Toward establishing the low-lying \( P \)-wave \( \Sigma_b \) states

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In the present work, we analyze the \( P \)-wave singly-heavy baryon spectrum belonging to \( 6_F \) 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 \( \Sigma_b(6079) \) observed in the \( \Lambda_b\pi\pi \) final state may arise from the overlapping of \( \Sigma_b(6072) \) and \( \Sigma_b(6079) \). (ii) The broad structure \( \Sigma_b(6072) \) observed in the \( \Lambda_b\pi\pi \) final state may arise from the overlapping of \( \Sigma_b(6072) \) and \( \Sigma_b(6105) \). (iii) The missing state \( \Sigma_b(6072) \) is most likely to be a narrow state with a width of \( \Gamma \sim 10 \) MeV, and mainly decays into \( \Lambda_b\pi\pi \) channel.

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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 \( \Omega_c \) states, \( \Omega_c(3000) \), \( \Omega_c(3050) \), \( \Omega_c(3066) \), \( \Omega_c(3090) \) and \( \Omega_c(3119) \), in the \( \Xi_c^0 K^+ \) 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 \( \Xi_b(2923)^0 \), \( \Xi_b(2939)^0 \), and \( \Xi_b(2965)^0 \) in the \( \Lambda_b^+ K^- \) mass spectrum with a large significance [3]. For the bottom baryon sector, a great progress has been achieved as well. In 2018, the LHCb collaboration reported two new bottom baryon states \( \Sigma_b(6097)^+ \) in the \( \Lambda_b^0 \pi^\pm \) channels [4], and another new state \( \Xi_b(6227)^- \) in both \( \Lambda_b^0 K^- \) 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 \( 6_F \), when compared with the predicted masses from various phenomenological models and methods [7–25]. In our previous works [26–30], 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 \( j-j \) 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 [31], which was confirmed by the subsequent LHCb experiments with high significance [32]. The mass and width for the structure are determined to be

\[
M = 6072.3 \pm 2.9 \pm 0.6 \pm 0.2 \text{ MeV},
\]

\[
\Gamma = 72 \pm 11 \pm 2 \text{ MeV}.
\]

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, \( \Lambda_b(25) \), in the literature [32, 33]. 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 re-study the \( 1P \) wave \( \Sigma_b \) states. We hope to understand the nature of the broad structure \( \Sigma_b(6072) \) observed by the CMS collaboration [31] and LHCb collaboration [32]. Furthermore, by combining the newest observations of the heavy baryon states, we give our opinion for establishing a complete \( P \)-wave \( \Sigma_b \) spectrum.

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 properties 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, \([|1^2P_{1/2}^+\rangle, |1^2P_{3/2}^+\rangle, |1^2P_{1/2}^-\rangle, |1^2P_{3/2}^-\rangle \) and \([|1^4P_{1/2}^+\rangle \) for a flavor multiplet \( 6_F \). The physical states may be closer to the \( j-j \) coupling scheme due to the heavy quark symmetry. In this coupling scheme, there five \( P \)-wave states are denoted as \( |J^P = 1/2^+, 0\rangle, |J^P = 1/2^-, 1\rangle, |J^P = 3/2^-, 1\rangle, |J^P = 3/2^+, 2\rangle \) and \( |J^P = 5/2^-, 2\rangle \). The two \( J^P = 1/2^- \) states \( |J^P = 1/2^-, 0\rangle \) and \( |J^P = 3/2^-, 1\rangle \) in the \( j-j \) scheme are mixed states between \([|1^2P_{1/2}^+\rangle \) and \([|1^4P_{1/2}^+\rangle \) of the \( L-S \) coupling scheme with a mixing angle \( \phi \approx 35^\circ \). While the two \( J^P = 3/2^- \) states \( |J^P = 3/2^-, 1\rangle \) and \( |J^P = 5/2^-, 2\rangle \) are mixed states via \([|1^2P_{3/2}^-\rangle \) and \([|1^4P_{3/2}^-\rangle \) mixing with a relatively small mixing angle \( \phi \approx 24^\circ \).
TABLE I: The quark model classifications of these newly observed resonances based on our previous works[26–30].

