.

B. $\Lambda_b(1D)$ states

There are two $\Lambda_b(1D)$ states in the constituent quark model, which form a doublet. From Table I, the predicted masses of the two $\Lambda_b(1D)$ states are 6190 and 6196 MeV, respectively. The predicted masses and small mass splitting suggest that the $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ are good candidates of this $\Lambda_b(1D)$ doublet. Although the predicted mass of the $J^P = 3/2^+$ state is slightly smaller than that of the $J^P = 5/2^+$ state with a normal mass order, the inversed mass order case is also possible physically. Hence, we consider both cases to fully examine the possible assignments. Their strong decays of the $\Lambda_b(1D)$ assignments are shown in Table V. The predicted total decay widths of these assignments are several MeV, which indicates the two $\Lambda_b(1D)$ states are both narrow states. The strong decays of these $\Lambda_b(1D)$ states are also investigated within the chiral quark model [46], which are consistent with our present results. Compared with the experimental data, our theoretical results seem to be larger. However, considering the uncertainties of the 3P_0 model and experiments, these assignments are acceptable.

Two factors in the quark pair creation model can affect the calculated total decay widths: One is the harmonic oscillator parameter α_p , and the other is the overall strength γ . The dependence on the harmonic oscillator parameter α_p of the initial states is shown in Fig. 2. When the α_p

TABLE IV. Strong decays of the $\Lambda_b(2S)$ state with a mass of 6089 MeV.

Mode	$\Lambda_b(2S)$
$\Sigma_b^+\pi^-$	1.75
$\Sigma_b^0\pi^0$	1.80
$\Sigma_b^-\pi^+$	1.64
$\Sigma_b^{*+}\pi^-$	2.47
$\Sigma_b^{*0}\pi^0$	2.56
$\Sigma_b^{*-}\pi^+$	2.34
Total width	12.56

TABLE V. Strong decays of the $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ as $\Lambda_b(1D)$ states in MeV.

Decay mode	$\Lambda_{b2}(\frac{3}{2}^+)$		$\Lambda_{b2}(\frac{5}{2}^+)$	
	$\Lambda_b(6146)^0$	$\Lambda_b(6152)^0$	$\Lambda_b(6146)^0$	$\Lambda_b(6152)^0$
$\Sigma_b^+ \pi^-$	1.79	1.91	0.01	0.01
$\Sigma_b^0 \pi^0$	1.82	1.94	0.01	0.01
$\Sigma_b^- \pi^+$	1.70	1.82	0.01	0.01
$\Sigma_b^{*+} \pi^-$	0.29	0.31	1.68	1.81
$\Sigma_b^{*0} \pi^0$	0.30	0.32	1.72	1.85
$\Sigma_b^{*-} \pi^+$	0.28	0.30	1.62	1.75
Total width	6.17	6.60	5.05	5.44
Experiments	$2.9 \pm 1.3 \pm 0.3$	$2.1 \pm 0.8 \pm 0.3$	$2.9 \pm 1.3 \pm 0.3$	$2.1 \pm 0.8 \pm 0.3$

increases, the total decay widths decrease in a wide parameter range, and the total decay widths remain to be several MeV. Within the reasonable range of the parameter α_ρ , our results suggest that the $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ can be clarified into the $\Lambda_b(1D)$ doublet.

The uncertainties arising from quark pair creation strength γ can be eliminated if we concentrate only on the branching ratios of $\Sigma_b \pi$ and $\Sigma_b^* \pi$ channels. Since $\Lambda_{b2}(\frac{3}{2}^+)$ and $\Lambda_{b2}(\frac{5}{2}^+)$ belong to the same $j = 2$ doublet, the heavy quark spin symmetry suggests that they may have the similar

properties, such as masses and total decay widths. The ratios between $\Sigma_b \pi$ and $\Sigma_b^* \pi$ channels decay modes may help us to distinguish these two states. For the $J^P = 3/2^+$ state, the partial decay width ratios are predicted to be

$$\Gamma[\Lambda_b(6146)^0 \rightarrow \Sigma_b \pi] : \Gamma[\Lambda_b(6146)^0 \rightarrow \Sigma_b^* \pi] = 6.14 \quad (18)$$

and

$$\Gamma[\Lambda_b(6152)^0 \rightarrow \Sigma_b \pi] : \Gamma[\Lambda_b(6152)^0 \rightarrow \Sigma_b^* \pi] = 6.07. \quad (19)$$

FIG. 2. The dependence on the harmonic oscillator parameter α_ρ of the initial states. The green bands stand for the measured total decay widths with errors.

