# Toward establishing the low-lying P-wave $\Sigma_b$ states

Li-Ye Xiao[1,2,*] and Xian-Hui Zhong[2,3,†]

[1]*School of Mathematics and Physics, University of Science and Technology Beijing, Beijing 100083, China*
[2]*Department of Physics, Hunan Normal University, and Key Laboratory of Low-Dimensional*
*Quantum Structures and Quantum Control of Ministry of Education, Changsha 410081, China*
[3]*Synergetic Innovation Center for Quantum Effects and Applications (SICQEA),*
*Hunan Normal University, Changsha 410081, China*

In the present work, we analyze the $P$-wave singly heavy baryon spectrum belonging to $\mathbf{6}_F$ by combining the observations of the heavy baryon states, and restudy the strong decays of the $1P$-wave $\Sigma_b$ states within the $j$-$j$ coupling scheme using the chiral quark model. We obtain that (i) the structure $\Sigma_b(6097)$ observed in the $\Lambda_b\pi$ final state may arise from the overlapping of $\Sigma_b|J^P = \frac{3}{2}^-, 2\rangle$ and $\Sigma_b|J^P = \frac{5}{2}^-, 2\rangle$. (ii) The broad structure $\Sigma_b(6072)$ observed in the $\Lambda_b\pi\pi$ final state may arise from the overlapping of $\Sigma_b|J^P = \frac{1}{2}^-, 1\rangle$ and $\Sigma_b|J^P = \frac{3}{2}^-, 1\rangle$. (iii) The missing state $\Sigma_b|J^P = \frac{1}{2}^-, 0\rangle$ is most likely to be a narrow state with a width of $\Gamma \sim 10$ MeV, and mainly decays into the $\Lambda_b\pi$ channel.

## I. INTRODUCTION

The LHC experiments have demonstrated their discovery capability of heavy flavored baryons. During the past several years, many missing heavy baryon states have been discovered by LHC experiments. For the charmed baryon sector, in 2017 the LHCb Collaboration observed five extremely narrow $\Omega_c(X)$ states, $\Omega_c(3000)$, $\Omega_c(3050)$, $\Omega_c(3066)$, $\Omega_c(3090)$, and $\Omega_c(3119)$, in the $\Xi_c^+ K^-$ channel [1], and the first four of them were confirmed by the subsequent Belle experiments [2]. Very recently, the LHCb Collaboration observed three new states $\Xi_c(2923)^0$, $\Xi_c(2939)^0$, and $\Xi_c(2965)^0$ in the $\Lambda_c^+ K^-$ mass spectrum with a large significance [3]. For the bottom baryon sector, great progress has been achieved as well. In 2018, the LHCb Collaboration reported two new bottom baryon states $\Sigma_b(6097)^\pm$ in the $\Lambda_b^0\pi^\pm$ channels [4], and another new state $\Xi_b(6227)^-$ in both the $\Lambda_b^0 K^-$ and $\Xi_b^0\pi$ decay modes [5]. Very recently, the LHCb Collaboration observed four narrow $\Omega_b(X)$ states $\Omega_b(6316)$, $\Omega_b(6330)$, $\Omega_b(6340)$, and $\Omega_b(6350)$ [6], in the $\Xi_b^0 K^-$ final state.

These newly observed heavy baryon states may be good candidates of the $P$-wave heavy baryons belonging to the flavor sextet $\mathbf{6}_F$, when compared with the predicted masses

from virous phenomenological models and methods [7–28]. In our previous works [29–33], we discussed the quark model classifications of these newly observed resonances. Our results are summarized in Table I. It is found that a relatively complete $\lambda$-mode $P$-wave heavy baryon spectrum may have been established with discovering the series of heavy baryons.

Recently, the CMS Collaboration observed a broad enhancement around 6070 MeV in the $\Lambda_b^0\pi^+\pi^-$ invariant mass spectrum [34], which was confirmed by the subsequent LHCb experiments with high significance [35]. The mass and width for the structure are determined to be

$$M = 6072.3 \pm 2.9 \pm 0.6 \pm 0.2 \text{ MeV}, \qquad (1)$$

$$\Gamma = 72 \pm 11 \pm 2 \text{ MeV}. \qquad (2)$$

From the point of view of mass, this structure around 6070 MeV [denoted with $\Sigma_b(6072)$] may be some signals of the $P$-wave states in the $\Sigma_b$ family, although it was interpreted as the first radially excited $\Lambda_b$ state, $\Lambda_b(2S)$, in the literature [35,36]. Together with the other $P$-wave candidate $\Sigma_b(6097)$ observed in the $\Lambda_b^0\pi^\pm$ channels about two years ago at LHCb [4], the $\Sigma_b(6072)$ provide us a good chance to establish a fairly complete $P$-wave spectrum in the $\Sigma_b$ family.

In the present work we restudy the $1P$-wave $\Sigma_b$ states. We hope to understand the nature of the broad structure $\Sigma_b(6072)$ observed by the CMS Collaboration [34] and LHCb Collaboration [35]. Furthermore, by combining the newest observations of the heavy baryon states, we give our opinion for establishing a complete $P$-wave $\Sigma_b$ spectrum.

