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

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The strong decays of the low-lying $\lambda$-mode $\Lambda_b(1D,2S)$ and $\Sigma_b(2S)$ states are studied in a chiral quark model. We find that: (i) the newly observed $\Lambda_b(6146/6152)$ resonances in the $\Lambda_b\pi^+\pi^-$ spectrum by the LHCb Collaboration might be explained with the $\lambda$-mode $\Lambda_b(1D)$ states in the quark model. It should be emphasized that whether the structure in the $\Lambda_b\pi^+\pi^-$ spectrum correspond to two states or one state should be further clarified with more observations in future experiments. (ii) The $\Lambda_b(2S)$ $|J^P=\frac{1}{2}^-,0\rangle$ state mainly decays into $\Sigma_b\pi$ channel, which may be an ideal channel for searching for this $\Lambda_b(2S)$ state in future experiments. (iii) The $\Sigma_b(2S)$ $|J^P=\frac{1}{2}^+,1\rangle$ and $|J^P=\frac{3}{2}^+,1\rangle$ dominantly decay into $\Lambda_b\pi$ with $\Gamma\approx3.82$ MeV and $\Gamma\approx4.72$ MeV, respectively.

PACS numbers:

I. INTRODUCTION

Understanding the heavy baryon spectrum and searching for the missing heavy baryons and new exotic states are interesting topics in hadronic physics [1–15]. The LHC facility provides good opportunities for us to establish the heavy baryon spectra. In 2017, five extremely narrow $\Omega_b$ states, $\Omega_b(3000)$, $\Omega_b(3050)$, $\Omega_b(3066)$, $\Omega_b(3090)$, and $\Omega_b(3119)$, were observed in the $\Xi_b^+K^-$ channel by the LHCb Collaboration [1]. The measured masses and widths of the $\Lambda_b(6146)$ and $\Lambda_b(6152)$ are presented as follows,

\[ m[\Lambda_b(6146)] = 6146.17 \pm 0.33 \pm 0.22 \pm 0.16 \text{ MeV}, \]
\[ \Gamma[\Lambda_b(6146)] = 2.9 \pm 1.3 \pm 0.3 \text{ MeV}, \]
\[ m[\Lambda_b(6152)] = 6152.51 \pm 0.26 \pm 0.22 \pm 0.16 \text{ MeV}, \]
\[ \Gamma[\Lambda_b(6152)] = 2.1 \pm 0.8 \pm 0.3 \text{ MeV}. \]

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

Since the $\Lambda_b$ and $\Sigma_b$ baryons contains a heavy bottom quark and two light $u/d$ quarks, the low-lying internal excitations favor excitations of the so-called $\lambda$-mode where the orbital excitation lies between the light quarks and the heavy quark in a Jacobi coordinate. In the $\Lambda_b$ family, the ground state $\Lambda_b$, and two low-lying orbitally excited states $\Lambda_b(5912)$ $1/2^−$ and $\Lambda_b(5920)3/2^−$, have been well established [16–24]. According to the mass spectrum predicted in various models [26–30,32–34], the two newly observed resonances $\Lambda_b(6146)$ and $\Lambda_b(6152)$, lie in the mass region of the $\lambda$-mode $\Lambda_b(1D,2S)$ states and the neutral excited $\Sigma_b(2S)$ states.

To identify the $\Lambda_b(6146)$ and $\Lambda_b(6152)$ resonances in the quark model, their strong decay behaviors were studied with the $\Lambda_b(1D)$ model in Ref. [41]. The results indicated that the $\Lambda_b(6146)$ and $\Lambda_b(6152)$ can be assigned as the $\Lambda_b(1D)$ doublet with $J^P=5/2^+$ and $J^P=3/2^+$, respectively. In our previous works [21–23, 31, 32], we have studied the strong decays of the singly bottom baryons $\Sigma_b(1P)$ within the chiral quark model. We find that the $\Sigma_b(6097)$ favors the light spin $j=2$ states with spin-parity numbers $J^P=3/2^-$ or $J^P=5/2^-$. If $\Sigma_b(6097)$ corresponds to the $|J^P=\frac{3}{2}^-,2\rangle$ or $|J^P=\frac{5}{2}^-,2\rangle$ state, the typical mass for the $\Sigma_b(1P)$ states should be around 6090 MeV since the mass splitting between them is within 10 MeV according to quark model predictions [28]. Thus, one should exclude the $\Sigma_b(6146)$ and $\Sigma_b(6152)$ resonances as the $\Sigma_b(1P)$ states for the masses of $\Sigma_b(6146)$ and $\Sigma_b(6152)$ are obviously larger than the quark model predictions.