| $L-S$ scheme | $j$-scheme | Observations |
|--------------|------------|--------------|
| $|^{1}S_{\frac{1}{2}}|^1$ | $^{1}S_{1/2}$ | $\Omega_c(2770)$ $\Sigma_c(2455)$ $\Omega_b(6046)$ $\Xi_c'(5935)$ $\Sigma_b(5810)$ |
| $|^{1}S_{\frac{3}{2}}|^1$ | $^{2}S_{1/2}$ | $\Omega_c(2920)$ $\Sigma_c(2520)$ $\Omega_b(6046)$ $\Xi_c'(5935)$ $\Sigma_b(5810)$ |
| $|^{1}P_{\frac{1}{2}}|^1$ | $^{1}P_{1/2}$ | $\Omega_c(3000)$ $\Xi_c(2880)$ $\Omega_b(6316)$ $\Sigma_b(6072)$ |
| $|^{1}P_{\frac{3}{2}}|^1$ | $^{2}P_{1/2}$ | $\Omega_c(3065)$ $\Xi_c(2939)$ $\Omega_b(6340)$ $\Xi_b'(6227)$ $\Sigma_b(6097)$ |

TABLE II: The predicted masses (MeV) of the $\Sigma_c^b$ states within various phenomenological models and methods. $|^{J^P, j}(nl)|$ denotes the state within the $j$-$j$ coupling scheme.

| $|^{J^P, j}(nl)|$ | RQM [14] | hQM [17] | RQM [18] | ChQM [19] | QM [20] | CQM [21] | CQM [22] | Observed state |
|--------------|----------|---------|----------|-----------|---------|----------|----------|----------------|
| $|^{1}S_{1/2}|$ | 7595 | 5811 | 5808 | 5812 | 5833 | 5789 | 5805 | $\Sigma_c^b$ |
| $|^{1}S_{3/2}|$ | 5805 | 5832 | 5834 | 5824 | 5858 | 5844 | 5834 | $\Sigma_c^b$ |
| $|^{2}S_{1/2}|$ | 6070 | 6139 | 6101 | 6039 | 6099 | 6039 | 6122 | $\Sigma_b(6072)$ |
| $|^{2}P_{1/2}|$ | 6070 | 6148 | 6095 | 6039 | 6106 | 6142 | 6108 | $\Sigma_b(6072)$ |
| $|^{2}P_{3/2}|$ | 6070 | 6120 | 6096 | 6039 | 6091 | 6039 | 6096 | $\Sigma_b(6097)$ |
| $|^{1}S_{1/2}|$ | 6085 | 6129 | 6086 | 6039 | 6105 | 6142 | 6076 | $\Sigma_b(6072)$ |
| $|^{2}S_{3/2}|$ | 6090 | 6104 | 6084 | 6039 | 6172 | 6083 | $\Sigma_b(6097)$ |

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 $|^{2}P_{1/2}|$-$|^{2}P_{1/2}|$ mixing with a mixing angle $\phi \approx 24^\circ$ [30], which is smaller than $35^\circ$ from the $j$-$j$ coupling scheme. This may indicate that the physical states of the singly-heavy baryon states should lie between $L-S$ and $j$-$j$ coupling schemes. 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 heavier 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 Figure 1. Combining the equal spacing rule predicted in [34, 35], 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 $\Omega_b(6340)$ and $\Omega_b(6350)$ are predicted to be $\Omega_b(6316)$ : $\Xi_b(6203)$, $\Sigma_b(6072)$, $\Omega_b(6330)$ : $\Xi_b(6217)$, $\Sigma_b(6087)$, $\Omega_b(6340)$ : $\Xi_b(6227)$, $\Sigma_b(6097)$, $\Omega_b(6350)$ : $\Xi_b(6237)$, $\Sigma_b(6107)$, respectively. The states labeled with “$\nu$” are waiting to be discovered in future experiments.

