Strong decays of the newly observed narrow Ω_b structures

Wei Liang^{1,2,3}, Qi-Fang Lü^{1,2,3,a}

¹ Department of Physics, Hunan Normal University, Changsha 410081, China

² Synergetic Innovation Center for Quantum Effects and Applications (SICQEA), Changsha 410081, China

³ Key Laboratory of Low-Dimensional Quantum Structures and Quantum Control of Ministry of Education, Changsha 410081, China

Received: 7 January 2020 / Accepted: 19 February 2020 / Published online: 3 March 2020
 © The Author(s) 2020

Abstract Motivated by the newly observed narrow structures $\Omega_b(6316)^-$, $\Omega_b(6330)^-$, $\Omega_b(6340)^-$, and $\Omega_b(6350)^-$ in the $\Xi_b^0 K^-$ mass spectrum, we investigate the strong decays of the low-lying Ω_b states within the 3P_0 model systematically. According to their masses and decay widths, the observed $\Omega_b(6316)^-$, $\Omega_b(6330)^-$, $\Omega_b(6340)^-$, and $\Omega_b(6350)^-$ resonances can be reasonably assigned as the λ -mode $\Omega_b(1P)$ states with $J^P = 1/2^-, 3/2^-, 3/2^-,$ and $5/2^-$. Meanwhile, the remaining P -wave state with $J^P = 1/2^-$ should have a rather broad width, which can hardly be observed by experiments. For the $\Omega_b(2S)$ and $\Omega_b(1D)$ states, our predictions show that these states have relatively narrow total widths and mainly decay into the $\Xi_b \bar{K}$, $\Xi_b' \bar{K}$ and $\Xi_b^{*'} \bar{K}$ final states. These abundant theoretical predictions may be valuable for searching more excited Ω_b states in future experiments.

1 Introduction

Two kinds of excitations, the ρ -mode and λ -mode, exist for the Ω_b family. The ρ -mode one is the excitation between two strange quarks, while the λ -mode case is the excitation between the strange quark subsystem and bottom quark. Such a structure is illustrated in Fig. 1. For this system, the λ -mode is more easily excited due to its heavy reduced mass. To understand the internal structures of these states and establish the low-lying Ω_b spectrum, experimental and theoretical efforts on their strong decay behaviors are urgently needed.

Although the constituent quark models have predicted plenty of heavy baryons for a long time [1–4], the experimental information on the Ω_c and Ω_b states was scarce in the past years [5]. Before 2017, there were only three Ω_c and Ω_b ground states in experiments: $\Omega_c(2695)$, $\Omega_c(2770)$ and $\Omega_b(6046)$, while the ground state Ω_b^* was missing. In 2017, the LHCb Collaboration observed five narrow resonances

$\Omega_c(3000)$, $\Omega_c(3050)$, $\Omega_c(3066)$, $\Omega_c(3090)$, and $\Omega_c(3119)$ in the $\Xi_c^+ K^-$ channel [6]. Meanwhile, the evidence of a relatively broad signal $\Omega_c(3188)$ was also reported [6]. Subsequently, the Belle Collaboration confirmed most of them except for the $\Omega_c(3119)$ structure [7].

Very recently, the LHCb Collaboration reported four narrow peaks $\Omega_b(6316)^-$, $\Omega_b(6330)^-$, $\Omega_b(6340)^-$, and $\Omega_b(6350)^-$ in the $\Xi_b^0 K^-$ mass spectrum [8]. Their measured masses and decay widths are listed as follows:

$$m[\Omega_b(6316)^-] = 6315.64 \pm 0.31 \pm 0.07 \pm 0.50 \text{ MeV}, \quad (1)$$

$$\Gamma[\Omega_b(6316)^-] < 2.8 \text{ MeV}, \quad (2)$$

$$m[\Omega_b(6330)^-] = 6330.30 \pm 0.28 \pm 0.07 \pm 0.50 \text{ MeV}, \quad (3)$$

$$\Gamma[\Omega_b(6330)^-] < 3.1 \text{ MeV}, \quad (4)$$

$$m[\Omega_b(6340)^-] = 6339.71 \pm 0.26 \pm 0.05 \pm 0.50 \text{ MeV}, \quad (5)$$

$$\Gamma[\Omega_b(6340)^-] < 1.5 \text{ MeV}, \quad (6)$$

$$m[\Omega_b(6350)^-] = 6349.88 \pm 0.35 \pm 0.05 \pm 0.50 \text{ MeV}, \quad (7)$$

$$\Gamma[\Omega_b(6350)^-] = 1.4_{-0.8}^{+1.0} \pm 0.1 \text{ MeV}, \quad (8)$$

where only the upper limits are determined for the three lower mass states. The experimental data shows that the four resonances are about $6316 \sim 6350$ MeV and their mass splittings are rather small. In the constituent quark model, the masses of excited Ω_b states can be obtained by calculating the eigenvalues of the total Hamiltonian with the QCD inspired potential, and naturally present the small mass splittings due to the small spin-orbit interaction. Compared with the masses predicted by the constituent quark models [9–17], these four resonances are good candidates of the λ -mode $\Omega_b(1P)$ states.

