Possible interpretation of the newly observed Ω_b states

Li-Ye Xiao^{1,a}, Kai-Lei Wang^{2,b}, Ming-Sheng Liu^{3,4,c}, Xian-Hui Zhong^{3,4,d}

¹ School of Mathematics and Physics, University of Science and Technology Beijing, Beijing 100083, China

² Department of Electronic Information and Physics, Changzhi University, Changzhi 046011, Shanxi, China

³ Department of Physics, Hunan Normal University, and Key Laboratory of Low-Dimensional Quantum Structures and Quantum Control of Ministry of Education, Changsha 410081, China

⁴ Synergetic Innovation Center for Quantum Effects and Applications (SICQEA), Hunan Normal University, Changsha 410081, China

Received: 20 January 2020 / Accepted: 10 March 2020 / Published online: 27 March 2020
© The Author(s) 2020

Abstract Inspired by the newly observed Ω_b states by the LHCb Collaboration, we investigate the two-body strong decays of the low-lying λ -mode Ω_b baryons up to $N = 2$ shell using the chiral quark model within the j - j coupling scheme. Our results indicate that: (i) the newly observed states $\Omega_b(6316)^-$ and $\Omega_b(6330)^-$ are good candidates of the light spin $j = 1$ states, while the spin-parity $J^P = 1/2^-$ and $J^P = 3/2^-$ cannot be distinguished. The other two states, $\Omega_b(6340)$ and $\Omega_b(6350)$ mostly correspond to the light spin $j = 2$ states, while the spin-parity $J^P = 3/2^-$ and $J^P = 5/2^-$ cannot be distinguished as well. (ii) The $2S$ states with spin-parity $J^P = 1/2^+$ and $J^P = 3/2^+$, respectively, might be narrow states with a width of $\Gamma < 2$ MeV. (iii) The $1D$ states are not broad and the total decay widths vary from several to dozens of MeV, which have a good potential to be observed in future experiments.

1 Introduction

Since the heavy quark provides a “flavour tag” that may give insight into the systematics of hadron resonances and the mechanism of confinement, the studies of hadrons containing heavy quarks (c or b) are important topics in hadron physics. It is evident that heavy-quark hadrons play an important role in our understanding of QCD. Since the first observation of the beauty baryon Λ_b at the CERN $p\bar{p}$ collider [1], many singly heavy baryons were observed by various world wide experimental facilities in the past three decades [2]. In recent years, there have been specially fruitful in the observation of the heavy baryon states [3–9]. The rapidly growth of the

experimental progress attracts a great deal of attention from the hadron physics community.

Very recently, in the $\Xi_b^0 K^-$ mass spectrum obtained using pp collisions the LHCb Collaboration reported four narrow peaks [10],

$$m[\Omega_b(6316)^-] = 6315.64 \pm 0.31 \pm 0.07 \pm 0.50 \text{ MeV},$$
$$\Gamma[\Omega_b(6316)^-] < 2.8(4.2) \text{ MeV}, \quad (1)$$

$$m[\Omega_b(6330)^-] = 6330.30 \pm 0.28 \pm 0.07 \pm 0.50 \text{ MeV},$$
$$\Gamma[\Omega_b(6330)^-] < 3.1(4.7) \text{ MeV}, \quad (2)$$

$$m[\Omega_b(6340)^-] = 6339.71 \pm 0.26 \pm 0.05 \pm 0.50 \text{ MeV},$$
$$\Gamma[\Omega_b(6340)^-] < 1.5(1.8) \text{ MeV}, \quad (3)$$

$$m[\Omega_b(6350)^-] = 6349.88 \pm 0.35 \pm 0.05 \pm 0.50 \text{ MeV},$$
$$\Gamma[\Omega_b(6350)^-] < 2.8(3.2) \text{ MeV}, \quad (4)$$

where the uncertainties are statistical, systematic and the limited knowledge of the Ξ_b^0 mass, respectively. The natural widths Γ correspond to 90% (95%) confidence level upper limits.

Before the LHCb’s measurement [10], there exist many theoretical calculations of the mass spectrum of the excited Ω_b states with various quark models [11–18], Regge phenomenology [19], QCD two-point sum rule method [20, 21], molecular model [22], etc. We collect the theoretical predictions in Table 1. From the table, the four peaks observed by the LHCb Collaboration [10] are in the predicted mass region of the $1P$ wave excitations [11–14, 16–18]. In addition, the possibility as $2S$ excitations cannot be excluded absolutely based simply on the predicted masses [15, 17]. There are also some discussions of the strong decay properties of the excited Ω_b^- states. In the framework of the QCD sum rule method [23], the $1P$ - and $2S$ -wave states with spin-1/2 and spin-3/2 are predicted to be narrow resonances. Within an harmonic oscillator based model, the authors in Ref. [14] obtained that the $1P$ -wave states should be narrow resonances as well.

^a e-mail: lyxiao@ustb.edu.cn (corresponding author)

^b e-mail: wangkaileicz@foxmail.com

^c e-mail: liumingsheng0001@126.com

^d e-mail: zhongxh@hunnu.edu.cn

Table 1 The predicted masses (MeV) of the Ω_b^- states within various phenomenal models and methods. $|J^P, j\rangle (nl)$ denotes the state within the j - j coupling scheme

$ ^{2S+1}L_J\rangle(NL)$	NRQM [11]	hCQM [12]	RQM [13]	QM [14]	ChQM [15]	QM [16]	CQM [17]	CQM [18]	Exp [2]
$ J^P = \frac{1}{2}^+, 1\rangle(1S)$	6076	6048	6064	6061 ± 15	6045	6081	6037	6065	6046
$ J^P = \frac{3}{2}^+, 1\rangle(1S)$	6094	6086	6088	6082 ± 20	6045	6102	6090	6088	
$ J^P = \frac{1}{2}^-, 0\rangle(1P)$	6333	6338	6339	6305 ± 15	6288	6301	6278	6352	
$ J^P = \frac{1}{2}^-, 1\rangle(1P)$	6340	6343	6330	6317 ± 19	6288	6312	6373	6361	
$ J^P = \frac{3}{2}^-, 1\rangle(1P)$	6336	6328	6340	6313 ± 15	6288	6304	6278	6330	
$ J^P = \frac{3}{2}^-, 2\rangle(1P)$	6344	6333	6331	6325 ± 19	6288	6311	6373	6351	
$ J^P = \frac{5}{2}^-, 2\rangle(1P)$	6345	6320	6334	6338 ± 20	6288	6311	...	6336	
$ J^P = \frac{1}{2}^+, 1\rangle(2S)$	6517	6455	6450	...	6384	6472	6367	6440	
$ J^P = \frac{3}{2}^+, 1\rangle(2S)$	6528	6481	6461	...	6384	6478	6398	6450	
$ J^P = \frac{1}{2}^+, 1\rangle(1D)$	6561	6601	6540	...	...	...	...	6526	
$ J^P = \frac{3}{2}^+, 1\rangle(1D)$	6559	6583	6549	...	...	...	...	6518	
$ J^P = \frac{3}{2}^+, 2\rangle(1D)$	6559	6589	6530	...	...	...	...	6520	
$ J^P = \frac{5}{2}^+, 2\rangle(1D)$	6561	6567	6529	...	...	6492	...	6512	
$ J^P = \frac{5}{2}^+, 3\rangle(1D)$	6566	6573	6520	...	...	6494	...	6490	
$ J^P = \frac{7}{2}^+, 3\rangle(1D)$	...	6553	6517	...	...	6497	...	6502	