*lyxiao@ustb.edu.cn
†zhongxh@hunnu.edu.cn

TABLE I.    The quark model classifications of these newly observed resonances based on our previous works [29–33].

| $L$-$S$ scheme | $j$-$j$ scheme | Observed states and structures belonging to the $\mathbf{6}_F$ multiplet. | | | | | |
|---|---|---|---|---|---|---|---|
| $\lvert n^{2S+1}L_\lambda J^P\rangle$ | $\lvert J^P, j\rangle(nl)$ | $\Omega_c$ states | $\Xi'_c$ states | $\Sigma_c$ states | $\Omega_b$ states | $\Xi'_b$ states | $\Sigma_b$ states |
| $\lvert 1^2S_{\frac{1}{2}}^{1+}\rangle$ | $\lvert J^P=\frac{1}{2}^+,1\rangle(1S)$ | $\Omega_c(2695)$ | $\Xi'_c(2578)$ | $\Sigma_c(2455)$ | $\Omega_b(6046)$ | $\Xi'_b(5935)$ | $\Sigma_b(5810)$ |
| $\lvert 1^4S_{\frac{3}{2}}^{3+}\rangle$ | $\lvert J^P=\frac{3}{2}^+,1\rangle(1S)$ | $\Omega_c^*(2770)$ | $\Xi_c^*(2645)$ | $\Sigma_c^*(2520)$ | $\cdots$ | $\Xi_b^*(5955)$ | $\Sigma_b^*(5830)$ |
| $\lvert 1P_{\lambda\frac{1}{2}}^{1-}\rangle_1$ | $\lvert J^P=\frac{1}{2}^-,1\rangle(1P)$ | $\Omega_c(3000)$ | $\cdots$ | $\cdots$ | $\Omega_b(6316)$ | $\cdots$ | $\Sigma_b(6072)$ |
| $\lvert 1P_{\lambda\frac{1}{2}}^{1-}\rangle_2$ | $\lvert J^P=\frac{1}{2}^-,0\rangle(1P)$ | $\cdots$ | $\Xi_c(2880)$ | $\cdots$ | $\cdots$ | $\cdots$ | $\cdots$ |
| $\lvert 1^4P_{\lambda\frac{3}{2}}^{3-}\rangle$ | $\lvert J^P=\frac{3}{2}^-,1\rangle(1P)$ | $\Omega_c(3050)$ | $\Xi_c(2923)$ | $\cdots$ | $\Omega_b(6330)$ | $\cdots$ | $\Sigma_b(6072)$ |
| $\lvert 1^2P_{\lambda\frac{3}{2}}^{3-}\rangle$ | $\lvert J^P=\frac{3}{2}^-,2\rangle(1P)$ | $\Omega_c(3065)$ | $\Xi_c(2939)$ | $\Sigma_c(2800)$ | $\Omega_b(6340)$ | $\Xi'_b(6227)$ | $\Sigma_b(6097)$ |
| $\lvert 1^4P_{\lambda\frac{5}{2}}^{5-}\rangle$ | $\lvert J^P=\frac{5}{2}^-,2\rangle(1P)$ | $\Omega_c(3090)$ | $\Xi_c(2965)$ | $\Sigma_c(2800)$ | $\Omega_b(6350)$ | $\Xi'_b(6227)$ | $\Sigma_b(6097)$ |

For the three quark systems with one heavy quark ($Q$), it is convenient to introduce the Jacobi coordinates [37], $\boldsymbol{\rho}=\frac{1}{\sqrt{2}}(\mathbf{r}_1-\mathbf{r}_2)$ and $\boldsymbol{\lambda}=\frac{1}{\sqrt{6}}(\mathbf{r}_1+\mathbf{r}_2-2\mathbf{r}_3)$, respectively. $\mathbf{r}_{1,2}$ and $\mathbf{r}_3$ stand for the coordinates of the light and heavy quarks, respectively. In the simplified case of the harmonic oscillator potential, the $\boldsymbol{\rho}$ and $\boldsymbol{\lambda}$ degrees of freedom decouple, then one can obtain two kinds of oscillator excitations, i.e., $\lambda$- and $\rho$-mode excitations. The excited energy ratio between the $\lambda$- and $\rho$-mode excitations is given by [16,31]

$$\frac{\omega_\lambda}{\omega_\rho}=\sqrt{\frac{1}{3}+\frac{2m_q}{3m_Q}}<1, \tag{3}$$

where $m_q$ and $m_Q$ stand for the masses of the light and heavy quarks, respectively. From the above equation one can see that for the singly heavy baryon system the excited energy of the $\lambda$ mode should be much smaller than that of the $\rho$ mode. The $\lambda$- and $\rho$-modes are well separated for the charm and bottom baryons, because of the weak spin-dependent interaction [16]. The smaller excited energy of the $\lambda$-mode excitation indicates that the $\lambda$-mode excitations should be more easily formed than the $\rho$-mode excitations for the singly heavy baryon states [31]. Meanwhile, the observed structures around 6070 MeV are in the predicted mass region of the $\lambda$-mode $P$-wave $\Sigma_b$ states (see Table II). So, we focus on the strong decay properties of the $\lambda$-mode $P$-wave $\Sigma_b$ states in this manuscript.

This paper is organized as follows. In Sec. II we give an analysis of the $1P$-wave singly heavy baryons' spectra. We discuss the strong decay properites of the $1P$-wave $\Sigma_b$ states within the $j-j$ coupling scheme in Sec. III, and summarize our results in Sec. IV.