The observations of the low-lying Ω_c resonances have made an important progress towards a better understanding of the heavy baryon spectrum and aroused widespread interests

^a e-mail: lvqifang@hunnu.edu.cn (corresponding author)

Fig. 1 The Ω_b system with λ - or ρ -mode excitation. The s_1 and s_2 stand for the strange quarks, and b corresponds to the bottom quark

in hadron physics. Lots of conventional and exotic interpretations on these low-lying states have been done, especially for their strong decays [18–42]. However, the conclusions from various theoretical works with different models and parameters are not consistent with each other, and the spectrum of the low-lying Ω_c states have not been established so far. The situation is even worse for the low-lying Ω_b spectrum. Compared with the excited Ω_c states, the strong decays of the low-lying Ω_b states were only investigated by several works [15, 32–35, 43, 44]. Nevertheless, due to the lack of experimental information, the choices of parameters may be adjustable and indeterminate, and the predictions of these different works do not agree with each other. Hence, it is crucial to investigate the strong decays of these low-lying Ω_b baryons within the unified model and coincident parameters, which has been adopted to describe the excited $\Lambda_{c(b)}$ and $\Sigma_{c(b)}$ states successfully [45–47].

In this work, we calculate the strong decay behaviors of the low-lying Ω_b states within the 3P_0 model systematically. Our results show that the observed $\Omega_b(6316)^-$, $\Omega_b(6330)^-$, $\Omega_b(6340)^-$, and $\Omega_b(6350)^-$ resonances can be reasonably assigned as the λ -mode $\Omega_b(1P)$ states with $J^P = 1/2^-, 3/2^-, 3/2^-,$ and $5/2^-$. Meanwhile, the remaining P -wave state with $J^P = 1/2^-$ is predicted to be rather broad, which can hardly be observed by experiments. Moreover, the strong decays of the $\Omega_b(2S)$ and $\Omega_b(1D)$ states suggest that these states have relatively narrow total widths and mainly decay into the $\Xi_b \bar{K}$, $\Xi'_b \bar{K}$ and $\Xi_b^* \bar{K}$ final states. We hope these abundant theoretical predictions can provide helpful information for the future experimental searches.

This paper is organized as follows. In Sect. 2, a brief introduction of the 3P_0 model and notations are illustrated. The strong decays of the low-lying Ω_b states are presented in Sect. 3. A short summary is given in the last section.

2 3P_0 model and notations

In this work, we adopt the 3P_0 model to calculate the two-body Okubo-Zweig-Iizuka (OZI) allowed strong decays of

Fig. 2 The baryon decay process $A \rightarrow B + C$ in the 3P_0 model

the low-lying Ω_b states. In this model, a quark-antiquark pair with the quantum number $J^{PC} = 0^{++}$ is created from the vacuum, and then regroups into two outgoing hadrons by a quark rearrangement process [48]. This model has been successfully employed to study different kinds of the hadron systems for their strong decays with considerable successes [27, 45–64]. Here, we perform a brief introduction of this model. In the nonrelativistic limit, to describe the decay process $A \rightarrow BC$, the transition operator T in the 3P_0 model can be taken as

$$T = -3\gamma \sum_m \langle 1m1 - m | 00 \rangle \int d^3p_4 d^3p_5 \delta^3(\mathbf{p}_4 + \mathbf{p}_5) \times \mathcal{Y}_1^m \left(\frac{\mathbf{p}_4 - \mathbf{p}_5}{2} \right) \chi_{1,-m}^{45} \phi_0^{45} \omega_0^{45} b_{4i}^\dagger(\mathbf{p}_4) d_{4j}^\dagger(\mathbf{p}_5), \quad (9)$$

where γ is a dimensionless $q_4 \bar{q}_5$ 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 i and j are the color indices of the created quark and antiquark. $\phi_0^{45} = (u\bar{u} + d\bar{d} + s\bar{s})/\sqrt{3}$, $\omega^{45} = \delta_{ij}$, 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 $\mathcal{Y}_1^m(\mathbf{p}) \equiv |p| Y_1^m(\theta_p, \phi_p)$ is the solid harmonic polynomial reflecting the P -wave momentum-space distribution of the created quark pair.

For the strong decay of a baryon Ω_b , there are three possible rearrangements,

$$A(s_1, s_2, b_3) + P(q_4, \bar{q}_5) \rightarrow B(s_2, q_4, b_3) + C(s_1, \bar{q}_5), \quad (10)$$

$$A(s_1, s_2, b_3) + P(q_4, \bar{q}_5) \rightarrow B(s_1, q_4, b_3) + C(s_2, \bar{q}_5), \quad (11)$$

$$A(s_1, s_2, b_3) + P(q_4, \bar{q}_5) \rightarrow B(s_1, s_2, q_4) + C(b_3, \bar{q}_5). \quad (12)$$

These three ways of recouplings are also presented in Fig. 2. It should be mentioned that the first and second ones stand for the heavy baryon plus the light meson channels, while the last one denotes the light baryon plus the heavy meson decay mode.

The S matrix can be written as

$$\langle f | S | i \rangle = I - i2\pi \delta(E_f - E_i) \mathcal{M}^{M_{JA} M_{JB} M_{JC}}, \quad (13)$$

where the $\mathcal{M}^{M_{JA} M_{JB} M_{JC}}$ is the helicity amplitude of the decay process $A \rightarrow B + C$. The explicit expression of the

helicity amplitude $\mathcal{M}^{M_{JA} M_{JB} M_{JC}}$ can be found in Refs. [45–47, 54].