TABLE VI. Strong decays of the $\Sigma_b(6146)$ and $\Sigma_b(6152)$ as $\Sigma_b(2S)$ and $\Sigma_b^*(2S)$ states in MeV.

Decay mode	$\Sigma_b(2S)$		$\Sigma_b^*(2S)$	
	$\Sigma_b(6146)$	$\Sigma_b(6152)$	$\Sigma_b(6146)$	$\Sigma_b(6152)$
$\Lambda_b\pi$	13.55	13.85	13.55	13.85
$\Sigma_b\pi$	9.92	10.57	2.48	2.64
$\Sigma_b^*\pi$	3.90	4.19	9.75	10.48
Total width	27.37	28.62	25.78	26.98
Experiments	$2.9 \pm 1.3 \pm 0.3$	$2.1 \pm 0.8 \pm 0.3$	$2.9 \pm 1.3 \pm 0.3$	$2.1 \pm 0.8 \pm 0.3$

TABLE VII. Strong decays of the $\Sigma_b(2S)$ and $\Sigma_b^*(2S)$ states with predicted masses.

Mode	$\Sigma_b(2S)$	$\Sigma_b^*(2S)$
$\Lambda_b\pi$	16.50	16.94
$\Sigma_b\pi$	18.29	5.03
$\Sigma_b^*\pi$	7.74	21.53
Total width	42.53	43.50

For the $J^P = 5/2^+$ state, the partial decay width ratios are predicted to be

$$\Gamma[\Lambda_b(6146)^0 \rightarrow \Sigma_b\pi] : \Gamma[\Lambda_b(6146)^0 \rightarrow \Sigma_b^*\pi] = 6 \times 10^{-3} \quad (20)$$

and

$$\Gamma[\Lambda_b(6152)^0 \rightarrow \Sigma_b\pi] : \Gamma[\Lambda_b(6152)^0 \rightarrow \Sigma_b^*\pi] = 6 \times 10^{-3}. \quad (21)$$

It can be seen that the branching ratio of the $\Sigma_b\pi$ channel is rather small for the $J^P = 5/2^+$ state, which may be hardly seen in experiments. Experimentally, $\Lambda_b(6146)^0 \rightarrow \Sigma_b^*\pi$, $\Lambda_b(6152)^0 \rightarrow \Sigma_b\pi$, and $\Lambda_b(6152)^0 \rightarrow \Sigma_b^*\pi$ processes have been clearly visible, while the $\Lambda_b(6146)^0 \rightarrow \Sigma_b\pi$ mode is no significant evidence [1]. This suggests that $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ may favor the $J^P = 5/2^+$ and $J^P = 3/2^+$ states, respectively. More information on masses, partial decay widths, and spins is needed to test our present assignments.

TABLE VIII. Decay widths of the $\Sigma_b(6146)$ and $\Sigma_b(6152)$ as $\Sigma_b(1P)$ states in MeV.