## II. MASS SPECTRUM ANALYSIS

In the $L-S$ coupling scheme, there are five $P$-wave states, $\lvert 1^2P_{\lambda\frac{1}{2}}^{1-}\rangle$, $\lvert 1^2P_{\lambda\frac{3}{2}}^{3-}\rangle$, $\lvert 1^4P_{\lambda\frac{1}{2}}^{1-}\rangle$, $\lvert 1^4P_{\lambda\frac{3}{2}}^{3-}\rangle$, and $\lvert 1^4P_{\lambda\frac{5}{2}}^{5-}\rangle$, for a flavor multiplet $\mathbf{6}_F$. The physical states may be closer to the $j-j$ coupling scheme due to the heavy quark symmetry. In this coupling scheme, the five $P$-wave states are denoted as $\lvert J^P=\frac{1}{2}^-,0\rangle$, $\lvert J^P=\frac{1}{2}^-,1\rangle$, $\lvert J^P=\frac{3}{2}^-,1\rangle$, $\lvert J^P=\frac{3}{2}^-,2\rangle$, and $\lvert J^P=\frac{5}{2}^-,2\rangle$. The two $J^P=1/2^-$ states $\lvert J^P=\frac{1}{2}^-,0\rangle$ and $\lvert J^P=\frac{1}{2}^-,1\rangle$ in the $j-j$ scheme are mixed states between $\lvert^2P_{1/2}\rangle$ and $\lvert^4P_{1/2}\rangle$ of the $L-S$ coupling scheme with a mixing angle $\phi\simeq 35°$. While the two $J^P=3/2^-$ states $\lvert J^P=\frac{3}{2}^-,1\rangle$ and $\lvert J^P=\frac{3}{2}^-,2\rangle$ are mixed states via a $\lvert^2P_{\lambda\frac{3}{2}}^{3-}\rangle-\lvert^4P_{\lambda\frac{3}{2}}^{3-}\rangle$ mixing with a relatively small mixing angle $\phi\simeq 24°$.

It is interesting to find that the newly observed state $\Omega_c(3000)$ at LHCb [1] may be explained as a $J^P=1/2^-$ resonance via a $\lvert^2P_{\lambda\frac{1}{2}}^{1-}\rangle-\lvert^4P_{\lambda\frac{1}{2}}^{1-}\rangle$ mixing with a mixing angle $\phi\simeq 24°$ [33], which is smaller than $35°$ from the $j-j$ coupling scheme. This indicates that the physical states of the singly heavy baryon states may be mixed states between $\lvert^2P_\lambda J^P\rangle$ and $\lvert^4P_\lambda J^P\rangle$ within the $L-S$ coupling scheme,

TABLE II.    The predicted masses (MeV) of the $\Sigma_b^+$ states within various phenomenal models and methods. $\lvert J^P, j\rangle(nl)$ denotes the state within the $j$-$j$ coupling scheme.

| $\lvert J^P, j\rangle(nl)$ | RQM [14] | hCQM [17] | RQM [18] | ChQM [19] | QM [20] | CQM [21] | CQM [22] | Observed state |
|---|---|---|---|---|---|---|---|---|
| $\lvert J^P=\frac{1}{2}^+,1\rangle(1S)$ | 5795 | 5811 | 5808 | 5812 | 5833 | 5789 | 5805 | $\Sigma_b^+$ |
| $\lvert J^P=\frac{3}{2}^+,1\rangle(1S)$ | 5805 | 5832 | 5834 | 5824 | 5858 | 5844 | 5834 | $\Sigma_b^{*+}$ |
| $\lvert J^P=\frac{1}{2}^-,1\rangle(1P)$ | 6070 | 6139 | 6101 | 6039 | 6099 | 6039 | 6122 | $\Sigma_b(6072)$ |
| $\lvert J^P=\frac{1}{2}^-,0\rangle(1P)$ | 6070 | 6148 | 6095 | 6039 | 6106 | 6142 | 6108 | $\cdots$ |
| $\lvert J^P=\frac{3}{2}^-,2\rangle(1P)$ | 6070 | 6120 | 6096 | 6039 | 6101 | 6039 | 6106 | $\Sigma_b(6097)$ |
| $\lvert J^P=\frac{3}{2}^-,1\rangle(1P)$ | 6085 | 6129 | 6087 | 6039 | 6105 | 6142 | 6076 | $\Sigma_b(6072)$ |
| $\lvert J^P=\frac{5}{2}^-,2\rangle(1P)$ | 6090 | 6104 | 6084 | 6039 | 6172 | $\cdots$ | 6083 | $\Sigma_b(6097)$ |
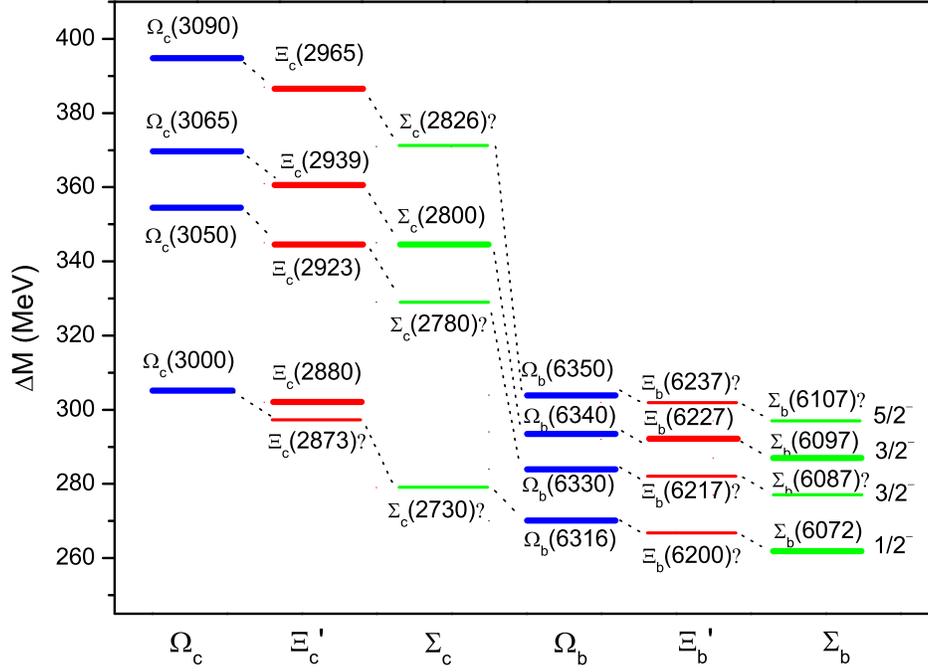
FIG. 1.    The mass splitting ($\Delta M$) between the newly observed heavy baryons and their ground states. The states labeled with a question mark are predictions in this work.