In this work, we adopt the simplest vertex which assumes a spatially constant pair production strength γ , the relativistic phase space, and the simple harmonic oscillator wave functions [48]. Then, the decay width $\Gamma(A \rightarrow BC)$ is calculated directly

$$\Gamma = \pi^2 \frac{p}{M_A^2} \frac{1}{2J_A + 1} \sum_{M_{JA}, M_{JB}, M_{JC}} \left| \mathcal{M}^{M_{JA} M_{JB} M_{JC}} \right|^2, \quad (14)$$

where $p = |\mathbf{p}| = \frac{\sqrt{[M_A^2 - (M_B + M_C)^2][M_A^2 - (M_B - M_C)^2]}}{2M_A}$, and M_A , M_B , and M_C are the masses of the hadrons A , B , and C , respectively.

For the $\Omega_b(1P)$ states, we employ the masses of four newly observed structures from LHCb experimental data by assuming that they are possible candidates. For the masses of the $\Omega_b(2S)$ and $\Omega_b(1D)$ states, we adopt the theoretical predictions in the relativistic quark model [9] which are listed in Table 1. For the final ground states, their masses are taken from the Review of Particle Physics [5]. For the harmonic oscillator parameters of mesons, we use the effective values as in Ref. [61]. For the baryon parameters, we use $\alpha_\rho = 440$ 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 [20, 45–47, 65]. The $m_{u/d} = 220$ MeV, $m_s = 419$ MeV, $m_c = 1628$ MeV and $m_b = 4977$ MeV are introduced to consider the mass differences of the heavy and light quarks [61, 66, 67].

The overall parameter γ is determined by the well established $\Sigma_c(2520)^{++} \rightarrow \Lambda_c \pi^+$ process. Then, the $\gamma = 9.83$ is obtained by reproducing the width $\Gamma[\Sigma_c(2520)^{++} \rightarrow \Lambda_c \pi^+] = 14.78$ MeV [5, 45]. Certainly, it should be checked whether a different parameter γ for the bottom sector should be adopted or not. In Ref. [46], we have calculated the decay behaviors of the ground states in bottom sector using $\gamma = 9.83$ compared with the experimental data, which show that the parameter γ taken from the charm sector can describe the bottom states well. If we fit the parameter γ from these bottom states, a nearly identical value will be obtained. To reduce the model parameter, we prefer to use an overall parameter γ from charm to bottom sector, which do not affect all the conclusions in present calculations. In the heavy quark limit, the decay behaviors should only depend on the light systems. Due to the finite mass of charm and bottom quarks, the heavy flavor symmetry should also be preserved approximately, which may result in the nearly identical quark pair creation strength γ for charm and bottom sectors.

3 Strong decay

3.1 $\Omega_b(1P)$ states

There are five λ -mode $\Omega_b(1P)$ states in the constituent quark model, which are denoted as $\Omega_{b0}(\frac{1}{2}^-)$, $\Omega_{b1}(\frac{1}{2}^-)$, $\Omega_{b1}(\frac{3}{2}^-)$, $\Omega_{b2}(\frac{3}{2}^-)$ and $\Omega_{b2}(\frac{5}{2}^-)$, respectively. From Table 1, the predicted masses of the five $\Omega_b(1P)$ states are around 6330 ~ 6340 MeV. As mentioned in the Introduction, four narrow structures $\Omega_b(6316)^-$, $\Omega_b(6330)^-$, $\Omega_b(6340)^-$, and $\Omega_b(6350)^-$ have been observed in the $\Xi_b^0 K^-$ mass spectrum. Given the uncertainties of quark model prediction, these structures are good candidates of the $\Omega_b(1P)$ states. With these experimental masses, all possibilities of these four observed resonances as the $\Omega_b(1P)$ states are considered and the total decay widths are listed in the Table 2. For the $j = 0$ state, the total decay width is predicted to be rather large, while for the two $j = 1$ states, their OZI-allowed strong decays are forbidden due to the quantum number conservation and the phase space constraint. For the two $j = 2$ states, the total decay widths are about several MeV, which may correspond to the experimental observations. Moreover, the decay widths for these excited $\Omega_b(1P)$ states with different quantum numbers show large discrepancy. In the 3P_0 model,

Table 1 Notations, quantum numbers and masses of initial baryons. The n_ρ and L_ρ denote the nodal quantum number and orbital angular momentum between the two strange quarks, respectively. The n_λ and L_λ represent the nodal quantum number and orbital angular momentum between the bottom quark and strange quark system. The S_ρ stands for the total spin of the two strange quarks, L is the total orbital angular momentum, j represent total angular momentum of L and S_ρ , J is the total angular momentum, and P is the parity. The masses are taken from the theoretical predictions from relativistic quark model [9]. The units are in MeV

State	j	J^P	L	n_ρ	n_λ	L_ρ	L_λ	S_ρ	Mass
$\Omega_b(2S)$	1	$\frac{1}{2}^+$	0	0	1	0	0	1	6450
$\Omega_b^*(2S)$	1	$\frac{3}{2}^+$	0	0	1	0	0	1	6461
$\Omega_{b0}(\frac{1}{2}^-)$	0	$\frac{1}{2}^-$	1	0	0	0	1	1	6339
$\Omega_{b1}(\frac{1}{2}^-)$	1	$\frac{1}{2}^-$	1	0	0	0	1	1	6330
$\Omega_{b1}(\frac{3}{2}^-)$	1	$\frac{3}{2}^-$	1	0	0	0	1	1	6340
$\Omega_{b2}(\frac{3}{2}^-)$	2	$\frac{3}{2}^-$	1	0	0	0	1	1	6331
$\Omega_{b2}(\frac{5}{2}^-)$	2	$\frac{5}{2}^-$	1	0	0	0	1	1	6334
$\Omega_{b1}(\frac{1}{2}^+)$	1	$\frac{1}{2}^+$	2	0	0	0	2	1	6540
$\Omega_{b1}(\frac{3}{2}^+)$	1	$\frac{3}{2}^+$	2	0	0	0	2	1	6549
$\Omega_{b2}(\frac{3}{2}^+)$	2	$\frac{3}{2}^+$	2	0	0	0	2	1	6530
$\Omega_{b2}(\frac{5}{2}^+)$	2	$\frac{5}{2}^+$	2	0	0	0	2	1	6529
$\Omega_{b3}(\frac{5}{2}^+)$	3	$\frac{5}{2}^+$	2	0	0	0	2	1	6520
$\Omega_{b3}(\frac{7}{2}^+)$	3	$\frac{7}{2}^+$	2	0	0	0	2	1	6517