With a chiral quark model our group predicted that in the L - S coupling scheme the $1P$ -wave states with spin-parity $J^P = 3/2^-$ and $J^P = 5/2^-$ should be narrow states with a width of a few MeV, while two $J^P = 1/2^-$ $1P$ -wave states $|^2P_{1/2}\rangle$ and $|^4P_{1/2}\rangle$ are most likely to be broad states with a width of $\Gamma \sim (50\text{--}100)$ MeV [24]; however, in the j - j coupling scheme only the $j = 0$ P -wave state with $J^P = 1/2^-$ is a broad state, the other four $1P$ -wave states should be narrow states [25]. Recently, Liang et al. [26] assigned the observed four peaks as the $1P$ wave states within the quark pair creation model. The similar results were obtained in Refs. [27, 28]. In addition, inspired by the LHCb's measurement [10], the possible interpretations of the peaks in the higher energy as the meson-baryon molecular states were presented as well in Ref. [29].

We notice that for the singly heavy flavour quark systems, proper consideration of the heavy quark symmetry is necessary, thus, the states may more favor the j - j coupling scheme. With this coupling scheme, we have studied the strong decays of the $1P$ -wave singly bottom heavy baryons in our previous work [25]. In the present work, we further conduct a systematical study of the strong decay properties of the low-lying λ -mode Ω_b states in the j - j coupling scheme, and attempt to decode the inner structures of the four peaks observed by the LHCb Collaboration [10]. Our theoretical results suggest that both the $\Omega_b(6316)^-$ and $\Omega_b(6330)^-$ are good candidates of the light spin $j = 1$ states, while the spin-parity $J^P = 1/2^-$ and $J^P = 3/2^-$ cannot be distinguished due to the limited data. The other two states, $\Omega_b(6340)^-$ and $\Omega_b(6350)^-$ are

good candidates of the light spin $j = 2$ states, while the spin-parity $J^P = 3/2^-$ and $J^P = 5/2^-$ cannot be distinguished as well. In addition, we notice that the light spin $j = 0$ states with the spin-parity $J^P = 1/2^-$ are most likely to be a moderate state with a width of $\Gamma \sim 100$ MeV, and the $\Xi_b K$ decay channel almost saturates its total decay widths. For the $2S$ -wave Ω_b states with $J^P = 1/2^+$ and $J^P = 3/2^+$, they might be narrow states with a width of $\Gamma < 2$ MeV. We notice that the $1D$ states are not broad and the total decay widths vary from several to dozens of MeV, which have a good potential to be observed in future experiments.

This paper is organized as follows. In Sect. II we give a brief introduction of the strong decay model and the relationship of the singly-heavy baryon spectrum between the j - j coupling scheme and the L - S coupling scheme. We discuss the strong decays of the low-lying $1P$ -, $2S$ -, and $1D$ -wave Ω_b states within the j - j coupling scheme in Sect. III and summarize our results in Sect. IV.

2 The model

In this work we study the strong decay properties with the chiral quark model. This model has been successfully applied to study the strong decays of baryons and heavy-light mesons [24, 25, 30–42]. In the chiral quark model, the effective low energy quark-pseudoscalar-meson coupling in the SU(3) flavor basis at tree level is described by [43]

$$H_m = \sum_j \frac{1}{f_m} \bar{\psi}_j \gamma_\mu^j \gamma_5^j \psi_j \vec{\tau} \cdot \partial^\mu \vec{\phi}_m, \quad (5)$$

where ψ_j corresponds to the j th quark field in a baryon. f_m stands for the pseudoscalar meson decay constant. ϕ_m denotes the pseudoscalar meson octet.

To match the nonrelativistic harmonic oscillator spatial wave function $N\Psi_{LL_z}$ in the calculations, we adopt a nonrelativistic form of the quark-pseudoscalar coupling and obtain [44–46]

$$H_m^{nr} = \sum_j \left\{ \frac{\omega_m}{E_f + M_f} \sigma_j \cdot \mathbf{p}_f + \frac{\omega_m}{E_i + M_i} \sigma_j \cdot \mathbf{p}_i - \sigma_j \cdot \mathbf{q} + \frac{\omega_m}{2\mu_q} \sigma_j \cdot \mathbf{p}_j' \right\} I_j e^{-i\mathbf{q} \cdot \mathbf{r}_j}, \quad (6)$$

where $(E_i, M_i, \mathbf{p}_i)$ and $(E_f, M_f, \mathbf{p}_f)$ represent the energy, mass and three-vector momentum of the initial and final baryon, respectively. $(\omega_m, \mathbf{q})$ are the energy and three-vector momentum of the final light pseudoscalar meson. $\mathbf{p}_j' = \mathbf{p}_j - (m_j/M)\mathbf{P}_{c.m.}$ is the internal momentum of the j th quark in the baryon rest frame. μ_q stands for a reduced mass expressed as $1/\mu_q = 1/m_j + 1/m_j'$, and σ_j denotes the Pauli spin vector on the j th quark. The isospin operator I_j associated with K meson is given by

$$I_j = \begin{cases} a_j^\dagger(u)a_j(s) & \text{for } K^-, \\ a_j^\dagger(d)a_j(s) & \text{for } \bar{K}^0. \end{cases} \quad (7)$$

Here, $a_j^\dagger(u, d)$ and $a_j(s)$ are the creation and annihilation operator for the u , d and s quarks on j th quark.