and the mixing angle approaches but is not equal to the value determined by the $j - j$ coupling scheme. The physical state for the bottom sector may be closer to the $j - j$ coupling scheme than that for the charmed sector because the bottom quark is much heavy than the charm quark.

It is difficult to predict the mass order and mass splittings in theory due to the unclear spin-dependent interactions for quarks. In fact, the mass order and mass splittings between the *P*-wave spin multiplets are crucial to determine their quantum numbers. Fortunately, the recent observations of the heavy baryons in the $\Omega_c$, $\Xi'_c$, and $\Omega_b$ families provide us important information about the mass order and mass splitting. For clarity, we further plot the mass splittings between the newly observed heavy baryons and their ground states in Fig. 1. Combining the equal spacing rule predicted in Refs. [38,39], we predict that for the charmed sector the flavor partners of the four $\Omega_c(X)$ states $\Omega_c(3000)$, $\Omega_c(3050)$, $\Omega_c(3065)$, and $\Omega_c(3090)$ are most likely to be

$$\Omega_c(3000)\colon \Xi_c(2873)?, \Sigma_c(2730)?,$$
$$\Omega_c(3050)\colon \Xi_c(2923), \Sigma_c(2780)?,$$
$$\Omega_c(3065)\colon \Xi_c(2939), \Sigma_c(2800),$$
$$\Omega_c(3090)\colon \Xi_c(2965), \Sigma_c(2826)?,$$

respectively. While for the bottom sector, the flavor partners of the four $\Omega_b(X)$ states $\Omega_b(6316)$, $\Omega_b(6330)$, $\Omega_b(6340)$, and $\Omega_b(6350)$ are predicted to be

$$\Omega_b(6316)\colon \Xi_b(6203)?, \Sigma_b(6072),$$
$$\Omega_b(6330)\colon \Xi_b(6217)?, \Sigma_b(6087)?,$$
$$\Omega_b(6340)\colon \Xi_b(6227), \Sigma_b(6097),$$
$$\Omega_b(6350)\colon \Xi_b(6237)?, \Sigma_b(6107)?,$$

respectively. The states labeled with "?" are waiting to be discovered in future experiments.

According to our previous studies in Refs. [29,33] we further find that the four $\Omega_b(6316)$, $\Omega_b(6330)$, $\Omega_b(6340)$, and $\Omega_b(6350)$ are flavor partners of the four $\Omega_c(X)$ states $\Omega_c(3000)$, $\Omega_c(3050)$, $\Omega_c(3065)$, and $\Omega_c(3090)$, respectively. They are good candidates of the *P*-wave singly heavy baryon states with spin-parity numbers $J^P = 1/2^-$, $J^P = 3/2^-$, $J^P = 3/2^-$, $J^P = 5/2^-$, respectively. The possible quark model classifications of these possible *P*-wave singly heavy baryons observed in experiments are summarized in Table I. If our assignments are correct, in the heavy quark symmetry limit, the mass order for the *P*-wave singly heavy baryon states might be

$$M(|J^P = 5/2^-, 2\rangle) > M(|J^P = 3/2^-, 2\rangle)$$
$$> M(|J^P = 3/2^-, 1\rangle) > M(|J^P = 1/2^-, 1\rangle). \quad (4)$$

Until now, we may conclude that the $\Sigma_b(6097)$ and $\Sigma_b(6072)$, as the flavor partners of $\Omega_b(6340)$ and $\Omega_b(6316)$, may favor the assignments $|J^P = \frac{3}{2}^-, 2\rangle$ and $|J^P = \frac{1}{2}^-, 1\rangle$, respectively, according to our classifications

of the newly observed $\Sigma_b(X)$ states. The other two missing $P$-wave $\Sigma_b$ states $\Sigma_b(6087)$ and $\Sigma_b(6107)$, as flavor partners of $\Omega_b(6330)$ and $\Omega_b(6350)$, may correspond to the states $|J^P = \frac{3^-}{2}, 1\rangle$ and $|J^P = \frac{5^-}{2}, 2\rangle$. Furthermore, we also should mention that the $\Sigma_b(6097)$ and $\Sigma_b(6072)$ observed in experiments may be caused by several nearby states due to a rather small mass splitting, $\sim 10$ MeV, between two nearby states. Finally, it should be pointed out that there is less knowledge about the $P$-wave state $|J^P = \frac{1^-}{2}, 0\rangle$. Only a hint comes from the recent LHCb experiments [3]. It is found a broad structure $\Xi_c(2880)$ in the $\Lambda_c^+ K^-$ mass spectrum with a small significance [3]. The $\Xi_c(2880)$ may be a candidate of the $|J^P = \frac{1^-}{2}, 0\rangle$ in the $\Xi_c'$ family. If this is confirmed by future experiments, the two $P$-wave $J^P = 1/2^-$ states $|J^P = \frac{1^-}{2}, 1\rangle$ and $|J^P = \frac{1^-}{2}, 0\rangle$ may be largely overlapping states according to the equal spacing rule [38,39].