Table 2 The decay widths of the four observed resonances as the $\Omega_b(1P)$ states in MeV

	$\Omega_{b0}(\frac{1}{2}^-, 1P)$	$\Omega_{b1}(\frac{1}{2}^-, 1P)$	$\Omega_{b1}(\frac{3}{2}^-, 1P)$	$\Omega_{b2}(\frac{3}{2}^-, 1P)$	$\Omega_{b2}(\frac{5}{2}^-, 1P)$	Experiments
$\Omega_b(6316)$	870.52	—	—	0.35	0.35	< 2.8
$\Omega_b(6330)$	1056.79	—	—	1.08	1.08	< 3.1
$\Omega_b(6340)$	1146.35	—	—	1.85	1.85	< 1.5
$\Omega_b(6350)$	1224.29	—	—	2.98	2.98	$1.4^{+1.0}_{-0.8} \pm 0.1$

the formula of decay widths can be divided into the phase factors and amplitudes. Since the masses and final states of these resonances are similar, the phase factors are almost the same. More precisely, the amplitudes include color parts, flavor parts, Clebsch-Gordan coefficients, and spatial overlaps [46, 54]. For the excited $\Omega_b(1P)$ states, these five states have different quantum numbers, and the difference of the decay widths arises from Clebsch-Gordan coefficients of the spin and orbital angular momentum couplings. It can be seen that the pure $\Omega_b(1P)$ assignments can hardly interpret these four resonances simultaneously.

In fact, the physical resonances can be the mixing of the quark model states with the same J^P , that is

$$\begin{pmatrix} |1P \ 1/2^-\rangle_1 \\ |1P \ 1/2^-\rangle_2 \end{pmatrix} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} |1/2^-, j=0\rangle \\ |1/2^-, j=1\rangle \end{pmatrix}, \quad (16)$$

$$\begin{pmatrix} |1P \ 3/2^-\rangle_1 \\ |1P \ 3/2^-\rangle_2 \end{pmatrix} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} |3/2^-, j=1\rangle \\ |3/2^-, j=2\rangle \end{pmatrix}. \quad (17)$$

Under the heavy quark limit, the mixing angle should equals to zero. Given the finite mass of the bottom quark, the heavy quark symmetry should be approximately preserved, and the mixing angle between the physical states and the quark model states can have a small divergence with the $j-j$ coupling scheme. The total decay widths of various assignments versus the mixing angle θ in the range $-30^\circ \sim 30^\circ$ are plotted in Fig. 3.

With the similar masses and total widths, the strong decays of the four resonances are all consistent with the experimental data under the $J^P = 1/2^-$ and $J^P = 3/2^-$ assignments. However, only three states $|1P \ 1/2^-\rangle_2$, $|1P \ 3/2^-\rangle_1$, and $|1P \ 3/2^-\rangle_2$ belong to the narrow resonances, while the $|1P \ 1/2^-\rangle_1$ state is too large to be occupied. Fortunately, there is also a $J^P = 5/2^-$ state, which is suitable for all four resonances. Hence, four narrow structures $\Omega_b(6316)^-$, $\Omega_b(6330)^-$, $\Omega_b(6340)^-$, and $\Omega_b(6350)^-$ can be clarified into the $|1P \ 1/2^-\rangle_2$, $|1P \ 3/2^-\rangle_1$, $|1P \ 3/2^-\rangle_2$, and $|1P \ 5/2^-\rangle$ states. However, from current experimental information, we can hardly provide the exact correspondence between the physical resonances and theoretical states.

The predicted total decay width of the $|1P \ 1/2^-\rangle_1$ state is rather large, which can be hardly observed experimentally.

Fig. 3 The total decay widths of various assignments as functions of the mixing angle θ in the range $-30^\circ \sim 30^\circ$. The red solid lines are the $|1P \ 1/2^-\rangle_1$ and $|1P \ 3/2^-\rangle_1$ states, and the blue dashed curves correspond to the $|1P \ 1/2^-\rangle_2$ and $|1P \ 3/2^-\rangle_2$ states. The green bands stand for the measured total decay widths with errors

This explains why the LHCb experiment only observed four peaks in the $\Xi_b^0 K^-$ mass spectrum. Our present results are consistent with the previous chiral quark model calculations

Fig. 4 The allowed mixing angle θ under the assignment of the $\Omega_b(6316)^-$ as $J^P = 1/2^-$ state. The red solid line is the $|1P\ 1/2^->_1$ state, and the blue dashed curve corresponds to the $|1P\ 1/2^->_2$ state. The green band stands for the measured total decay width with error

under the $j-j$ coupling scheme [43]. In Ref. [15], the authors predicted one narrow $j = 0$ state, two OZI-forbidden $j = 1$ states, and two narrow $j = 2$ states with the $j-j$ couplings. If the mixing mechanism was considered, the authors could also perform four narrow $\Omega_b(1P)$ states which agree with our present calculations except for the $j = 0$ state. Moreover, based on the $L-S$ couplings, the authors predicted five narrow $\Omega_b(1P)$ states within the 3P_0 model [35], and three narrow states within the chiral quark model [32], which show different features with our results. Present experiment data suggests that the physical states of these P -wave Ω_b baryons more favor the $j-j$ coupling scheme.