In previous works, the decays of the $P$- and $D$-wave singly heavy baryons have been studied within the chiral quark model [34–42]. Since the newly observed $\Lambda_b(6146)$ and $\Lambda_b(6152)$ resonances may favor the $D$-wave $\Lambda_b$ states, to confirm this assignment, in present work we revisit the strong decays of the $D$-wave $\Lambda_b$ states by adopting the measured masses. Moreover, the $2S$-wave $\Lambda_b$ and $\Sigma_b$ states were not investigated in the frame work of chiral quark model. Hence, in this work, as a supplement of Refs. [34–42], we employ the chiral quark model to study the strong decays with emission of one light pseudoscalar meson for the low-lying $\Lambda_b(1D,2S)$ and $\Sigma_b(2S)$ states. Combining the masses, total widths and decay modes, our results suggest that the $\Lambda_b(6146)$ and $\Lambda_b(6152)$ states may favor the $\Lambda_b(1D)$ $|J^P=\frac{5}{2}^+,2\rangle$ and

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TABLE I: Mass spectra of the $\Lambda_b$ up to $D$ wave and the $\Sigma_b$ up to $2S$ wave from various quark models \[24, 27, 28, 31, 57\] compared with the data from the Particle Data Group \[1\]. The units are in MeV.

| State       | $\Lambda_b$     | $\Sigma_b$     |
|-------------|-----------------|----------------|
| $|J^P = \frac{1}{2}^+, 0\rangle$ | 5620            | 5620           |
| $|J^P = \frac{1}{2}^+, 1\rangle$ | 5930            | 5912           |
| $|J^P = \frac{3}{2}^+, 0\rangle$ | 5942            | 5920           |
| $|J^P = \frac{3}{2}^+, 2\rangle$ | 6190            | 6147           |
| $|J^P = \frac{5}{2}^+, 2\rangle$ | 6196            | 6153           |

$|J^P = \frac{3}{2}^+, 0\rangle$ states, respectively.

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

II. SPECTROSCOPY

TABLE II: The classifications of the low-lying $1P$ and $2S$-wave states belonging to $6_F$ in the $j - j$ coupling scheme.

| $J^P, j$ | $J^P, j$ | $n_p, n_L, n_q, L_s, L, s_Q$ |
|----------|----------|-------------------------------|
| $\frac{1}{2}^+, 0$ | $\frac{1}{2}^-$ | 0 0 0 1 1 1 1 1 1 |
| $\frac{1}{2}^-, 1$ | $\frac{1}{2}^-$ | 1 0 0 1 1 1 1 1 1 |
| $\frac{3}{2}^-, 1$ | $\frac{3}{2}^-$ | 1 0 0 1 1 1 1 1 1 |
| $\frac{3}{2}^-, 2$ | $\frac{3}{2}^-$ | 2 0 0 1 1 1 1 1 1 |
| $\frac{5}{2}^-, 1$ | $\frac{5}{2}^-$ | 1 0 0 1 0 1 |
| $\frac{5}{2}^-, 1$ | $\frac{5}{2}^-$ | 1 0 0 1 0 1 |

The heavy baryon containing a heavy quark violates the SU(4) symmetry. However, the SU(3) symmetry between the other two light quarks ($u, d, or s$) is approximately kept. According to the symmetry, the heavy baryons containing a single heavy quark belong to two different SU(3) flavor representations: the symmetric sextet $6_F$ and antisymmetric antitriplet $\overline{3}_F$. In the singly bottom baryons, $\Lambda_b$ and $\Sigma_b^{0^{-}}$ belonging to $\overline{3}_F$ representation and the $\Sigma_b^{-0^{+}}, \Xi_b^{0^{-}}$ and $\Omega_b$ form a $6_F$ representation.