As a whole, combining the equal spacing rule with the observations of the heavy baryon states, we can predict a fairly complete $P$-wave singly heavy baryon spectrum belonging to $\mathbf{6}_F$. These predictions may be helpful to looking for the missing state in forthcoming experiments at LHC and/or Belle II.

## III. STRONG DECAY ANALYSIS

As a possible explanation of the broad structure below 6100 MeV in the $\Lambda_b \pi \pi$ invariant mass spectrum observed by the CMS Collaboration [34] and LHCb Collaboration [35], it is crucial to re-study the strong decay properties of the low-lying $\lambda$-mode $1P$-wave $\Sigma_b$ states. In the following we will analyze the strong decays of the $P$-wave $\Sigma_b$ states with the chiral quark model. This model has been successfully applied to the strong decays of heavy-light mesons, charmed and strange baryons [33,40–48]. The model parameters have been well determined in these works. In present work, the parameters are adopted the same as those of our previous studies of the singly heavy baryons [33,40,42,43,48], where the details for the framework can be found as well.

### A. $J^P = 1/2^-$ states

In previous mass spectrum analysis, it is found that the $\Sigma_b(6072)$ may be assigned as the $J^P = 1/2^-$ states $\Sigma_b|J^P = \frac{1^-}{2}, 1\rangle$. We further test this assignment from the sector of strong decay properties.

There are two $J^P = 1/2^-$ states $\Sigma_b|J^P = \frac{1^-}{2}, 1\rangle$ and $\Sigma_b|J^P = \frac{1^-}{2}, 0\rangle$ within the $j$-$j$ coupling scheme (see Table II). They can be expressed as mixed states between $|^2P_\lambda\frac{1}{2}\rangle$ and $|^4P_\lambda\frac{1}{2}\rangle$ with the $L-S$ coupling scheme:

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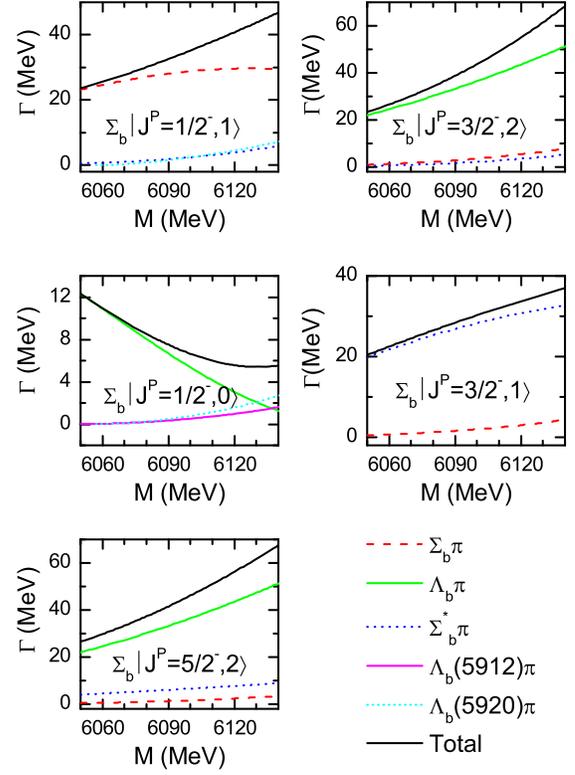


FIG. 2. The strong decay properties of the $\lambda$-mode $1P$-wave $\Sigma_b$ states as functions of the masses.

$$\left|J^P = \frac{1^-}{2}, 0\right\rangle = -\sqrt{\frac{1}{3}}\left|^2P_\lambda\frac{1^-}{2}\right\rangle + \sqrt{\frac{2}{3}}\left|^4P_\lambda\frac{1^-}{2}\right\rangle. \quad (6)$$

Their masses are predicted to about $M \simeq (6050 - 6140)$ MeV (see Table II), and their OZI-allowed two body strong decay channels are $\Sigma_b^{(*)}\pi$, $\Lambda_b\pi$, $\Lambda_b(5912)\pi$, and $\Lambda_b(5920)\pi$. To know about the effects of the uncertainties of the masses on the decay properties of the $\Sigma_b|J^P = \frac{1^-}{2}, 1\rangle$ and $\Sigma_b|J^P = \frac{1^-}{2}, 0\rangle$ states, we plot the partial decay widths as functions of the masses in the range of $M = (6050 - 6140)$ MeV in Fig. 2. From the figure, it is found that $\Sigma_b|J^P = \frac{1^-}{2}, 1\rangle$ has a total decay width of $\Gamma \sim (24 - 47)$ MeV with the mass varied in the range we considered, and dominantly decays into the $\Sigma_b\pi$ channel. Meanwhile, the $\Lambda_b\pi$ decay mode is forbidden for $\Sigma_b|J^P = \frac{1^-}{2}, 1\rangle$.