Also, one can determine the mixing angle θ of the two $J^P = 1/2^-$ states. If we choose the normal mass order for the $\Omega_b(1P)$ states, the mixing angle θ can be constrained by the width of $\Omega_b(6316)^-$ resonance. From Fig. 4, one can see that the mixing angle θ should lie in $-3.3^\circ \sim 3.3^\circ$ except for zero. When the mixing angle equals to zero, the $|1P\ 1/2^->_2$ state corresponds to the $\Omega_{b1}(\frac{1}{2}^-)$, which cannot decay into the $\Xi_b \bar{K}$ channel. Thanks to the finite mass of bottom quark, the small mixing between two $J^P = 1/2^-$ states can occur, and the narrow one can be observed in the $\Xi_b \bar{K}$ final state experimentally. For the two $J^P = 3/2^-$ states, the mixing angle cannot be determined by current experimental data. More theoretical and experimental efforts are needed to solve this problem.

Furthermore, the dependence on the harmonic oscillator parameter α_ρ for the pure $J^P = 5/2^-$ state is also investigated. With the normal mass order for the $\Omega_b(1P)$ states, the $\Omega_b(6350)$ should be assigned as the pure $J^P = 5/2^-$ state. The result is presented in Fig. 5. When the α_ρ varies from 420 to 460 MeV, the decay width of $\Omega_b(6350)$ with $J^P = 5/2^-$ lie in the range $2.55 \sim 3.47$ MeV. Compared with the predicted central value 2.98 MeV, the uncertainty

Fig. 5 The dependence of the decay width on the harmonic oscillator parameter α_ρ for the $J^P = 5/2^-$ state

Table 3 Decay widths of the $\Omega_b(2S)$ states in MeV

Mode	$\Omega_b(2S)$	$\Omega_b^*(2S)$
$\Xi_b^0 K^-$	23.76	25.47
$\Xi_b^- \bar{K}^0$	22.56	24.32
$\Xi_b^{*0} K^-$	1.87	0.86
$\Xi_b^{*-} \bar{K}^0$	1.40	0.72
$\Xi_b^{*+0} K^-$	0.08	1.39
$\Xi_b^{*+-} \bar{K}^0$	—	0.56
Total width	49.67	53.32

of the predicted width is about 16%, which show relatively stable prediction.

3.2 $\Omega_b(2S)$ states

In the traditional quark model, there are two λ -mode $2S$ -wave excitations, which are denoted as $\Omega_b(2S)$ and $\Omega_b^*(2S)$. From Table 1, the predicted masses of these two $\Omega_b(2S)$ states are 6450 MeV and 6461 MeV, respectively. With the calculated masses, their strong decays within the 3P_0 model are estimated and shown in Table 3.

The total decay width of the $J^P = 1/2^+$ state is about 50 MeV and the dominating decay mode is $\Xi_b \bar{K}$. The branching ratios are predicted to be

$$Br(\Xi_b^0 K^-, \Xi_b^- \bar{K}^0) \sim 48\%, 45\%. \quad (18)$$

For the $J^P = 3/2^+$ state, the total width is predicted to be 53 MeV and the $\Xi_b \bar{K}$ channel also dominates. The branching ratios of the dominating channels $\Xi_b^0 \bar{K}^0$ and $\Xi_b^+ K^-$ are

$$Br(\Xi_b^0 K^-, \Xi_b^- \bar{K}^0) \sim 48\%, 46\%. \quad (19)$$

Fig. 6 The dependence of the decay widths on the harmonic oscillator parameter α_ρ for the two $\Omega_b(2S)$ states

In Fig. 6, we perform the dependence on the harmonic oscillator parameter α_ρ for these two $\Omega_b(2S)$ states. It can be seen that the total and partial decay widths are almost unchanged with the α_ρ variation. Within this reasonable range of the parameter α_ρ , all conclusions remain. The total decay widths of our predictions are larger than that of the potential model, but the main decay mode is consistent with each other [15]. With the relatively narrow total widths and dominating decay mode $\Xi_b \bar{K}$, these two $\Omega_b(2S)$ states have good potentials to be observed in the $\Xi_b \bar{K}$ mass spectrum in future experiments.