Then the partial decay width for the emission of a light pseudoscalar meson is

$$\Gamma = \left(\frac{\delta}{f_m} \right)^2 \frac{(E_f + M_f)|\mathbf{q}|}{4\pi M_i} \frac{1}{2J_i + 1} \sum_{J_{iz} J_{fz}} |\mathcal{M}_{J_{iz}, J_{fz}}|^2, \quad (8)$$

where J_{iz} and J_{fz} are the third components of the total angular momenta of the initial and final baryons, respectively. δ denotes a global parameter accounting for the strength of the quark-meson couplings. $\mathcal{M}_{J_{iz}, J_{fz}}$ stands for the transition amplitude.

According to our previous works [25, 30] together with the nature of the newly observed four peaks [10], the physical states of the singly heavy baryons seem more favor the j - j coupling scheme. Thus, in the present work we study the strong decay properties within this coupling scheme.

In the L - S coupling scheme, the states are constructed by [16]

$$|^{2S+1}L_J\rangle = \left| [(l_\rho l_\lambda)_L (s_\rho s_Q)_S]_{J^P} \right\rangle, \quad (9)$$

where l_ρ and l_λ are the quantum numbers of the orbital angular momenta $\mathbf{l}_\rho$ and $\mathbf{l}_\lambda$ for the ρ - and λ -mode oscillators,

Table 2 The classifications of the low-lying λ -mode $1P$ -, $1D$ - and $2S$ -wave states within the L - S coupling scheme

$ ^{2S+1}L_J\rangle$	J^P	n_ρ	l_ρ	n_λ	l_λ	L	s_ρ	s_Q	S
$ ^2P_{\lambda \frac{1}{2}^-}\rangle(1P)$	$\frac{1}{2}^-$	0	0	0	1	1	1	$\frac{1}{2}$	$\frac{1}{2}$
$ ^2P_{\lambda \frac{3}{2}^-}\rangle(1P)$	$\frac{3}{2}^-$	0	0	0	1	1	1	$\frac{1}{2}$	$\frac{1}{2}$
$ ^4P_{\lambda \frac{1}{2}^-}\rangle(1P)$	$\frac{1}{2}^-$	0	0	0	1	1	1	$\frac{1}{2}$	$\frac{3}{2}$
$ ^4P_{\lambda \frac{3}{2}^-}\rangle(1P)$	$\frac{3}{2}^-$	0	0	0	1	1	1	$\frac{1}{2}$	$\frac{3}{2}$
$ ^4P_{\lambda \frac{5}{2}^-}\rangle(1P)$	$\frac{5}{2}^-$	2	0	0	0	1	1	$\frac{1}{2}$	$\frac{3}{2}$
$ ^2S_{\frac{1}{2}^+}\rangle(2S)$	$\frac{1}{2}^+$	0	0	1	0	0	1	$\frac{1}{2}$	$\frac{1}{2}$
$ ^4S_{\frac{3}{2}^+}\rangle(2S)$	$\frac{3}{2}^+$	0	0	1	0	0	1	$\frac{1}{2}$	$\frac{3}{2}$
$ ^2D_{\lambda\lambda \frac{3}{2}^+}\rangle(1D)$	$\frac{3}{2}^+$	0	0	0	2	2	1	$\frac{1}{2}$	$\frac{1}{2}$
$ ^2D_{\lambda\lambda \frac{5}{2}^+}\rangle(1D)$	$\frac{5}{2}^+$	0	0	0	2	2	1	$\frac{1}{2}$	$\frac{1}{2}$
$ ^4D_{\lambda\lambda \frac{1}{2}^+}\rangle(1D)$	$\frac{1}{2}^+$	0	0	0	2	2	1	$\frac{1}{2}$	$\frac{3}{2}$
$ ^4D_{\lambda\lambda \frac{3}{2}^+}\rangle(1D)$	$\frac{3}{2}^+$	0	0	0	2	2	1	$\frac{1}{2}$	$\frac{3}{2}$
$ ^4D_{\lambda\lambda \frac{5}{2}^+}\rangle(1D)$	$\frac{5}{2}^+$	0	0	0	2	2	1	$\frac{1}{2}$	$\frac{3}{2}$
$ ^4D_{\lambda\lambda \frac{7}{2}^+}\rangle(1D)$	$\frac{7}{2}^+$	0	0	0	2	2	1	$\frac{1}{2}$	$\frac{3}{2}$

respectively. L corresponds to the quantum number of the total orbital angular momentum $\mathbf{L} = \mathbf{l}_\rho + \mathbf{l}_\lambda$, which determine the parity of a state by $P = (-1)^{l_\rho + l_\lambda}$. s_ρ and s_Q stand for the quantum numbers of the total spin of the two light quarks s_ρ and the spin of the heavy quark s_Q , respectively. S is the quantum number of the total spin angular momentum $\mathbf{S} = \mathbf{s}_\rho + \mathbf{s}_Q$. According to the quark model classification, there are five λ -mode $1P$ -wave states, six λ -mode $1D$ -wave states and two $2S$ -wave states, and their corresponding quantum numbers have been collected in Table 2.

Under the heavy-quark symmetry limit [47], the states within the j - j coupling scheme are constructed by

$$|J^P, j\rangle = \left| \left[[(\ell_\rho \ell_\lambda)_L s_\rho]_j s_Q \right]_{J^P} \right\rangle. \quad (10)$$

Here, the total orbital angular momentum $\mathbf{L} = \mathbf{l}_\rho + \mathbf{l}_\lambda$ couples to the total spin of the two light quarks s_ρ , and then gets $\mathbf{j} = \mathbf{L} + \mathbf{s}_\rho$. $\mathbf{j}$ couples to the spin of the heavy quark s_Q , and gives the total angular momentum $\mathbf{J} = \mathbf{j} + \mathbf{s}_Q$. Similarly, with this coupling scheme the low-lying λ -mode $1P$ -, $1D$ - and $2S$ -wave states are listed in Table 3.