According to our previous studies in Refs. [26, 30] we further find that the four $\Omega_c(6316)$, $\Omega_b(6330)$, $\Omega_b(6340)$ 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

$$M(|J^P = 5/2^-, 2|) > M(|J^P = 3/2^-, 2|)$$

$$> M(|J^P = 3/2^-, 1|) > M(|J^P = 1/2^-, 1|).$$

(3)

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 $|J^P = 3/2^-, 2|$ and $|J^P = 5/2^-, 1|$, respectively, according to our classifications of the newly observed $\Sigma_c^b(X)$ states. The other two missing $P$-wave $\Sigma_c^b$ 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 \(|J^P = \frac{1}{2}^-, 2\rangle\). Furthermore, we should also mention that the \( \Sigma_b(6097) \) and \( \Xi_b(6072) \) observed in experiments may be caused by several nearby states due to a rather small mass splitting, \( \sim 10 \text{ MeV} \), between two nearby states. Finally, it should be pointed out that there is less knowledge about the \( P \)-wave state \(|J^P = \frac{1}{2}^-\rangle, 0\rangle\). 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 \(|J^P = \frac{1}{2}^-\rangle, 0\rangle\) in the \( \Xi_c \) family. If this is confirmed by future experiments, the two \( P \)-wave \( J^P = 1/2^- \) states \(|J^P = \frac{1}{2}^-\rangle, 1\rangle\) and \(|J^P = \frac{1}{2}^-\rangle, 0\rangle\) may be largely overlapping states according to the equal spacing rule [34, 35].

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 \( 6\Sigma \). 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 [31] and LHCb collaboration [32], 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 analyse 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 [30, 36–44]. 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 [30, 36, 38, 39, 44], 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 \( \Sigma_b|J^P = \frac{1}{2}^-\rangle, 1\rangle \). We further test this assignment from the sector of strong decay properties.

There are two \( J^P = 1/2^- \) states \( \Sigma_b|J^P = \frac{1}{2}^-\rangle, 1\rangle \) and \( \Sigma_b|J^P = \frac{1}{2}^-\rangle, 0\rangle \) within the \( j-j \) coupling scheme (see Table II). They can be expressed as mixed states between \( |2P_{\frac{1}{2}^-}\rangle \) and \( |4P_{\frac{1}{2}^-}\rangle \).
The predicted branching fraction of the dominant decay mode $\Sigma_b\pi$ is

$$B(\Sigma_b(6072) \rightarrow \Sigma_b\pi) \approx 93\%.$$  

The observed $\Lambda_b\pi\pi$ decay mode of $\Sigma_b(6072)$ can be naturally explained with the cascade decay process $\Sigma_b(6072) \rightarrow \Sigma_b\pi \rightarrow \Lambda_b\pi\pi$. The decay rates into the $\Sigma_b\pi\pi$ and $\Lambda_b(5920)\pi$ final states are small (see Table III). The decay predicted width of $\Sigma_b(6072)$ is about a factor 2 smaller than the observations from the CMS [31] and LHCb [32], which indicates that the structure $\Sigma_b(6072)^0$ observed at CMS [31] and LHCb [32] may not be well understood with the $\Sigma_b|J^P = \frac{1}{2}^- , 1\rangle$ state only.

The other $J^P = 1/2^-$ state $\Sigma_b|J^P = \frac{5}{2}^- , 0\rangle$ should be a 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 $\Sigma_b|J^P = \frac{5}{2}^- , 0\rangle$ may be very close to that of $\Sigma_b(6072)$. Fixing the mass of $\Sigma_b|J^P = \frac{1}{2}^- , 0\rangle$ at $M = 6072$ MeV, we obtain

$$\Gamma \approx 9\ MeV,$$

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 $\Sigma_b|J^P = \frac{5}{2}^- , 0\rangle$ 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 $\Sigma_b|J^P = \frac{1}{2}^- , 0\rangle$ 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.