3.3 $\Omega_b(1D)$ states

From Table 1, the masses of the six $\Omega_b(1D)$ states are predicted to be around 6517 ~ 6549 MeV. The strong decay widths for these D -wave states are estimated and presented in Table 4. It can be seen that the total decay widths of $\Omega_{b1}(\frac{1}{2}^+)$, $\Omega_{b1}(\frac{3}{2}^+)$, $\Omega_{b2}(\frac{3}{2}^+)$, $\Omega_{b2}(\frac{5}{2}^+)$, $\Omega_{b3}(\frac{5}{2}^+)$ and $\Omega_{b3}(\frac{7}{2}^+)$ states are about 106, 108, 27, 21, 3, and 3 MeV, respectively. For the two $j = 1$ states, the dominating decay mode is $\Xi_b \bar{K}$, while other decay channels are rela-

Table 4 Decay widths of the $\Omega_b(1D)$ states in MeV

Mode	$\Omega_{b1}(\frac{1}{2}^+)$	$\Omega_{b1}(\frac{3}{2}^+)$	$\Omega_{b2}(\frac{3}{2}^+)$	$\Omega_{b2}(\frac{5}{2}^+)$	$\Omega_{b3}(\frac{5}{2}^+)$	$\Omega_{b3}(\frac{7}{2}^+)$
$\Xi_b^0 K^-$	45.29	46.45	—	—	1.54	1.46
$\Xi_b^- \bar{K}^0$	44.37	45.61	—	—	1.36	1.29
$\Xi_b'^0 K^-$	5.99	1.66	11.87	0.03	0.03	0.01
$\Xi_b'^- \bar{K}^0$	5.79	1.61	11.40	0.03	0.02	0.01
$\Xi_b'^* K^-$	2.38	6.75	1.86	10.82	0.02	0.02
$\Xi_b'^* \bar{K}^0$	2.17	6.22	1.67	9.70	0.01	0.01
Total width	105.99	108.30	26.80	20.58	2.98	2.80

tively small. For the two $j = 2$ states, the $\Xi_b^0 K^-$ and $\Xi_b^- \bar{K}^0$ final states are forbidden due to the quantum number conservation, and the main decay modes for the $\Omega_{b2}(\frac{3}{2}^+)$ and $\Omega_{b2}(\frac{5}{2}^+)$ states are $\Xi_b' \bar{K}$ and $\Xi_b'^* \bar{K}$, respectively. To distinguish these two $j = 2$ states, the partial decay ratios between $\Xi_b \bar{K}$ and $\Xi_b' \bar{K}$ modes are helpful. For the two $j = 3$ states, the calculated decay widths are about several MeV, which are quite narrow. The main decay mode is $\Xi_b \bar{K}$ with the branching ratio up to 97.3% and 98.2% for the $J^P = 5/2^+$ and $J^P = 7/2^+$ states, respectively. Moreover, the uncertainties raising from the parameter α_ρ for the pure $J^P = 1/2^+$ and $7/2^+$ states are studied. From Fig. 7, one can see that our results are relatively stable when the parameter α_ρ varies in a reasonable range.

Within the chiral quark model and the $L - S$ scheme, the authors predicted that the total decay widths of these six states lie in 7 ~ 29 MeV [34], which show different features with ours. Also, our predictions on these D -wave Ω_b states are quite different with the potential model calculations, where six $\Omega_b(1D)$ states all have widths of several MeV [44]. Future experimental searches can help us to clarify these theoretical divergences.

4 Summary

In this work, we study the strong decay behaviors of the low-lying λ -mode Ω_b states within the 3P_0 model systematically. According to the masses and decay modes, four newly observed Ω_b resonances can be reasonably interpreted. It is found that the $\Omega_b(6316)^-$, $\Omega_b(6330)^-$, $\Omega_b(6340)^-$, and $\Omega_b(6350)^-$ can be assigned as the λ -mode $\Omega_b(1P)$ states with $J^P = 1/2^-, 3/2^-, 3/2^-,$ and $5/2^-$. Meanwhile, the remaining P -wave state with $J^P = 1/2^-$ should have a rather broad width, which can hardly be observed by experiments. For the $\Omega_b(2S)$ and $\Omega_b(1D)$ states, our predictions suggest that these states have relatively narrow total widths and mainly decay into the $\Xi_b \bar{K}$, $\Xi_b' \bar{K}$ and $\Xi_b'^* \bar{K}$ final

Fig. 7 The dependence of the decay widths on the harmonic oscillator parameter α_ρ for the pure $J^P = 1/2^+$ and $7/2^+$ states

states. We hope these theoretical calculations are valuable for searching more excited Ω_b states in future experiments.

Acknowledgements We would like to thank Xian-Hui Zhong and Long-Cheng Gui for valuable discussions. This project is supported by the National Natural Science Foundation of China under Grants No. 11705056, No. 11775078, and No. U1832173.

Data Availability Statement This manuscript has no associated data or the data will not be deposited. [Authors' comment: This work is theoretical, and the results have been presented in our paper. Hence, there is no more data to be deposited elsewhere.]

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

Funded by SCOAP³.