The states within the j - j coupling scheme can be expressed as linear combinations of the states within the L - S coupling scheme by [16]

$$|[(l_\rho l_\lambda)_L s_\rho]_j s_Q\rangle_J = (-1)^{L+s_\rho+1/2+J} \sqrt{2j+1} \sum_S \sqrt{2S+1} \begin{Bmatrix} L & s_\rho & j \\ s_Q & J & S \end{Bmatrix} |[(l_\rho l_\lambda)_L (s_\rho s_Q)_S]_J\rangle. \quad (11)$$

Table 3 The classifications of the low-lying λ -mode $1P$ -, $1D$ - and $2S$ -wave states within the j - j coupling scheme

$ J^P, j\rangle$	J^P	j	n_ρ	ℓ_ρ	n_λ	ℓ_λ	L	s_ρ	s_Q
$ J^P = \frac{1}{2}^-, 0\rangle (1P)$	$\frac{1}{2}^-$	0	0	0	0	1	1	1	$\frac{1}{2}$
$ J^P = \frac{1}{2}^-, 1\rangle (1P)$	$\frac{1}{2}^-$	1	0	0	0	1	1	1	$\frac{1}{2}$
$ J^P = \frac{3}{2}^-, 1\rangle (1P)$	$\frac{3}{2}^-$	1	0	0	0	1	1	1	$\frac{1}{2}$
$ J^P = \frac{3}{2}^-, 2\rangle (1P)$	$\frac{3}{2}^-$	2	0	0	0	1	1	1	$\frac{1}{2}$
$ J^P = \frac{5}{2}^-, 2\rangle (1P)$	$\frac{5}{2}^-$	2	0	0	0	1	1	1	$\frac{1}{2}$
$ J^P = \frac{1}{2}^+, 1\rangle (2S)$	$\frac{1}{2}^+$	1	0	0	1	0	0	1	$\frac{1}{2}$
$ J^P = \frac{3}{2}^+, 1\rangle (2S)$	$\frac{3}{2}^+$	1	0	0	1	0	0	1	$\frac{1}{2}$
$ J^P = \frac{1}{2}^+, 1\rangle (1D)$	$\frac{1}{2}^+$	1	0	0	0	2	2	1	$\frac{1}{2}$
$ J^P = \frac{3}{2}^+, 1\rangle (1D)$	$\frac{3}{2}^+$	1	0	0	0	2	2	1	$\frac{1}{2}$
$ J^P = \frac{3}{2}^+, 2\rangle (1D)$	$\frac{3}{2}^+$	2	0	0	0	2	2	1	$\frac{1}{2}$
$ J^P = \frac{5}{2}^+, 2\rangle (1D)$	$\frac{5}{2}^+$	2	0	0	0	2	2	1	$\frac{1}{2}$
$ J^P = \frac{5}{2}^+, 3\rangle (1D)$	$\frac{5}{2}^+$	3	0	0	0	2	2	1	$\frac{1}{2}$
$ J^P = \frac{7}{2}^+, 3\rangle (1D)$	$\frac{7}{2}^+$	3	0	0	0	2	2	1	$\frac{1}{2}$

This relationship between the two different coupling schemes indicates that the states may well be mixed with the same spin-parity J^P within the L - S coupling scheme for the singly heavy baryons. The mixing angles can be estimated by Eq. (11).

In this work, the standard quark model parameters are adopted. Namely, we set $m_u = m_d = 330$ MeV, $m_s = 450$ MeV, and $m_b = 5000$ MeV for the constituent quark masses. The decay constants for K is taken as $f_K = 160$ MeV. The harmonic oscillator space-wave functions are adopted to describe the spatial wave function of the initial and final baryons, and the harmonic oscillator parameter α_ρ in the wave functions for ds/us and ss systems are taken as $\alpha_\rho = 420$ and 440 MeV, respectively. Another harmonic oscillator parameter α_λ is determined by $\alpha_\lambda = (\frac{3m'}{2m+m'})^{1/4}\alpha_\rho$, where m' denotes the heavy quark mass and m denote the light quark mass. The masses of the final baryons and mesons are taken from the PDG [48]. For the global parameter δ , we fix its value the same as our previous works [25,31,39], i.e., $\delta = 0.557$.

3 Results and analysis

Inspired by the newly observed four peaks by the LHCb Collaboration [10], we carry out a systematic study of the strong decay behaviors of the singly bottom baryons Ω_b up to $N = 2$ shell within the j - j coupling scheme in the framework of the chiral quark model. Our results and theoretical predictions are presented as follows.

3.1 $1P$ states

The predicted masses of the λ -mode $1P$ -wave baryons Ω_b are about 6.3 GeV (see Table 1), which are in good agreement with the masses of the newly observed four Ω_b states [10]. In addition, via evaluation the OZI-allowed two-body decays, some people obtained that the $1P$ Ω_b states have a narrow decay widths [14,23], which are in accordance with the nature of the newly observed Ω_b states. To pin down the inner structures of the four peaks, it is crucial to study the decay properties of those $1P$ states carefully.

3.1.1 $J^P = 1/2^-$ states

There are two $J^P = 1/2^-$ states $|J^P = \frac{1}{2}^-, 0\rangle$ and $|J^P = \frac{1}{2}^-, 1\rangle$ within the j - j coupling scheme (see Table 3). They can be expressed as mixed states between $|^2P_{\lambda\frac{1}{2}}^-\rangle$ and $|^4P_{\lambda\frac{1}{2}}^-\rangle$:

$$|J^P = \frac{1}{2}^-, 0\rangle = -\sqrt{\frac{1}{3}}|^2P_{\lambda\frac{1}{2}}^-\rangle + \sqrt{\frac{2}{3}}|^4P_{\lambda\frac{1}{2}}^-\rangle, \quad (12)$$

$$|J^P = \frac{1}{2}^-, 1\rangle = \sqrt{\frac{2}{3}}|^2P_{\lambda\frac{1}{2}}^-\rangle + \sqrt{\frac{1}{3}}|^4P_{\lambda\frac{1}{2}}^-\rangle. \quad (13)$$

Their masses are predicted to be above the threshold of $\Xi_b K$. Considering the uncertainties of the predicted mass, we plot the variation of the decay width of the $\Xi_b K$ decay mode as a function of the mass of the state $|J^P = 1/2^-, 0\rangle$ in Fig. 1. The decay width increases with the mass increasing in the range of (6290–6350) MeV, and varies in the region of $\Gamma \sim (33 - 151)$ MeV. The decay properties of this state is inconsistent with the natures of the four Ω_b states, thus, the four Ω_b states as the state $|J^P = 1/2^-, 0\rangle$ should be excluded. Since the predicted width of $|J^P = 1/2^-, 0\rangle$ is not broad, this state might be observed in the $\Xi_b K$ channel when enough data are accumulated in experiments.