Considering the $\Sigma_b(6072)$ observed in the $\Lambda_b\pi^+\pi^-$ final state at CMS [34] and LHCb [35] as the $\Sigma_b|J^P = \frac{1^-}{2}, 1\rangle$ state, its width is predicted to be

$$\Gamma \simeq 28 \text{ MeV}. \quad (7)$$

The predicted branching fraction of the dominant decay mode $\Sigma_b\pi$ is

$$\mathcal{B}[\Sigma_b(6072) \rightarrow \Sigma_b\pi] \simeq 93\%. \quad (8)$$

TABLE III.	The decay properties of the $\lambda$-mode 1$P$-wave $\Sigma_b$ states. The units of mass and width are in MeV.

| State | Mass | $\Gamma[\Sigma_b\pi]$ | $\Gamma[\Lambda_b\pi]$ | $\Gamma[\Sigma_b^*\pi]$ | $\Gamma[\Lambda_b(5912)\pi]$ | $\Gamma[\Lambda_b(5920)\pi]$ | $\Gamma[\text{total}]$ |
|---|---|---|---|---|---|---|---|
| $\lvert J^P=\frac{1}{2}^-,1\rangle$ | 6072 | 26.2 | $\cdots$ | 1.11 | 0.42 | 0.44 | 28.2 |
| $\lvert J^P=\frac{1}{2}^-,0\rangle$ | 6072 | $\cdots$ | 9.18 | $\cdots$ | 0.12 | 0.13 | 9.43 |
| $\lvert J^P=\frac{3}{2}^-,2\rangle$ | 6097 | 3.26 | 35.2 | 1.97 | 0.50 | 0.75 | 41.7 |
| $\lvert J^P=\frac{3}{2}^-,1\rangle$ | 6087 | 1.46 | $\cdots$ | 26.4 | $\cdots$ | $\cdots$ | 27.8 |
| $\lvert J^P=\frac{5}{2}^-,2\rangle$ | 6107 | 1.84 | 38.9 | 7.00 | 0.71 | 1.12 | 49.5 |

The observed $\Lambda_b\pi\pi$ decay mode of $\Sigma_b(6072)$ can be naturally explain with the cascade decay process $\Sigma_b(6072) \to \Sigma_b\pi \to \Lambda_b\pi\pi$. The decay rates into the $\Sigma_b^*\pi$, $\Lambda_b(5912)\pi$, and $\Lambda_b(5920)\pi$ final states are small (see Table III). The predicted decay width of $\Sigma_b(6072)$ is about a factor 2 smaller than the observations from the CMS [34] and LHCb [35], which indicates that the structure $\Sigma_b(6072)^0$ observed at CMS [34] and LHCb [35] may not be well understood with the $\Sigma_b\lvert J^P=\frac{1}{2}^-,1\rangle$ state only.

The other $J^P = 1/2^-$ state $\Sigma_b\lvert J^P=\frac{1}{2}^-,0\rangle$ should be a very narrow state with a width of $\Gamma \sim (12-6)$ MeV with the mass varied in the range of $M = (6040 - 6140)$ MeV. According to our previous analysis in Sec. II, the mass of $\Sigma_b\lvert J^P=\frac{1}{2}^-,0\rangle$ may be very close to that of $\Sigma_b(6072)$. Fixing the mass of $\Sigma_b\lvert J^P=\frac{1}{2}^-,0\rangle$ at $M = 6072$ MeV, we obtain

$$\Gamma \simeq 9 \text{ MeV}, \tag{9}$$

and the $\Lambda_b\pi$ decay channel almost saturates its width (see Table III). The decay properties of this state is inconsistent with the nature of the broad structure around $M \sim 6072$ MeV in the $\Lambda_b\pi\pi$ invariant mass spectrum. The $\Sigma_b\lvert J^P=\frac{1}{2}^-,0\rangle$ may have large potentials to be observed in the $\Lambda_b\pi$ final state in forthcoming experiments. It may be a pity that the narrow state $\Sigma_b\lvert J^P=\frac{1}{2}^-,0\rangle$ was not observed in the previous LHCb experiments [4], which may be due to a too large energy scanned step, $\sim 6$ MeV, adopted in measurements.

### B. $J^P = 3/2^-$ states

In previous mass spectrum analysis, it is found that the $\Sigma_b(6097)$ may be assigned as the $J^P = 3/2^-$ states $\Sigma_b\lvert J^P=\frac{3}{2}^-,2\rangle$. We further test this assignment from the sector of strong decay properties.