It should be pointed out that the quark model states that we obtain for the baryons containing a single heavy quark respect the dictates of the heavy quark effective theory (HQET). In the heavy quark effective theory description, the total angular momentum of the two light quarks $j = L + s_Q$ is conserved and coupled to the spin of a heavy quark with spin $s_Q = 1/2$ \[27\]. The total angular momentum can take the values $j = j + s_Q$. In the heavy-quark symmetry limit, the quark model states may favor the $j - j$ coupling scheme

$$|J^P, j\rangle = |l(l', L, s_Q)\rangle.$$ (5)

The $\Sigma_b$ $1P$- and $2S$-wave states belonging to $6_F$ and the $\Lambda_b$ $1P$-, $2S$- and $1D$-wave states belonging to $\overline{3}_F$ in the $j - j$ coupling scheme and their corresponding quantum numbers have been collected in Table \[II\] and \[III\].
III. STRONG DECAY

In this work, strong decays of the singly heavy baryons with emission of one light pseudoscalar meson, i.e. $\pi$, $K$ and $\eta$, are studied within chiral quark model [43]. In this model, the light pseudoscalar mesons are treated as point-like Goldstone boson. This model has been successfully applied to study the strong decays of heavy-light mesons and strange and singly heavy baryons [13, 42, 44–52]. The effective quark-pseudoscalar-meson interactions at low energies can be described by the simple chiral Lagrangian [15, 44–50]:

$$H_m = \sum_j \frac{1}{f_m} \overline{\psi}_j \gamma_\mu \gamma_5 \psi_j \phi_m,$$

where $\psi_j$ represents the $j$th quark field in the hadron; $\phi_m$ is the pseudoscalar meson field; $f_m$ is the pseudoscalar meson decay constant.

To match the nonrelativistic harmonic oscillator wave functions in this work, one should adopt the quark-pseudoscalar-meson interactions in the nonrelativistic form [15, 44–50]:

$$H_m'' = \sum_j \left[ \mathcal{G} \sigma_j \cdot q + h \sigma_j \cdot p_j \right] I_j e^{-i q \cdot r},$$

with $\mathcal{G} \equiv -(1 + \frac{\omega_n}{\omega_n})$ and $h \equiv \frac{m_j}{m}$. In the above equation, $\omega_n$ and $q$ are the energy and three momenta of the emitted light meson, respectively; $\mu_j$ stands for a reduced mass given by $1/\mu_j = 1/m_j + 1/m_j'$ with $m_j$ and $m_j'$ for the masses of the $j$th quark in the initial and final heavy hadrons, respectively; $\sigma_j$ and $p_j$ are the Pauli spin vector and internal momentum operator for the $j$th quark of the initial hadron; and $I_j$ is the isospin operator associated with the pseudoscalar meson.

For a light pseudoscalar meson emission in a strong decay process, the partial decay width can be calculated with [43, 48]

$$\Gamma_m = \left( \frac{\delta}{f_m} \right)^2 \frac{(E_f + M_f) |q|}{4 \pi M_f (2J_f + 1)} \sum_{J_f, I_f} |M_{J_f, I_f}|^2,$$

where $M_{J_f, I_f}$ corresponds to the strong amplitudes. The quantum numbers $J_{lc}$ and $J_{fz}$ stand for the third components of the total angular momenta of the initial and final heavy baryons, respectively. $M_i$ is the mass of the initial heavy baryon. $E_f$ and $M_f$ are the energy and mass of the final heavy baryon. $\delta$ as a global parameter accounts for the strength of the quark-meson couplings. It has been determined in our previous work of the strong decays of the charmed baryons and heavy-light mesons [43, 48]. Here, we fix its value the same as that in Refs. [43, 48], i.e. $\delta = 0.557$.

In the calculation, the standard quark model parameters are adopted. Namely, we set $m_u = m_d = 330$ MeV and $m_s = 5000$ MeV for the constituent quark masses. The harmonic oscillator parameter $\alpha_\rho$ in the wave function $\phi_{\rho n}^m = R_{\rho n} Y_{\ell m}$ for $uu/ud/dd$ diquark systems is taken as $\alpha_\rho = 400$ MeV. Another harmonic oscillator parameter $\alpha_\pi$ can be related to $\alpha_\rho$ with the relation $\alpha_\pi^2 = \sqrt{3} m_\pi / (2m + m_\rho) \alpha_\rho^2$. The decay constant for $\pi$ meson is taken as $f_\pi = 132$ MeV. The masses of the well-established hadrons used in the calculations are taken from the Particle Data Group (PDG) [1], and the masses of the undiscovered initial states adopt from the predictions in Refs. [25, 28].