For the other $J^P = 1/2^-$ state $|J^P = 1/2^-, 1\rangle$, the decay mode $\Xi_b K$ is forbidden in the heavy quark symmetry limit (see Table 4), thus, this state should be very narrow state. We notice that the widths of two peaks, $\Omega_b(6316)$ and $\Omega_b(6330)$, observed in the $\Xi_b^0 K^-$ mass spectra [10] are $0.00_{-0.0}^{+0.7}$ MeV and $0.00_{-0.0}^{+0.4}$ MeV, respectively, which are good candidates of this state.

Considering the heavy-quark symmetry is only an approximation, the mixing angle between two states within the L - S coupling scheme should be slightly different from that determined in the j - j coupling scheme. Namely, the mixing angle ϕ for the physical states as mixed states between $|^2P_{\lambda J}\rangle$ and $|^4P_{\lambda J}\rangle$ within the L - S coupling scheme, i.e.,

$$\begin{pmatrix} |^1P_{J^P}\rangle_1 \\ |^1P_{J^P}\rangle_2 \end{pmatrix} = \begin{pmatrix} \cos \phi & \sin \phi \\ -\sin \phi & \cos \phi \end{pmatrix} \begin{pmatrix} |^2P_{\lambda J^P}\rangle \\ |^4P_{\lambda J^P}\rangle \end{pmatrix}, \quad (14)$$

Fig. 1 Partial decay widths of the $\Xi_b K$ channel for the $J^P = 1/2^-$, $J^P = 3/2^-$ and $J^P = 5/2^-$ Ω_b states as a function of the mass

Table 4 Partial decay widths (MeV) of the $1P$ states within the j - j coupling scheme in the Ω_b family. The value inside of the braces denotes the reference mass (MeV) of the corresponding state

State	$ J^P, j\rangle$	$\Gamma[\Xi_b K]$ (MeV)
$\Omega_b(6316)$	$ J^P = \frac{1}{2}^-, 1\rangle$	...
$\Omega_b(6316)$	$ J^P = \frac{1}{2}^-, 0\rangle$	126
$\Omega_b(6340)$	$ J^P = \frac{3}{2}^-, 2\rangle$	2.2
$\Omega_b(6330)$	$ J^P = \frac{3}{2}^-, 1\rangle$	...
$\Omega_b(6350)$	$ J^P = \frac{5}{2}^-, 2\rangle$	3.4

may range from the value of the L - S coupling scheme ($\phi = 0^\circ$) to that of the j - j coupling scheme.

For the P -wave states with $J^P = 1/2^-$, the mixing angle obtained in the heavy quark limit within the j - j coupling scheme is $\phi \simeq 35^\circ$, namely $\cos \phi = \sqrt{2/3}$ and $\sin \phi = \sqrt{1/3}$. Thus according to the mixing scheme defined in Eq. (14), in Fig. 2 we plot the strong decay widths of the $J^P = 1/2^-$ states as a function of the mixing angle ϕ in the region of $(0^\circ, 35^\circ)$ by fixing the mass of the resonance at $M = 6316$ MeV. It is found that the decay widths are strongly dependent on the mixing angle. The decay width of $|P_{\frac{1}{2}}^{\frac{1}{2}-}\rangle_2$ is about $\Gamma \sim (83 - 126)$ MeV with the mixing angle varied in the region what we considered. For the other mixed state $|P_{\frac{1}{2}}^{\frac{1}{2}-}\rangle_1$, the decay width is close to zero with the mixing angle tending to $\phi \simeq 35^\circ$ which is determined in the j - j coupling scheme. This may be evidence that the heavy quark symmetry is a good approximation for the physical states of the singly bottom baryons, thus, the

Fig. 2 Partial decay widths for the $J^P = 1/2^-$ and $J^P = 3/2^-$ Ω_b states as a function of the mixing angle

properties of the newly observed Ω_b states, $\Omega_b(6316)$ and $\Omega_b(6330)$, can be naturally understood.

3.1.2 $J^P = 3/2^-$ states

Within the j - j coupling scheme, there are two $J^P = 3/2^-$ P -wave states $|J^P = \frac{3}{2}^-, 1\rangle$ and $|J^P = \frac{3}{2}^-, 2\rangle$, which can be expressed as mixed states in the L - S coupling scheme by Eq. (11):

$$|J^P = \frac{3}{2}^-, 1\rangle = -\sqrt{\frac{1}{6}} |^2P_{\lambda} \frac{3}{2}^-\rangle + \sqrt{\frac{5}{6}} |^4P_{\lambda} \frac{3}{2}^-\rangle, \quad (15)$$

$$|J^P = \frac{3}{2}^-, 2\rangle = \sqrt{\frac{5}{6}} |^2P_{\lambda} \frac{3}{2}^-\rangle + \sqrt{\frac{1}{6}} |^4P_{\lambda} \frac{3}{2}^-\rangle. \quad (16)$$

For the two $J^P = 3/2^-$ states, the $\Xi_b K$ decay mode is the only OZI-allowed two-body strong decay channel. The decay mode $\Xi_b K$ is forbidden for the state $|J^P = \frac{3}{2}^-, 1\rangle$ in the heavy-quark symmetry limit, thus, this state should be very narrow state. Combining the natures of the newly observed states $\Omega_b(6316)$ and $\Omega_b(6330)$, we obtain that these two Ω_b resonances are good candidates of the $|J^P = \frac{3}{2}^-, 1\rangle$ state as well.

For the other $J^P = 3/2^-$ state $|J^P = \frac{3}{2}^-, 2\rangle$, we also plot the decay width as a function of the mass in the range of $M = (6290 - 6350)$ MeV in Fig. 1. It is found that the decay width is very narrow as well due to the D -wave suppression. Fixing the mass of $|J^P = \frac{3}{2}^-, 2\rangle$ at $M = 6340$ MeV, we obtain

$$\Gamma \left[|J^P = \frac{3}{2}^-, 2\rangle \rightarrow \Xi_b K \right] \simeq 2.2 \text{ MeV}. \quad (17)$$

This theoretical width is well comparable with the observations of the two resonances $\Omega_b(6340)$ and $\Omega_b(6350)$ [10], thus the two resonances are good candidates of the $J^P = 3/2^-$ state $|J^P = \frac{3}{2}^-, 2\rangle$.