Their masses are predicted to about $M = (6050 - 6140)$ 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 $\Sigma_b|J^P = \frac{5}{2}^- , 1\rangle$ and $\Sigma_b|J^P = \frac{5}{2}^- , 0\rangle$ 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 $\Sigma_b|J^P = \frac{5}{2}^- , 1\rangle$.

Considering the $\Sigma_b(6072)$ observed in the $\Lambda_b\pi\pi^-$ final state at CMS [31] and LHCb [32] as the $\Sigma_b|J^P = \frac{5}{2}^- , 1\rangle$ state, its width is predicted to be

$$\Gamma \approx 28\ MeV.$$  

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

**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 $\Sigma_b|J^P = \frac{3}{2}^- , 2\rangle$. We further test this assignment from the sector of strong decay properties.

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

$$|J^P = \frac{3}{2}^-, 2\rangle = + \sqrt{\frac{5}{6}} \left| P_{3/2} \right\rangle + \sqrt{\frac{1}{6}} \left| S_{1/2} \right\rangle = \sqrt{\frac{5}{6}} \left| P_{3/2} \right\rangle + \sqrt{\frac{1}{6}} \left| S_{1/2} \right\rangle,$$

$$|J^P = \frac{3}{2}^-, 1\rangle = - \sqrt{\frac{1}{6}} \left| P_{3/2} \right\rangle + \sqrt{\frac{5}{6}} \left| S_{1/2} \right\rangle = - \sqrt{\frac{1}{6}} \left| P_{3/2} \right\rangle + \sqrt{\frac{5}{6}} \left| S_{1/2} \right\rangle.$$  

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

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

\[ \Gamma \approx 42 \text{ MeV}, \quad (11) \]

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

\[ \mathcal{B}[\Sigma_b(6097) \to \Lambda_b \pi] \approx 84\%, \quad (12) \]

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

\[ \mathcal{B}[\Sigma_b(6097) \to \Sigma_b \pi] \approx 7.8\%. \quad (13) \]

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 \( \Sigma_b|J^P = 3/2, 2 \rangle \).

For the other \( J^P = 3/2^- \) state \( \Sigma_b|J^P = 3/2, 1 \rangle \), the decay width is predicted to be \( \Gamma \sim (20 - 37) \) MeV with the masses varied in the whole mass range that 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 \( \Sigma_b|J^P = 3/2, 2 \rangle \) indeed, the mass of \( \Sigma_b|J^P = 3/2, 1 \rangle \) is predicted to be 6087 MeV. Taking the mass of \( \Sigma_b|J^P = 3/2, 1 \rangle \) with \( M = 6087 \) MeV, we obtain the decay width

\[ \Gamma \approx 28 \text{ MeV}. \quad (14) \]

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

\[ \mathcal{B}[\Sigma_b|J^P = 3/2, 1 \rangle \to \Sigma_b^* \pi] \approx 95\%. \quad (15) \]

To establish the \( \Sigma_b|J^P = 3/2, 1 \rangle \) 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 \( \Sigma_b|J^P = 3/2, 1 \rangle \) state should also have a large decay rate into the \( \Lambda_b \pi \) channel via the intermediate \( \Sigma_b^* \pi \) process.

Considering the mass of \( \Sigma_b|J^P = 3/2, 1 \rangle \), \( M \approx 6087 \) MeV, is very to that of the broad structure \( \Sigma_b(6072) \) observed in the \( \Lambda_b \pi \) invariant mass spectrum [31, 32], thus, we may conclude that the \( \Sigma_b|J^P = 3/2, 1 \rangle \) 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 \( \Sigma_b|J^P = 3/2, 1 \rangle \) state only. As a conclusion, the broad structure may be caused by two highly overlapping states \( \Sigma_b|J^P = 1/2^-, 1 \rangle \) and \( \Sigma_b|J^P = 3/2^-, 1 \rangle \) with dominant decay channels \( \Sigma_b \pi \) and \( \Sigma_b^* \pi \), respectively.

It should be pointed out that in Refs. [32, 33] 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 [45]. Within the quark pair creation model, the authors in Ref. [46] 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 [32].