IV. RESULTS AND DISCUSSIONS

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

A. $\Lambda_b(1D)$

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

Our calculations are presented in Table IV. The $\Lambda_b(6146)$ resonance is most likely to be the $|J^P = 5/2^+\rangle |J^P = 3/2^+\rangle$ state. Assigning the $\Lambda_b(6146)$ as $|J^P = \frac{3}{2}^+, 2\rangle$, one can find that it has a narrow width of $\sim 5$ MeV, and dominantly decays into $\Sigma_b\pi$. The partial widths into $\Sigma_b\pi$ and $\Sigma_b^*\pi$ channels are predicted to be

$$\Gamma[\Lambda_b(6146) \to \Sigma_b\pi] \approx 0.64 \text{ MeV},$$
$$\Gamma[\Lambda_b(6146) \to \Sigma_b^*\pi] \approx 4.26 \text{ MeV}.$$

Both the decay width and decay mode are consistent with the observations of $\Lambda_b(6146)$ considering the model uncertainties. This conclusion is consistent with that of the $3P_0$ model [41]. To further confirm the nature of the $\Lambda_b(6146)$ resonance, the partial width ratio between $\Sigma_b\pi$ and $\Sigma_b^*\pi$ channels,

$$\frac{\Gamma(\Sigma_b\pi)}{\Gamma(\Sigma_b^*\pi)} \approx 0.15,$$

is worth to observing in future experiments.

On the other hand, the $\Lambda_b(6152)$ resonance most likely corresponds to the $\lambda$-mode $1D$-wave $\Lambda_b$ excitation $|J^P = \frac{5}{2}^+, 2\rangle$. When we assign the $\Lambda_b(6152)$ as $|J^P = \frac{3}{2}^+, 2\rangle$, it has a narrow width of $\sim 6$ MeV, and dominantly decays into $\Sigma_b\pi$ and $\Sigma_b^*\pi$. We predicted partial widths

$$\Gamma[\Lambda_b(6152) \to \Sigma_b\pi] \approx 4.67 \text{ MeV},$$
$$\Gamma[\Lambda_b(6152) \to \Sigma_b^*\pi] \approx 1.41 \text{ MeV}.$$
which are in agreement with the the $^3P_0$ model predictions $\Gamma(\Lambda_b(6152) \to \Sigma_b\pi) \approx 5.31$ MeV and $\Gamma(\Lambda_b(6152) \to \Sigma_b\pi) \approx 0.87$ MeV [41]. The partial width ratio between $\Sigma_b\pi$ and $\Sigma_b\pi$ channels is predicted to be

$$\frac{\Gamma(\Sigma_b\pi)}{\Gamma(\Sigma_b\pi)} \approx 3.3. \tag{14}$$

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

Finally, it should be mentioned that $\Lambda_c(2860)3/2^+$ and $\Lambda_c(2880)5/2^+$ are often assigned to $1D$ doublet in the $\Lambda_c$ family [42, 53, 54]. It indicates that the mass of the $J^P = 3/2^+,D$-wave state should be smaller than that of the $J^P = 5/2^+$ state. Then, if assigning $\Lambda_b(6146)$ and $\Lambda_b(6152)$ to be $J^P = 5/2^+$ and $J^P = 3/2^+$ $D$-wave states, respectively, one should face a serious problem of mass reverse. Whether the structure in the $\Lambda_b\pi\pi$ spectrum correspond to two states or one state should be further clarified with more observations in future experiments.