References

1. H.X. Chen, W. Chen, X. Liu, Y.R. Liu, S.L. Zhu, A review of the open charm and open bottom systems. Rep. Prog. Phys. **80**, 076201 (2017)
2. H.Y. Cheng, Charmed baryons circa 2015. Front. Phys. (Beijing) **10**, 101406 (2015)
3. V. Crede, W. Roberts, Progress towards understanding baryon resonances. Rep. Prog. Phys. **76**, 076301 (2013)
4. E. Klempt, J.M. Richard, Baryon spectroscopy. Rev. Mod. Phys. **82**, 1095 (2010)
5. M. Tanabashi et al., Particle Data Group. Phys. Rev. D **98**, 030001 (2018)
6. R. Aaij et al., (LHCb Collaboration), Observation of five new narrow Ω_c^0 states decaying to $\Xi_c^+ K^-$. Phys. Rev. Lett. **118**, 182001 (2017)
7. J. Yelton et al., (Belle Collaboration), Observation of Excited Ω_c Charmed Baryons in e^+e^- Collisions. Phys. Rev. D **97**, 051102 (2018)
8. R. Aaij et al., (LHCb Collaboration), First observation of excited Ω_b^- states, [arXiv:2001.00851](https://arxiv.org/abs/2001.00851)
9. D. Ebert, R.N. Faustov, V.O. Galkin, Spectroscopy and Regge trajectories of heavy baryons in the relativistic quark-diquark picture. Phys. Rev. D **84**, 014025 (2011)
10. W. Roberts, M. Pervin, Heavy baryons in a quark model. Int. J. Mod. Phys. A **23**, 2817 (2008)
11. D. Ebert, R.N. Faustov, V.O. Galkin, Masses of excited heavy baryons in the relativistic quark model. Phys. Lett. B **659**, 612 (2008)
12. H. Garcilazo, J. Vijande, A. Valcarce, Faddeev study of heavy baryon spectroscopy. J. Phys. G **34**, 961 (2007)
13. T. Yoshida, E. Hiyama, A. Hosaka, M. Oka, K. Sadato, Spectrum of heavy baryons in the quark model. Phys. Rev. D **92**, 114029 (2015)
14. K. Thakkar, Z. Shah, A.K. Rai, P.C. Vinodkumar, Excited state mass spectra and regge trajectories of bottom baryons. Nucl. Phys. A **965**, 57 (2017)
15. B. Chen, 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)
16. Z. Shah, A.K. Rai, Mass spectra of singly beauty Ω_b^- Baryon. Few Body Syst. **59**, 112 (2018)
17. S.X. Qin, C.D. Roberts, S.M. Schmidt, Spectrum of light- and heavy-baryons. Few Body Syst. **60**, 26 (2019)
18. H.X. Chen, Q. Mao, W. Chen, A. Hosaka, X. Liu, S.L. Zhu, Decay properties of P -wave charmed baryons from light-cone QCD sum rules. Phys. Rev. D **95**, 094008 (2017)
19. M. Karliner, J.L. Rosner, Very narrow excited Ω_c baryons. Phys. Rev. D **95**, 114012 (2017)
20. K.L. Wang, L.Y. Xiao, X.H. Zhong, Q. Zhao, Understanding the newly observed Ω_c states through their decays. Phys. Rev. D **95**, 116010 (2017)
21. W. Wang, R.L. Zhu, Interpretation of the newly observed Ω_c^0 resonances. Phys. Rev. D **96**, 014024 (2017)
22. M. Padmanath, N. Mathur, Quantum numbers of recently discovered Ω_c^0 Baryons from lattice QCD. Phys. Rev. Lett. **119**, 042001 (2017)
23. H.Y. Cheng, C.W. Chiang, Quantum numbers of Ω_c states and other charmed baryons. Phys. Rev. D **95**, 094018 (2017)
24. H. Huang, J. Ping, F. Wang, Investigating the excited Ω_c^0 states through $\Xi_c K$ and $\Xi_c' K$ decay channels. Phys. Rev. D **97**, 034027 (2018)
25. Z.G. Wang, Analysis of $\Omega_c(3000)$, $\Omega_c(3050)$, $\Omega_c(3066)$, $\Omega_c(3090)$ and $\Omega_c(3119)$ with QCD sum rules. Eur. Phys. J. C **77**, 325 (2017)