C. \( J^P = 5/2^- \) state

There is only one \( \lambda \)-mode 1\( P \) wave \( \Sigma_b \) state with \( J^P = 5/2^- \), which is not different between the \( j-j \) coupling scheme and \( L-S \) coupling scheme, namely

\[ |J^P = 5/2^-, 2 \rangle = |PJ^P = 5/2^-, 2 \rangle. \quad (16) \]

The predicted mass of the state \( \Sigma_b|J^P = 5/2^-, 2 \rangle \) is listed in Table II. From the table, the theoretical mass are about \( M \approx (6050 - 6140) \) MeV. The predicted mass of the \( \Sigma_b|J^P = 5/2^-, 2 \rangle \) 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 \( \Sigma_b|J^P = 5/2^-, 2 \rangle \) 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 \( \Sigma_b|J^P = 5/2^-, 2 \rangle \) may be 6107 MeV. Taking this mass for \( \Sigma_b|J^P = 5/2^-, 2 \rangle \), we predict its width to be

\[ \Gamma \approx 50 \text{ MeV}, \quad (17) \]

and the predicted branching ratio is

\[ \mathcal{B}[\Sigma_b|J^P = 5/2^-, 2 \rangle \to \Lambda_b \pi] \approx 78\%. \quad (18) \]

Meanwhile, the decay rate of \( \Sigma_b|J^P = 5/2^-, 2 \rangle \) into \( \Sigma_b^* \pi \) is considerable with the predicted branching fraction

\[ \mathcal{B}[\Sigma_b|J^P = 5/2^-, 2 \rangle \to \Sigma_b^* \pi] \approx 14\%. \quad (19) \]
We notice that the measured natures of the new peak Σ_b(6097) observed in the Λ_bπ [4] are good consistent with the predicted properties of the state Σ_b|J^P = 5/2^-, 2⟩. Thus, the new peak Σ_b(6097) can be explained as the J^P = 5/2^- state Σ_b|J^P = 5/2^-, 2⟩ as well. Hence, our predictions indicate that the new peak Σ_b(6097) has two candidates, Σ_b|J^P = 5/2^-, 2⟩ and Σ_b|J^P = 5/2^-, 2⟩. Since the similar decay properties and close masses for the two candidates, it is difficult to clearly distinguish them. Thus, the new peak Σ_b(6097) most likely arises from the overlapping of Σ_b|J^P = 5/2^-, 2⟩ and Σ_b|J^P = 5/2^-, 2⟩.

IV. SUMMARY

In this paper, we predict a fairly complete P-wave singly-heavy baryon spectrum belonging to Σ_b 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 Σ_b states, we give possible interpretations for the newly observed structures Σ_b(6072) and Σ_b(6097).

It is found that the newly observed peak Σ_b(6097) observed in the Λ_bπ final state is most likely to arise from the overlapping of Σ_b|J^P = 5/2^-, 2⟩ and Σ_b|J^P = 5/2^-, 2⟩. Both Σ_b|J^P = 5/2^-, 2⟩ and Σ_b|J^P = 5/2^-, 2⟩ dominantly decay into Λ_bπ with a comparable width, Γ ∼ 50 MeV.

The broad structure Σ_b(6072) observed in the Λ_bπ final state may arise from the overlapping of Σ_b|J^P = 5/2^-, 1⟩ and Σ_b|J^P = 5/2^-, 1⟩. The Σ_b|J^P = 5/2^-, 1⟩ and Σ_b|J^P = 5/2^-, 1⟩ state dominantly decay into Σ_bπ and Σ_bπ, respectively, with a comparable width, Γ ∼ 30 MeV.

The Σ_b|J^P = 5/2^-, 0⟩, is most likely to be a quite narrow state with a total decay width of Γ ∼ 10 MeV. The Λ_bπ decay channel almost saturates its total decay widths. Considering the predicted width of Σ_b|J^P = 5/2^-, 0⟩ being narrow, this state might be observed in the Λ_bπ channel when enough data are accumulated in experiments.

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