The mixing angle for the $J^P = 3/2^-$ physical states may be slightly different from the value $\phi = 24^\circ$ determined by

the j - j coupling scheme in the heavy-quark symmetry limit. Similarly we fix the masses at $M = 6330$ MeV and plot the variation of the strong decay widths of the $J^P = 3/2^-$ states as a function of the mixing angle in Fig. 2. From the figure, it is found that the decay widths for the two $J^P = 3/2^-$ states are slightly depend on the mixing angle and less than $\Gamma < 1.3$ MeV in the range of $(0^\circ, 24^\circ)$.

3.1.3 $J^P = 5/2^-$ states

There is only one P -wave state with $J^P = 5/2^-$. There is no differences between the j - j coupling scheme and L - S coupling scheme, namely

$$\left| J^P = \frac{5}{2}^-, 2 \right\rangle = \left| {}^4P_{\lambda} \frac{5}{2}^- \right\rangle. \quad (18)$$

According to the Table 1, the theoretical masses of the $J^P = 5/2^-$ states are about 6.3 GeV. Thus, we plot the decay width of this state as a function of the mass in Fig. 1 in the region of (6290–6350) MeV. It is found that this state is most likely narrow ($\Gamma < 3.5$ MeV) because of the D -wave suppression within the mass range what we considered, and comparable with the nature of the newly observed Ω_b states, $\Omega_b(6340)$ and $\Omega_b(6350)$. Fixing the mass of $|J^P = \frac{5}{2}^-, 2\rangle$ at $M = 6350$ MeV, we obtain

$$\Gamma \left[|J^P = \frac{5}{2}^-, 2\rangle \rightarrow \Xi_b K \right] \simeq 3.4 \text{ MeV}. \quad (19)$$

So far, we have calculated the strong decay properties of the five λ -mode P -wave Ω_b states within the j - j coupling scheme. Our results show that excepting the state $|1/2^-, 0\rangle$ being a middle width state with a width of $\Gamma \sim 100$ MeV, the other four states are most likely to be narrow states, which are good candidates for the newly observed four Ω_b states. The newly observed resonances $\Omega_b(6316)$ and $\Omega_b(6330)$ can be interpreted as the light spin $j = 1$ states, while their spin-parity $J^P = 1/2^-$ and $J^P = 3/2^-$ cannot be distinguished. The other two states $\Omega_b(6340)$ and $\Omega_b(6350)$ may be the light spin $j = 2$ states, but the spin-parity $J^P = 3/2^-$ and $J^P = 5/2^-$ cannot be distinguished.

3.2 $2S$ states

According to the predicted masses of the $2S$ states in the Ω_b family (see Table 1), the possibility as the candidates of the newly observed resonances cannot be excluded completely. It is necessary to study the strong decay properties of the $2S$ states.

There are two $2S$ states with spin-parity $J^P = 1/2^+$ and $J^P = 3/2^+$, respectively. For these two $2S$ -wave states, there is no differences between the j - j coupling scheme and L - S coupling scheme. Adopting the predicted masses from the Ref. [13], we calculate the partial decay widths of the two

Table 5 Partial decay widths (MeV) for the $2S$ -wave Ω_b states, whose masses (MeV) are taken the quark model predictions of Ref. [13]

Decay mode	$ J = \frac{1}{2}^+, 1\rangle(2S)$ $\Omega_b(6450)$	$ J = \frac{3}{2}^+, 1\rangle(2S)$ $\Omega_b(6461)$
$\Xi_b K$	0.51	0.36
$\Xi'_b K$	0.32	0.14
$\Xi_b^* K$	0.04	0.10
Sum	0.87	0.60

Fig. 3 Partial decay widths of the $2S$ states with $J^P = 1/2^+$ and $J^P = 3/2^+$, respectively, as a function of the masses

$2S$ states. Our results have been listed in Table 5. From the table, we get that the two $2S$ states may be narrow state with a comparable total decay width of $\Gamma \sim 1$ MeV.

Considering the uncertainty of the predicted masses, we plot the strong decay properties of the two states as functions of the masses in the range of (6.35, 6.55) MeV, as shown in Fig. 3. The total decay widths of the $2S$ states are about $\Gamma < 2$ MeV within the masses we considered. Meanwhile, we notice that the partial decay width of the $\Xi_b K$ mode has an oscillation as the mass increases. That's because the $2S$ -wave function has a node, and then the overlap between the initial and final states is a quadratic function of the momentum of the final state. As the mass increases, the tension between phase space and overlap makes the variation in Fig. 3.

The decay properties of the $2S$ states were calculated in Ref. [26] within quark pair creation model as well. The authors predicted that the total decay widths of the two $2S$ states were about $\Gamma \sim 50$ MeV, which were incomparable with our predictions.

It should be pointed out that although some people obtain the theoretical masses of the $2S$ states in the Ω_b family are about 6.3–6.4 GeV [15, 17] and the possibility as the new observed Ω_b states cannot be excluded absolutely, however,

Table 6 Partial widths (MeV) of strong decays for the λ -mode D -wave Ω_b baryons, whose masses (MeV) are taken the quark model predictions of Ref. [13]

Decay mode	M_f	$ J = \frac{1}{2}^+, 1\rangle(6540)$		$ J = \frac{3}{2}^+, 1\rangle(6530)$		$ J = \frac{3}{2}^+, 2\rangle(6549)$		$ J = \frac{5}{2}^+, 2\rangle(6520)$		$ J = \frac{5}{2}^+, 3\rangle(6529)$		$ J = \frac{7}{2}^+, 3\rangle(6517)$	
		Γ_i	$\mathcal{B}_i$ (%)	Γ_i	$\mathcal{B}_i$ (%)	Γ_i	$\mathcal{B}_i$ (%)	Γ	$\mathcal{B}_i$ (%)	Γ_i	$\mathcal{B}_i$ (%)	Γ_i	$\mathcal{B}_i$ (%)
$\Xi_b K$	5794	22.1	77.1	22.4	81.5	...	...	...	...	9.06	91.5	7.83	91.05
$\Xi'_b K$	5935	4.69	16.4	1.05	3.8	9.49	85.3	0.15	2.6	0.24	2.4	0.09	1.04
$\Xi_b^* K$	5955	1.86	6.5	4.04	14.7	1.63	14.7	5.61	97.4	0.60	6	0.68	7.91
total		28.65		27.49		11.12		5.76		9.90		8.6	

the mass splitting between the $1P$ and $2S$ is about 100–150 MeV. We notice that the splitting between the four newly observed resonances ranges from several to 10 MeV. If the four resonances are conventional baryons and two of them are interpreted as the $2S$ states, while how to understand the other two resonances will be a great challenge.