In the $\Sigma_b$ family, there are two $\lambda$-mode 1$P$-wave $J^P = 3/2^-$ states $\Sigma_b\lvert J^P=\frac{3}{2}^-,2\rangle$ and $\Sigma_b\lvert J^P=\frac{3}{2}^-,1\rangle$. They can relate to the states in the $L-S$ coupling scheme:

$$\left\lvert J^P=\frac{3}{2}^-,2\right\rangle = +\sqrt{\frac{5}{6}}\left\lvert^2P_\lambda\frac{3}{2}^-\right\rangle + \sqrt{\frac{1}{6}}\left\lvert^4P_\lambda\frac{3}{2}^-\right\rangle, \tag{10}$$

$$\left\lvert J^P=\frac{3}{2}^-,1\right\rangle = -\sqrt{\frac{1}{6}}\left\lvert^2P_\lambda\frac{3}{2}^-\right\rangle + \sqrt{\frac{5}{6}}\left\lvert^4P_\lambda\frac{3}{2}^-\right\rangle. \tag{11}$$

According to the predicted masses collected in Table II, the masses of the two $J^P = 3/2^-$ states are in the region of $M \simeq (6050 - 6140)$ MeV. Considering the uncertainties of the predicted masses, we plot the variations of partial decay widths as functions of the masses of the $\Sigma_b\lvert J^P=\frac{3}{2}^-,2\rangle$ and $\Sigma_b\lvert J^P=\frac{3}{2}^-,1\rangle$ states in Fig. 2 as well. It is found that the decay properties of the two $J^P = 3/2^-$ states are sensitive to the masses. For the $\Sigma_b\lvert J^P=\frac{3}{2}^-,2\rangle$ state, the decay width is about $\Gamma \sim (23 - 68)$ MeV with the mass in the region of $M = (6050 - 6140)$ MeV, and it mainly decays into $\Lambda_b\pi$.

Considering the $\Sigma_b(6097)$ as the $\Sigma_b\lvert J^P=\frac{3}{2}^-,2\rangle$ state, we find it has a relatively broad width of (see Table III)

$$\Gamma \simeq 42 \text{ MeV}, \tag{12}$$

which is slightly larger than the observed width of $\Gamma_{\text{exp.}} \simeq 30$ MeV at LHCb [4]. Our predicted branching fraction of the dominant decay mode $\Lambda_b\pi$ is

$$\mathcal{B}[\Sigma_b(6097) \to \Lambda_b\pi] \simeq 84\%, \tag{13}$$

which is consistent with the fact that the $\Sigma_b(6097)$ resonance was first observed in the final state $\Lambda_b\pi$ [4]. Meanwhile, the decay rate of $\Sigma_b(6097)$ into $\Sigma_b\pi$ is considerable, and the predicted branching fraction is

$$\mathcal{B}[\Sigma_b(6097) \to \Sigma_b\pi] \simeq 7.8\%. \tag{14}$$

The decay mode $\Sigma_b\pi$ may be observed in future experiments. As a whole, the state $\Sigma_b(6097)$ is a good candidate of the $J^P = 3/2^-$ state $\Sigma_b\lvert J^P=\frac{3}{2}^-,2\rangle$.

For the other $J^P = 3/2^-$ state $\Sigma_b\lvert J^P=\frac{3}{2}^-,1\rangle$, the decay width is predicted to be $\Gamma \sim (20 - 37)$ MeV with the masses varied in the range what we considered in the present work, and the $\Sigma_b^*\pi$ decay channel almost saturates its total decay widths. If the $\Sigma_b(6097)$ is the $\Sigma_b\lvert J^P=\frac{3}{2}^-,2\rangle$ indeed, the mass of $\Sigma_b\lvert J^P=\frac{3}{2}^-,1\rangle$ is predicted to be 6087 MeV. Taking the mass of $\Sigma_b\lvert J^P=\frac{3}{2}^-,1\rangle$ with $M = 6087$ MeV, we obtain the decay width

$$\Gamma \simeq 28 \text{ MeV}. \tag{15}$$

The dominant decay mode is $\Sigma_b^*\pi$ with the branching fraction

$$\mathcal{B}[\Sigma_b | J^P = 3/2^-, 1\rangle \to \Sigma_b^* \pi] \simeq 95\%. \qquad (16)$$

To establish the $\Sigma_b | J^P = \frac{3}{2}^-, 1\rangle$ state, the $\Sigma_b^* \pi$ is worth to observing in future experiments. Since the $\Sigma_b^*$ dominantly decay into the $\Lambda_b \pi$ channel, thus, the $\Sigma_b | J^P = \frac{3}{2}^-, 1\rangle$ state should also have a large decay rate into the $\Lambda_b \pi \pi$ channel via the intermediate $\Sigma_b^* \pi$ process.

Considering the mass of $\Sigma_b | J^P = \frac{3}{2}^-, 1\rangle$, $M \simeq 6087$ MeV, is very close to that of the broad structure $\Sigma_b(6072)$ observed in the $\Lambda_b \pi \pi$ invariant mass spectrum [34,35], thus, we may conclude that the $\Sigma_b | J^P = \frac{3}{2}^-, 1\rangle$ state should contribute to the structure $\Sigma_b(6072)$ as well. Then, we can understand why we cannot explain width of the $\Sigma_b(6072)$ with the $\Sigma_b | J^P = \frac{3}{2}^-, 1\rangle$ state only. As a conclusion, the broad structure may be caused by two highly overlapping states $\Sigma_b | J^P = \frac{1}{2}^-, 1\rangle$ and $\Sigma_b | J^P = \frac{3}{2}^-, 1\rangle$ with dominant decay channels $\Sigma_b \pi$ and $\Sigma_b^* \pi$, respectively.

It should be pointed out that in Refs. [35,36] the $\Sigma_b(6072)$ was suggested to be the $\Lambda_b(2S)$ resonance. However, as the $\Lambda_b(2S)$ assignment, the width of $\Sigma_b(6072)$ is predicted to be very narrow ($\Gamma \sim 1$ MeV) with our chiral quark model [49]. Within the quark pair creation model, the authors in Ref. [50] obtained that the total decay widths of $\Lambda_b(2S)$ was about $\sim 12$ MeV, which was also inconsistent with the measured widths $\Gamma = 72 \pm 11 \pm 2$ from the LHCb [35].