Decay mode	$\Sigma_{b0}(\frac{1}{2}^-)$		$\Sigma_{b1}(\frac{1}{2}^-)$		$\Sigma_{b1}(\frac{3}{2}^-)$		$\Sigma_{b2}(\frac{3}{2}^-)$		$\Sigma_{b2}(\frac{5}{2}^-)$	
	$\Sigma_b(6146)$	$\Sigma_b(6152)$	$\Sigma_b(6146)$	$\Sigma_b(6152)$	$\Sigma_b(6146)$	$\Sigma_b(6152)$	$\Sigma_b(6146)$	$\Sigma_b(6152)$	$\Sigma_b(6146)$	$\Sigma_b(6152)$
$\Lambda_b\pi$	247.60	245.01	...	...	...	...	19.21	20.34	19.21	20.34
$\Sigma_b\pi$	...	...	294.79	300.33	1.23	1.37	2.20	2.47	0.98	1.10
$\Sigma_b^*\pi$	...	...	1.62	1.83	274.59	281.07	1.45	1.65	2.26	2.56
Total	247.60	245.01	296.41	302.16	275.81	282.44	22.87	24.46	22.45	24.00
Experiments	2.9 ± 1.3 ± 0.3	2.1 ± 0.8 ± 0.3	2.9 ± 1.3 ± 0.3	2.1 ± 0.8 ± 0.3	2.9 ± 1.3 ± 0.3	2.1 ± 0.8 ± 0.3	2.9 ± 1.3 ± 0.3	2.1 ± 0.8 ± 0.3	2.9 ± 1.3 ± 0.3	2.1 ± 0.8 ± 0.3

C. $\Sigma_b(2S)$ states

From Table I, the predicted masses of $\Sigma_b(2S)$ and $\Sigma_b^*(2S)$ are 6213 and 6226 MeV, respectively. By assuming the two resonances are Σ_b states, the strong decays are calculated and listed in Table VI. Compared with experimental data, these assignments can be excluded.

With the predicted masses of $\Sigma_b(2S)$ and $\Sigma_b^*(2S)$, their strong decays are presented in Table VII. Our results show that the masses and total decay widths of $\Sigma_b(2S)$ and $\Sigma_b^*(2S)$ states are similar. For the $\Sigma_b(2S)$ state, the branching ratios are

$$\text{Br}(\Lambda_b\pi, \Sigma_b\pi, \Sigma_b^*\pi) = 39\%, 43\%, 18\%. \quad (22)$$

For the $\Sigma_b^*(2S)$ state, the branching ratios are

$$\text{Br}(\Lambda_b\pi, \Sigma_b\pi, \Sigma_b^*\pi) = 39\%, 12\%, 49\%. \quad (23)$$

These branching ratios are independent with the overall constant γ and can be adopted to distinguish these two states. Also, our predicted total widths of $\Sigma_b(2S)$ and $\Sigma_b^*(2S)$ states are smaller than that of Ref. [13], while the branching ratios are similar.

D. $\Sigma_b(1P)$ states

There are five λ -mode $\Sigma_b(1P)$ states, denoted as $\Sigma_{b0}(\frac{1}{2}^-)$, $\Sigma_{b1}(\frac{1}{2}^-)$, $\Sigma_{b1}(\frac{3}{2}^-)$, $\Sigma_{b2}(\frac{3}{2}^-)$, and $\Sigma_{b2}(\frac{5}{2}^-)$, respectively. The strong decays of $\Sigma_b(6146)$ and $\Sigma_b(6152)$ as these states are listed in Table VIII. It can be seen that the $\Sigma_b(6146)$ and $\Sigma_b(6152)$ as pure $\Sigma_b(1P)$ assignments can be excluded.

TABLE IX. Decay widths of the $\Sigma_b(6097)$ as $\Sigma_b(1P)$ states in MeV.

Mode	$\Sigma_{b0}(\frac{1}{2}^-)$	$\Sigma_{b1}(\frac{1}{2}^-)$	$\Sigma_{b1}(\frac{3}{2}^-)$	$\Sigma_{b2}(\frac{3}{2}^-)$	$\Sigma_{b2}(\frac{5}{2}^-)$
$\Lambda_b\pi$	261.68	...	...	11.54	11.54
$\Sigma_b\pi$	...	240.92	0.43	0.77	0.34
$\Sigma_b^*\pi$	...	0.49	214.45	0.45	0.69
Total	261.68	241.41	214.88	12.75	12.57
Experiments	$31.0 \pm 5.5 \pm 0.7$				

In the literature, the $\Sigma_b(6097)$ observed by LHCb Collaboration [47] are clarified into the $\Sigma_b(1P)$ states [13–18]. Here, we present the our calculations of $\Sigma_b(6097)$ as $\Sigma_b(1P)$ states in Table IX. Our results do not favor the $\Sigma_b(6097)$ as the pure $\Sigma_b(1P)$ states. However, the $\Sigma_b(6097)$ may correspond to the mixing state of $\Sigma_{b1}(\frac{3}{2}^-)$ and $\Sigma_{b2}(\frac{3}{2}^-)$ states.