3.3 $1D$ states

The $1D$ -wave Ω_b states are most likely to be observed in forthcoming experiments as well. In Ref. [34] we have studied the strong decays of the $1D$ -wave Ω_b states in the L - S coupling scheme. Since the heavy-quark symmetry indicates the the singly-heavy baryons may more favor the j - j coupling scheme, in present work we further give our predictions in the j - j coupling scheme.

For the λ -mode $1D$ states, there are six states within the j - j coupling scheme and the corresponding relations to the states in the L - S coupling scheme are

$$|J^P = \frac{1}{2}^+, 1\rangle = |^4D_{\lambda\lambda} \frac{1}{2}^+\rangle, \quad (20)$$

$$|J^P = \frac{3}{2}^+, 1\rangle = -\sqrt{\frac{1}{2}}|^2D_{\lambda\lambda} \frac{3}{2}^+\rangle + \sqrt{\frac{1}{2}}|^4D_{\lambda\lambda} \frac{3}{2}^+\rangle, \quad (21)$$

$$|J^P = \frac{3}{2}^+, 2\rangle = \sqrt{\frac{1}{2}}|^2D_{\lambda\lambda} \frac{3}{2}^+\rangle + \sqrt{\frac{1}{2}}|^4D_{\lambda\lambda} \frac{3}{2}^+\rangle, \quad (22)$$

$$|J^P = \frac{5}{2}^+, 2\rangle = -\frac{\sqrt{2}}{3}|^2D_{\lambda\lambda} \frac{5}{2}^+\rangle + \frac{\sqrt{7}}{3}|^4D_{\lambda\lambda} \frac{5}{2}^+\rangle, \quad (23)$$

$$|J^P = \frac{5}{2}^+, 3\rangle = \frac{\sqrt{7}}{3}|^2D_{\lambda\lambda} \frac{5}{2}^+\rangle + \frac{\sqrt{2}}{3}|^4D_{\lambda\lambda} \frac{5}{2}^+\rangle, \quad (24)$$

$$|J^P = \frac{7}{2}^+, 3\rangle = |^4D_{\lambda\lambda} \frac{7}{2}^+\rangle. \quad (25)$$

For the D -wave Ω_b states, within the masses adopted from Ref. [13] we calculate the strong decays of the $1D$ states and collect in Table 6.

From Table 6, it is seen that the total decay widths of $|J = 1/2^+, 1\rangle$ and $|J = 3/2^+, 1\rangle$ are about $\Gamma \sim 28$ MeV, and both mainly decay into $\Xi_b K$. The strong decays of the states $|J = 5/2^+, 3\rangle$ and $|J = 7/2^+, 3\rangle$ are governed by

the $\Xi_b K$ channel as well, and the total decay widths of both states are about $\Gamma \sim 10$ MeV. However, the decay mode $\Xi_b K$ is forbidden for the states $|J = 3/2^+, 2\rangle$ and $|J = 5/2^+, 2\rangle$. The two states might be narrow state with the total decay widths of $\Gamma \sim 11$ MeV and $\Gamma \sim 6$ MeV, respectively. Meanwhile, we notice that the strong decays of the state $|J = 3/2^+, 2\rangle$ is dominated by the $\Xi'_b K$ channel, while that of the state $|J = 5/2^+, 2\rangle$ is the $\Xi_b^* K$ channel.

Comparing with the predictions in Ref. [26], the main decay channel for each $1D$ states is consistent with each other. However the total decay widths are difference, especially for the states $|J = 1/2^+, 1\rangle$ and $|J = 3/2^+, 1\rangle$. The predicted total decay widths for the two states in Ref. [26] are about three times larger than ours.

4 Summary

In this paper, we carry out a systematic study of the OZI allowed two-body strong decays of the low-lying λ -mode Ω_b resonances up to the $N = 2$ shell in the framework of a chiral quark model within the j - j coupling scheme. For the newly observed four Ω_b states, we give a possible interpretation in theory. Meanwhile, we give the predictions for the decay properties of the $2S$ - and $1D$ -wave states, and hope to provide helpful information for searching these missing Ω_b states in the future.

Our theoretical results show that the newly observed states $\Omega_b(6316)$ and $\Omega_b(6330)$ are most likely to be explained as the $1P$ wave states with the light spin $j = 1$, while the spin-parity $J^P = 1/2^-$ and $J^P = 3/2^-$ cannot be distinguished. The other two newly observed states $\Omega_b(6340)$ and $\Omega_b(6350)$ may correspond to the $1P$ -wave states with the light spin $j = 2$ excepting the spin-parity $J^P = 3/2^-$ and $J^P = 5/2^-$ cannot being distinguished. In addition, we notice that the state $|1/2^-, 0\rangle(1P)$ might be a moderate width state with a total decay width of $\Gamma \sim 100$ MeV, and the $\Xi_b K$ channel mostly saturates its total decay width.

For the two $2S$ states with the spin-parity $J^P = 1/2^+$ and $J^P = 3/2^+$, they might be narrow states with a total width of $\Gamma < 2$ MeV. Considering the large mass splitting between

1 P - and 2 S -wave states together with the small mass splitting along the observed four peaks, it is unnatural to explain two of the four peaks as 2 S -wave states within the conventional baryon picture.

For the 1 D states, the total decay widths are not broad and vary from several to dozens of MeV. In addition, we notice that the strong decays of the states $|J = 1/2^+, 1\rangle$, $|J = 3/2^+, 1\rangle$, $|J = 5/2^+, 3\rangle$, and $|J = 7/2^+, 3\rangle$ are governed by the $\Xi_b K$ channel, while this channel is forbidden for the states $|J = 3/2^+, 2\rangle$ and $|J = 5/2^+, 2\rangle$. The state $|J = 3/2^+, 2\rangle$ dominantly decays to the $\Xi'_b K$ channel, and the state $|J = 5/2^+, 2\rangle$ are governed by the Ξ_{bK}^* channel.

Acknowledgements This work is supported by the National Natural Science Foundation of China under Grants No. 11775078, No. 11947048 and No. U1832173.

Data Availability Statement This manuscript has associated data in a data repository. [Authors' comment: All the data in this manuscript are available upon request by contacting with the corresponding author.]