### C. $J^P = 5/2^-$ state

There is only one $\lambda$-mode $1P$-wave $\Sigma_b$ state with $J^P = 5/2^-$, which is no difference between the $j - j$ coupling scheme and $L - S$ coupling scheme, namely,

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

The predicted mass of the state $\Sigma_b | J^P = \frac{5}{2}^-, 2\rangle$ is listed in Table II. From the table, the theoretical mass is about $M \simeq (6050 - 6140)$ MeV. The predicted mass of the $\Sigma_b | J^P = \frac{5}{2}^-, 2\rangle$ state certainly has a large uncertainty, which may bring uncertainties to the theoretical results. To investigate this effect, we plot the decay properties of this state as a function of the mass in Fig. 2 as well. Our results indicate that the total decay width of $\Sigma_b | J^P = \frac{5}{2}^-, 2\rangle$ is about $\Gamma \sim (26 - 68)$ MeV with the mass varied in the region of $M = (6050 - 6140)$ MeV, and its strong decays are governed by the $\Lambda_b \pi$ channel in the whole mass region considered in the present work.

According to our previous analysis in Sec. II, the mass of $\Sigma_b | J^P = \frac{5}{2}^-, 2\rangle$ may be 6107 MeV. Taking this mass for $\Sigma_b | J^P = \frac{5}{2}^-, 2\rangle$, we predict its width to be

$$\Gamma \simeq 50 \text{ MeV}, \qquad (18)$$

and the predicted branching ratio is

$$\mathcal{B}[\Sigma_b | J^P = 5/2^-, 2\rangle \to \Lambda_b \pi] \simeq 78\%. \qquad (19)$$

Meanwhile, the decay rate of $\Sigma_b | J^P = \frac{5}{2}^-, 2\rangle$ into $\Sigma_b^* \pi$ is considerable with the predicted branching fraction

$$\mathcal{B}[\Sigma_b | J^P = 5/2^-, 2\rangle \to \Sigma_b^* \pi] \simeq 14\%. \qquad (20)$$

We notice that the measured natures of the new peak $\Sigma_b(6097)$ observed in the $\Lambda_b \pi$ [4] are good consistent with the predicted properties of the state $\Sigma_b | J^P = \frac{5}{2}^-, 2\rangle$. Thus, the new peak $\Sigma_b(6097)$ can be explained as the $J^P = 5/2^-$ state $\Sigma_b | J^P = \frac{5}{2}^-, 2\rangle$ as well. Hence, our predictions indicate that the new peak $\Sigma_b(6097)$ has two candidates, $\Sigma_b | J^P = \frac{3}{2}^-, 2\rangle$ and $\Sigma_b | J^P = \frac{5}{2}^-, 2\rangle$. Since the similar decay properties and close masses for the two candidates, it is difficult to clearly distinguish them. Thus, the new peak $\Sigma_b(6097)$ most likely arises from the overlapping of $\Sigma_b | J^P = \frac{3}{2}^-, 2\rangle$ and $\Sigma_b | J^P = \frac{5}{2}^-, 2\rangle$.

### IV. SUMMARY

In this paper, we predict a fairly complete $P$-wave singly heavy baryon spectrum belonging to $\mathbf{6}_F$ by combining the equal spacing rule with the observations of the heavy baryon states. Further combining the mass spectrum with the strong decay properties of the $1P$-wave $\Sigma_b$ states, we give possible interpretations for the newly observed structures $\Sigma_b(6072)$ and $\Sigma_b(6097)$.

It is found that the newly observed peak $\Sigma_b(6097)$ observed in the $\Lambda_b \pi$ final state is most likely to arise from the overlapping of $\Sigma_b | J^P = \frac{3}{2}^-, 2\rangle$ and $\Sigma_b | J^P = \frac{5}{2}^-, 2\rangle$. Both $\Sigma_b | J^P = \frac{3}{2}^-, 2\rangle$ and $\Sigma_b | J^P = \frac{5}{2}^-, 2\rangle$ dominantly decay into $\Lambda_b \pi$ with a comparable width, $\Gamma \sim 50$ MeV.

The broad structure $\Sigma_b(6072)$ observed in the $\Lambda_b \pi \pi$ final state may arise from the overlapping of $\Sigma_b | J^P = \frac{1}{2}^-, 1\rangle$ and $\Sigma_b | J^P = \frac{3}{2}^-, 1\rangle$. The $\Sigma_b | J^P = \frac{1}{2}^-, 1\rangle$ and $\Sigma_b | J^P = \frac{3}{2}^-, 1\rangle$ state dominantly decay into $\Sigma_b \pi$ and $\Sigma_b^* \pi$, respectively, with a comparable width, $\Gamma \sim 30$ MeV.

The $\Sigma_b | J^P = \frac{1}{2}^-, 0\rangle$, is most likely to be a quite narrow state with a total decay width of $\Gamma \sim 10$ MeV. The $\Lambda_b \pi$ decay channel almost saturates its total decay widths. Considering the predicted width of $\Sigma_b | J^P = \frac{1}{2}^-, 0\rangle$ being narrow, this state might be observed in the $\Lambda_b \pi$ channel when enough data are accumulated in experiments.

### ACKNOWLEDGMENTS

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