For completeness, we investigate the possibilities of $\Sigma_b(6146)$, $\Sigma_b(6152)$, and $\Sigma_b(6097)$ as the P -wave mixing states. The physical states can be the mixing of the quark model states with the same J^P , that is,

$$\begin{pmatrix} |P1/2^-\rangle_1 \\ |P1/2^-\rangle_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} |1/2^-, j=0\rangle \\ |1/2^-, j=1\rangle \end{pmatrix}, \quad (24)$$

$$\begin{pmatrix} |P3/2^-\rangle_1 \\ |P3/2^-\rangle_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} |3/2^-, j=1\rangle \\ |3/2^-, j=2\rangle \end{pmatrix}. \quad (25)$$

In the heavy quark limit, the mixing angle should equal to zero. Given the finite mass of the bottom quark, the mixing angle may have a small divergence between the physical states and the $j-j$ coupling scheme to approximately preserve the heavy quark symmetry. The total decay widths of various assignments versus the mixing angle θ in the range -30° – 30° are plotted in Fig. 3. It is shown that the $\Sigma_b(6146)$ and $\Sigma_b(6152)$ as the $\Sigma_b(1P)$ states can be fully excluded. With the mixing angle $\theta \cong 17^\circ$, the $\Sigma_b(6097)$ can be interpreted as the $J^P = 3/2^-$ mixing state, where the $j=2$ component dominates. This assignment also agrees with other theoretical works [13–18]. The branching ratios are

$$\text{Br}(\Lambda_b\pi, \Sigma_b\pi, \Sigma_b^*\pi) = 35.0\%, 3.5\%, 61.5\%, \quad (26)$$

which are independent with the overall parameter γ and can be tested by the future experiments.

IV. SUMMARY

In this work, we study the strong decay behaviors of the newly observed two resonances $\Lambda_b(6146)^0[\Sigma_b(6146)^0]$ and $\Lambda_b(6152)^0[\Sigma_b(6152)^0]$ by the LHCb Collaboration. Given their masses and decay modes, the two resonances can be tentatively assigned as the λ -mode $\Lambda_b(2S)$, $\Lambda_b(1D)$, $\Sigma_b(2S)$, and $\Sigma_b(1P)$ states. Their strong decay behaviors are calculated with the quark pair creation model. Compared with the experimental data measured by the

FIG. 3. The total decay widths of various assignments as functions of the mixing angle θ in the range -30° – 30° . The red solid lines are the $|P3/2^-\rangle_1$ states, and the blue dashed curves correspond to the $|P3/2^-\rangle_2$ states. The green bands stand for the measured total decay widths with errors.

LHCb Collaboration, the $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ can be clarified into the $\Lambda_b(1D)$ doublet reasonably, while other canonical assignments are disfavored.

For the $J^P = 3/2^+$ state, the partial decay width ratios of $\Sigma_b\pi$ and $\Sigma_b^*\pi$ channels are about 6, while the ratios are about 6×10^{-3} for the $J^P = 5/2^+$ state. This indicates that the $\Sigma_b\pi$ channel may be hardly observed for the $J^P = 5/2^+$ state experimentally. Together with experimental decay modes, the $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ may favor the $J^P = 5/2^+$ and $J^P = 3/2^+$ states, respectively. More experimental data on masses, partial decay widths, and spins are needed to test our present assignments. Other investigations of the low-lying bottom states $\Lambda_b(2S)$, $\Sigma_b(2S)$, and $\Sigma_b(1P)$ can also provide helpful information for future experimental searches.

ACKNOWLEDGMENTS

This project is supported by the National Natural Science Foundation of China under Grants No. 11705056, No. 11775078, and No. U1832173.