26. Z. Zhao, D.D. Ye, A. Zhang, Hadronic decay properties of newly observed Ω_c baryons. *Phys. Rev. D* **95**, 114024 (2017)
27. B. Chen, X. Liu, New Ω_c^0 baryons discovered by LHCb as the members of $1P$ and $2S$ states. *Phys. Rev. D* **96**, 094015 (2017)
28. H.C. Kim, M.V. Polyakov, M. Praszalowicz, Possibility of the existence of charmed exotica. *Phys. Rev. D* **96**, 014009 (2017)
29. S.S. Agaev, K. Azizi, H. Sundu, Interpretation of the new Ω_c^0 states via their mass and width. *Eur. Phys. J. C* **77**, 395 (2017)
30. Z.G. Wang, X.N. Wei, Z.H. Yan, Revisit assignments of the new excited Ω_c states with QCD sum rules. *Eur. Phys. J. C* **77**, 832 (2017)
31. V.R. Debastiani, J.M. Dias, W.H. Liang, E. Oset, Molecular Ω_c states generated from coupled meson-baryon channels. *Phys. Rev. D* **97**, 094035 (2018)
32. K.L. Wang, Y.X. Yao, X.H. Zhong, Q. Zhao, Strong and radiative decays of the low-lying S - and P -wave singly heavy baryons. *Phys. Rev. D* **96**, 116016 (2017)
33. S.S. Agaev, K. Azizi, H. Sundu, *Phys. Rev. D* **96**, 094011 (2017)
34. Y.X. Yao, K.L. Wang, X.H. Zhong, Strong and radiative decays of the low-lying D -wave singly heavy baryons. *Phys. Rev. D* **98**, 076015 (2018)
35. E. Santopinto, A. Giachino, J. Ferretti, H. Garcia-Tecocoatz, M.A. Bedolla, R. Bijker, E. Ortiz-Pacheco, The Ω_c -puzzle solved by means of spectrum and strong decay amplitude predictions. *Eur. Phys. J. C* **79**, 1012 (2019)
36. G. Yang, J. Ping, Dynamical study of Ω_c^0 in the chiral quark model. *Phys. Rev. D* **97**, 034023 (2018)
37. C.S. An, H. Chen, Observed Ω_c^0 resonances as pentaquark states. *Phys. Rev. D* **96**, 034012 (2017)
38. G. Montaña, A. Feijoo, A. Ramos, A meson-baryon molecular interpretation for some Ω_c excited states. *Eur. Phys. J. A* **54**, 64 (2018)
39. C. Wang, L.L. Liu, X.W. Kang, X.H. Guo, R.W. Wang, Possible open-charmed pentaquark molecule $\Omega_c(3188)$ - the $D\Xi$ bound state - in the Bethe-Salpeter formalism. *Eur. Phys. J. C* **78**, 407 (2018)
40. Y. Huang, C.J. Xiao, Q.F. Lü, R. Wang, J. He, L. Geng, Strong and radiative decays of $D\Xi$ molecular state and newly observed Ω_c states. *Phys. Rev. D* **97**, 094013 (2018)
41. V.R. Debastiani, J.M. Dias, W.H. Liang, E. Oset, $\Omega_b^- \rightarrow (\Xi_c^+ K^-) \pi^-$ and the Ω_c states. *Phys. Rev. D* **98**, 094022 (2018)
42. Z.G. Wang, J.X. Zhang, Possible pentaquark candidates: new excited Ω_c states. *Eur. Phys. J. C* **78**, 503 (2018)
43. K.L. Wang, Q.F. Lü, 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)
44. B. Chen, S.Q. Luo, X. Liu, T. Matsuki, Interpretation of the observed $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ states as $1D$ bottom baryons. *Phys. Rev. D* **100**, 094032 (2019)
45. Q.F. Lü, L.Y. Xiao, Z.Y. Wang, 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)
46. W. Liang, Q.F. Lü, X.H. Zhong, Canonical interpretation of the newly observed $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ via strong decay behaviors. *Phys. Rev. D* **100**, 054013 (2019)
47. Q.F. Lü, X.H. Zhong, Strong decays of the higher excited Λ_Q and Σ_Q baryons. *Phys. Rev. D* **101**, 014017 (2020)
48. L. Micu, Decay rates of meson resonances in a quark model. *Nucl. Phys. B* **10**, 521 (1969)
49. A. Le Yaouanc, L. Oliver, O. Pene, J.C. Raynal, *Hardon Transitions in the quark model* (Gordon and Breach, New York, 1988)
50. W. Roberts, B. Silvestr-Brac, General method of calculation of any hadronic decay in the 3P_0 model. *Few-Body Syst.* **11**, 171 (1992)
51. E.S. Ackleh, T. Barnes, E.S. Swanson, On the mechanism of open flavor strong decays. *Phys. Rev. D* **54**, 6811 (1996)
52. T. Barnes, F.E. Close, P.R. Page, E.S. Swanson, Higher quarkonia. *Phys. Rev. D* **55**, 4157 (1997)
53. T. Barnes, N. Black, P.R. Page, Strong decays of strange quarkonia. *Phys. Rev. D* **68**, 054014 (2003)
54. C. Chen, X.L. Chen, X. Liu, W.Z. Deng, S.L. Zhu, Strong decays of charmed baryons. *Phys. Rev. D* **75**, 094017 (2007)
55. Z. Zhao, D.D. Ye, A. Zhang, Nature of charmed strange baryons $\Xi_c(3055)$ and $\Xi_c(3080)$. *Phys. Rev. D* **94**, 114020 (2016)
56. D.D. Ye, Z. Zhao, A. Zhang, Study of $2S$ - and $1D$ - excitations of observed charmed strange baryons. *Phys. Rev. D* **96**, 114003 (2017)
57. B. Chen, K.W. Wei, X. Liu, T. Matsuki, Low-lying charmed and charmed-strange baryon states. *Eur. Phys. J. C* **77**, 154 (2017)
58. Q.F. Lü, 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)
59. Q.F. Lü, T.T. Pan, Y.Y. Wang, E. Wang, D.M. Li, Excited bottom and bottom-strange mesons in the quark model. *Phys. Rev. D* **94**, 074012 (2016)
60. J. Ferretti, G. Galata, E. Santopinto, Quark structure of the $X(3872)$ and $\chi_b(3P)$ resonances. *Phys. Rev. D* **90**, 054010 (2014)
61. S. Godfrey, K. Moats, Properties of excited charm and charm-strange mesons. *Phys. Rev. D* **93**, 034035 (2016)
62. J. Segovia, D.R. Entem, F. Fernandez, Scaling of the 3P_0 strength in heavy meson strong decays. *Phys. Lett. B* **715**, 322 (2012)
63. C. Mu, X. Wang, X.L. Chen, X. Liu, S.L. Zhu, Dipion decays of heavy baryons. *Chin. Phys. C* **38**, 113101 (2014)
64. J.J. Guo, P. Yang, A. Zhang, Strong decays of observed Λ_c baryons in the 3P_0 model. *Phys. Rev. D* **100**, 014001 (2019)
65. X.H. Zhong, Q. Zhao, Charmed baryon strong decays in a chiral quark model. *Phys. Rev. D* **77**, 074008 (2008)
66. S. Godfrey, N. Isgur, Mesons in a relativized quark model with chromodynamics. *Phys. Rev. D* **32**, 189 (1985)
67. S. Capstick, N. Isgur, Baryons in a relativized quark model with chromodynamics. *Phys. Rev. D* **34**, 2809 (1986)