**B. $\Lambda_b(2S)$**

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

In the $\Lambda_b$ family, there is only one $\Lambda_b$-mode $2S$-wave excitation $|J^P = \frac{1}{2}^+, 0\rangle$ according to the quark model classification. The mass for the $\Lambda_b$-mode $2S$-wave $\Lambda_b$ excitation is predicted to be $\sim 6.1$ GeV in various quark models (see Table I). According to the predicted masses in Ref. [57], the measured mass of the $\Lambda_b(6146)$ or $\Lambda_b(6152)$ indicates that it might be a good candidate of the $\Lambda_b$-mode $2S$-wave excitation. Considering $\Lambda_b(6146)$ or $\Lambda_b(6152)$ as the $2S$-wave state, the strong decay properties are studied, our results are listed in Table V. It is found that if assigning $\Lambda_b(6146)$ to the $2S$-wave state, both the total wave $\Gamma \approx 2$ MeV and the dominant decay mode $\Sigma_b\pi$ predicted in theory are consistent with the observations. However, the other resonance $\Lambda_b(6152)$ cannot be understood in the quark model. It cannot be assigned to any $D$-wave states in the $\Lambda_b$ family, because the mass splitting between the $2S$-wave and $D$-wave $\Lambda_b$ states is $\sim 50 – 100$ MeV. The $D$-wave $\Sigma_b$ states should be excluded as well for their typical mass is $\sim 6.3$ GeV [28, 52]. As a whole if we assign $\Lambda_b(6146)$ as the $\Lambda_b(2S)$ state, the other state $\Lambda_b(6152)$ cannot be reasonably explained according to the classification of quark models and mass splitting [37].

Since the $\Lambda_b(2S)\ |J^P = \frac{1}{2}^+, 0\rangle$ state may not favor $\Lambda_b(6146)$, in this work, we take its mass $M = 6045$ MeV as predicted in Ref. [25], and estimate the strong decay of $\Lambda_b(2S)$ into the $\Sigma_b\pi$ and $\Sigma_b\pi$ channels. It is found that $\Lambda_b(2S)$ mainly decays into $\Sigma_b\pi$ and $\Sigma_b\pi$ modes. The predicted partial widths are

$$\Gamma[\Sigma_b\pi] \approx 0.21 \text{ MeV,} \quad \Gamma[\Sigma_b\pi] \approx 0.39 \text{ MeV}, \tag{15}$$

and the corresponding total decay width reads

$$\Gamma_{total} \approx 0.6 \text{ MeV}. \tag{16}$$

The $\Sigma_b\pi$ might be an ideal channel for searching for the $\Lambda_b(2S)$-wave $\Lambda_b$ state $|J^P = \frac{1}{2}^+, 0\rangle$ in future experiments.

**C. $\Sigma_b(2S)$**

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

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

$$\Gamma[\Sigma_b(6213) \to \Lambda_b\pi\pi] \approx 3.82 \text{ MeV,} \tag{17}$$

$$\Gamma[\Sigma_b(6226) \to \Lambda_b\pi\pi] \approx 4.72 \text{ MeV.} \tag{18}$$

The $\Lambda_b\pi\pi$ might be an ideal channel to look for these radial excitations in future experiments.

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

**V. SUMMARY**

In this work, we study the strong decays of the low-lying $\Lambda_b$-mode $\Lambda_b(1D, 2S) \Sigma_b(2S)$ states. Our results indicate that the newly observed $\Lambda_b(6146)$ might be assigned as the $\Lambda_b(1D)\ |J^P = \frac{5}{2}^+, 2\rangle$ state, which dominantly decays into $\Sigma_b(2S)$ channel.
The $\Lambda_b(6152)$ seems to favor the $\Lambda_b(1D) |J^P = 4^+, 2\rangle$ states, with this assignment, its decay behaviors are dominated by the $\Sigma_b^0\pi$ and $\Sigma_b^+\pi$ channels, which are consistent with the experimental observations. However, if we assign $\Lambda_b(6146)$ and $\Lambda_b(6152)$ to the $J^P = 5/2^+$ and $J^P = 3/2^+$ $D$-wave states, respectively, one should face a serious problem of mass reverse. Whether the structure in the $\Lambda_b\pi^+\pi^-$ spectrum corresponds to two states or one state should be further clarified with more observations in future experiments. Moreover, we find that the $\Lambda_b(2S) |J^P = 1^-, 0\rangle$ state mainly decays into $\Sigma_b^0\pi$, and the $\Sigma_b(2S) |J^P = 1^+, 1\rangle$ and $|J^P = 2^+, 1\rangle$ dominantly decay into $\Lambda_b\pi$ with narrow widths $\Gamma \approx 3.82$ MeV and $\Gamma \approx 4.72$ MeV, respectively. These theoretical predictions may provide helpful information for future experimental searches.

Acknowledgments

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

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