- [1] R. Aaij *et al.* (LHCb Collaboration), Observation of new resonances in the $\Lambda_b^0 \pi^\pm \pi^-$ system, [arXiv:1907.13598](#).
- [2] S. Capstick and N. Isgur, Baryons in a relativized quark model with chromodynamics, *Phys. Rev. D* **34**, 2809 (1986).
- [3] D. Ebert, R. N. Faustov, and V. O. Galkin, Masses of excited heavy baryons in the relativistic quark model, *Phys. Lett. B* **659**, 612 (2008).
- [4] W. Roberts and M. Pervin, Heavy baryons in a quark model, *Int. J. Mod. Phys. A* **23**, 2817 (2008).
- [5] D. Ebert, R. N. Faustov, and V. O. Galkin, Spectroscopy and Regge trajectories of heavy baryons in the relativistic quark-diquark picture, *Phys. Rev. D* **84**, 014025 (2011).
- [6] B. Chen, K. W. Wei, and A. Zhang, Assignments of Λ_Q and Ξ_Q baryons in the heavy quark-light diquark picture, *Eur. Phys. J. A* **51**, 82 (2015).
- [7] M. Tanabashi *et al.* (Particle Data Group), Review of particle physics, *Phys. Rev. D* **98**, 030001 (2018).
- [8] H. Garcilazo, J. Vijande, and A. Valcarce, Faddeev study of heavy baryon spectroscopy, *J. Phys. G* **34**, 961 (2007).
- [9] M. Karliner and J. L. Rosner, Prospects for observing the lowest-lying odd-parity Σ_c and Σ_b baryons, *Phys. Rev. D* **92**, 074026 (2015).
- [10] Q. Mao, H. X. Chen, W. Chen, A. Hosaka, X. Liu, and S. L. Zhu, QCD sum rule calculation for P-wave bottom baryons, *Phys. Rev. D* **92**, 114007 (2015).
- [11] K. Thakkar, Z. Shah, A. K. Rai, and P. C. Vinodkumar, Excited state mass spectra and Regge trajectories of bottom Baryons, *Nucl. Phys. A* **965**, 57 (2017).
- [12] K. L. Wang, Y. X. Yao, X. H. Zhong, and Q. Zhao, Strong and radiative decays of the low-lying S- and P-wave singly heavy baryons, *Phys. Rev. D* **96**, 116016 (2017).
- [13] B. Chen and 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).
- [14] K. L. Wang, Q. F. Lü, and 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).
- [15] P. Yang, J. J. Guo, and A. Zhang, Identification of the newly observed $\Sigma_b(6097)^\pm$ baryons from their strong decays, *Phys. Rev. D* **99**, 034018 (2019).
- [16] T. M. Aliev, K. Azizi, Y. Sarac, and H. Sundu, Determination of the quantum numbers of $\Sigma_b(6097)^\pm$ via their strong decays, *Phys. Rev. D* **99**, 094003 (2019).
- [17] E. L. Cui, H. M. Yang, H. X. Chen, and 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).
- [18] D. Jia, W. N. Liu, and A. Hosaka, Regge behaviors in low-lying singly charmed and bottom baryons, [arXiv:1907.04958](#).
- [19] H. X. Chen, W. Chen, X. Liu, Y. R. Liu, and S. L. Zhu, A review of the open charm and open bottom systems, *Rep. Prog. Phys.* **80**, 076201 (2017).
- [20] V. Crede and W. Roberts, Progress towards understanding baryon resonances, *Rep. Prog. Phys.* **76**, 076301 (2013).
- [21] H. Y. Cheng, Charmed baryons circa 2015, *Front. Phys.* **10**, 101406 (2015).
- [22] J. M. Richard, The nonrelativistic three-body problem for baryons, *Phys. Rep.* **212**, 1 (1992).
- [23] E. Klempt and J. M. Richard, Baryon spectroscopy, *Rev. Mod. Phys.* **82**, 1095 (2010).
- [24] L. Micu, Decay rates of meson resonances in a quark model, *Nucl. Phys. B* **110**, 521 (1969).
- [25] A. Le Yaouanc, L. Oliver, O. Pene, and J. C. Raynal, *Hardon Transitions in the Quark Model* (Gordon and Breach, New York, 1988).
- [26] W. Roberts and B. Silberstein-Brac, General method of calculation of any hadronic decay in the 3P_0 model, *Few-Body Syst.* **11**, 171 (1992).
- [27] E. S. Ackleh, T. Barnes, and E. S. Swanson, On the mechanism of open flavor strong decays, *Phys. Rev. D* **54**, 6811 (1996).
- [28] T. Barnes, F. E. Close, P. R. Page, and E. S. Swanson, Higher quarkonia, *Phys. Rev. D* **55**, 4157 (1997).
- [29] T. Barnes, N. Black, and P. R. Page, Strong decays of strange quarkonia, *Phys. Rev. D* **68**, 054014 (2003).
- [30] C. Chen, X. L. Chen, X. Liu, W. Z. Deng, and S. L. Zhu, Strong decays of charmed baryons, *Phys. Rev. D* **75**, 094017 (2007).
- [31] Z. Zhao, D. D. Ye, and A. Zhang, Nature of charmed strange baryons $\Xi_c(3055)$ and $\Xi_c(3080)$, *Phys. Rev. D* **94**, 114020 (2016).
- [32] D. D. Ye, Z. Zhao, and A. Zhang, Study of 2S- and 1D-excitations of observed charmed strange baryons, *Phys. Rev. D* **96**, 114003 (2017).
- [33] B. Chen and X. Liu, New Ω_c^0 baryons discovered by LHCb as the members of 1P and 2S states, *Phys. Rev. D* **96**, 094015 (2017).
- [34] B. Chen, K. W. Wei, X. Liu, and T. Matsuki, Low-lying charmed and charmed-strange baryon states, *Eur. Phys. J. C* **77**, 154 (2017).
- [35] Q. F. Lü and D. M. Li, Understanding the charmed states recently observed by the LHCb and BABAR Collaborations in the quark model, *Phys. Rev. D* **90**, 054024 (2014).
- [36] Q. F. Lü, T. T. Pan, Y. Y. Wang, E. Wang, and D. M. Li, Excited bottom and bottom-strange mesons in the quark model, *Phys. Rev. D* **94**, 074012 (2016).
- [37] J. Ferretti, G. Galata, and E. Santopinto, Quark structure of the $X(3872)$ and $\chi_b(3P)$ resonances, *Phys. Rev. D* **90**, 054010 (2014).
- [38] S. Godfrey and K. Moats, Properties of excited charm and charm-strange mesons, *Phys. Rev. D* **93**, 034035 (2016).
- [39] J. Segovia, D. R. Entem, and F. Fernandez, Scaling of the 3P_0 strength in heavy meson strong decays, *Phys. Lett. B* **715**, 322 (2012).
- [40] C. Mu, X. Wang, X. L. Chen, X. Liu, and S. L. Zhu, Dipion decays of heavy baryons, *Chin. Phys. C* **38**, 113101 (2014).
- [41] Q. F. Lü, L. Y. Xiao, Z. Y. Wang, and 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).
- [42] J. J. Guo, P. Yang, and A. Zhang, Strong decays of observed Λ_c baryons in the 3P_0 model, *Phys. Rev. D* **100**, 014001 (2019).

- [43] C. Hayne and N. Isgur, Beyond the wave function at the origin: Some momentum dependent effects in the non-relativistic quark model, [Phys. Rev. D **25**, 1944 \(1982\)](#).
- [44] X. H. Zhong and Q. Zhao, Charmed baryon strong decays in a chiral quark model, [Phys. Rev. D **77**, 074008 \(2008\)](#).
- [45] S. Godfrey and N. Isgur, Mesons in a relativized quark model with chromodynamics, [Phys. Rev. D **32**, 189 \(1985\)](#).
- [46] Y. X. Yao, K. L. Wang, and X. H. Zhong, Strong and radiative decays of the low-lying D -wave singly heavy baryons, [Phys. Rev. D **98**, 076015 \(2018\)](#).
- [47] 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 \(2019\)](#).