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. C. Albajar et al., [UA1 Collaboration], First observation of the beauty baryon Λ_b in the decay channel $\Lambda_b \rightarrow J/\psi \Lambda$ at the CERN $p\bar{p}$ collider". Phys. Lett. B **273**, 540 (1991)
2. M. Tanabashi et al., [Particle Data Group], Review of Particle Physics. Phys. Rev. D **98**, 030001 (2018)
3. R. Aaij et al., [LHCb Collaboration], Study of the $D^0 p$ amplitude in $\Lambda_b^0 \rightarrow D^0 p \pi^-$ decays. JHEP **1705**, 030 (2017)
4. 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)
5. J. Yelton et al., [Belle Collaboration], Observation of excited Ω_c charmed baryons in e^+e^- collisions. Phys. Rev. D **97**, 051102 (2018)
6. R. Aaij et al., [LHCb Collaboration], Observation of two resonances in the $\Lambda_b^0 \pi^\pm$ systems and precise measurement of $\Sigma_b^\pm$ and $\Sigma_b^{*\pm}$ properties. Phys. Rev. Lett. **122**, 012001 (2019)
7. R. Aaij et al., [LHCb Collaboration], Observation of a new Ξ_b^- resonance. Phys. Rev. Lett. **121**, 072002 (2018)
8. R. Aaij et al., [LHCb Collaboration], Observation of new resonances in the $\Lambda_b^0 \pi^+ \pi^-$ system. Phys. Rev. Lett. **123**, 152001 (2019)
9. R. Aaij et al., [LHCb Collaboration], Observation of the doubly charmed baryon Ξ_{cc}^{++} . Phys. Rev. Lett. **119**, 112001 (2017)
10. R. Aaij et al. [LHCb Collaboration], First observation of excited Ω_b^- states, [arXiv:2001.00851](https://arxiv.org/abs/2001.00851) [hep-ex]
11. T. Yoshida, E. Hiyama, A. Hosaka, M. Oka, K. Sadato, Spectrum of heavy baryons in the quark model. Phys. Rev. D **92**, 114029 (2015)
12. 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)
13. 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)
14. E. Santopinto, A. Giachino, J. Ferretti, H. Garca-Tecocoatz, M.A. Bedolla, R. Bijker, E. Ortiz-Pacheco, The Ω_c -puzzle solved by means of quark model predictions. Eur. Phys. J. C **79**, 1012 (2019)
15. G. Yang, J. Ping, J. Segovia, The S - and P -wave low-lying Baryons in the Chiral quark model. Few Body Syst. **59**, 113 (2018)
16. W. Roberts, M. Pervin, Heavy baryons in a quark model. Int. J. Mod. Phys. A **23**, 2817 (2008)
17. H. Garcilazo, J. Vijande, A. Valcarce, Faddeev study of heavy baryon spectroscopy. J. Phys. G **34**, 961 (2007)
18. D. Ebert, R.N. Faustov, V.O. Galkin, Masses of excited heavy baryons in the relativistic quark model. Phys. Lett. B **659**, 612 (2008)
19. K.W. Wei, B. Chen, N. Liu, Q.Q. Wang, X.H. Guo, Spectroscopy of singly, doubly, and triply bottom baryons. Phys. Rev. D **95**, 116005 (2017)
20. S.S. Agaev, K. Azizi, H. Sundu, On the nature of the newly discovered Ω states. EPL **118**, 61001 (2017)
21. Q. Mao, H.X. Chen, W. Chen, A. Hosaka, X. Liu, S.L. Zhu, QCD sum rule calculation for P -wave bottom baryons. Phys. Rev. D **92**, 114007 (2015)
22. W.H. Liang, J.M. Dias, V.R. Debastiani, E. Oset, Molecular Ω_b states. Nucl. Phys. B **930**, 524 (2018)
23. S.S. Agaev, K. Azizi, H. Sundu, Decay widths of the excited Ω_b baryons. Phys. Rev. D **96**, 094011 (2017)
24. 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)
25. K.L. Wang, Q.F. L, 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)
26. W. Liang, Q. F. L., Strong decays of the newly observed narrow Ω_b structures, [arXiv:2001.02221](https://arxiv.org/abs/2001.02221) [hep-ph]
27. Z.G. Wang, Analysis of the $\Omega_b(6316)$, $\Omega_b(6330)$, $\Omega_b(6340)$ and $\Omega_b(6350)$ with QCD sum rules, [arXiv:2001.02961](https://arxiv.org/abs/2001.02961) [hep-ph]
28. H. X. Chen, E. L. Cui, A. Hosaka, Q. Mao, H. M. Yang, Excited Ω_b baryons and fine structure of strong interaction, [arXiv:2001.02147](https://arxiv.org/abs/2001.02147) [hep-ph]
29. W. H. Liang, E. Oset, The observed Ω_b spectrum and meson-baryon molecular states, [arXiv:2001.02929](https://arxiv.org/abs/2001.02929) [hep-ph]
30. 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)
31. X.H. Zhong, Q. Zhao, Charmed baryon strong decays in a chiral quark model. Phys. Rev. D **77**, 074008 (2008)
32. L.H. Liu, L.Y. Xiao, X.H. Zhong, Charm-strange baryon strong decays in a chiral quark model. Phys. Rev. D **86**, 034024 (2012)
33. K.L. Wang, Q.F. L, X.H. Zhong, Interpretation of the newly observed $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ states in a chiral quark model. Phys. Rev. D **100**, 114035 (2019)
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. L. Y. Xiao, K. L. Wang, Q. f. Lu, X. H. Zhong, S. L. Zhu, Strong and radiative decays of the doubly charmed baryons. *Phys. Rev. D* **96**, 094005 (2017)
36. L. Y. Xiao, X. H. Zhong, Ξ baryon strong decays in a chiral quark model. *Phys. Rev. D* **87**, 094002 (2013)
37. L. Y. Xiao, X. H. Zhong, Possible interpretation of the newly observed $\Omega(2012)$ state. *Phys. Rev. D* **98**, 034004 (2018)
38. M. S. Liu, K. L. Wang, Q. F. Lü, X. H. Zhong, Ω baryon spectrum and their decays in a constituent quark model, *Phys. Rev. D* **101**, 016002 (2020)
39. X. h. Zhong, Q. Zhao, Strong decays of heavy-light mesons in a chiral quark model. *Phys. Rev. D* **78**, 014029 (2008)
40. X. H. Zhong, Q. Zhao, Strong decays of newly observed $D(sJ)$ states in a constituent quark model with effective Lagrangians. *Phys. Rev. D* **81**, 014031 (2010)
41. X. H. Zhong, Strong decays of the newly observed $D(2550)$, $D(2600)$, $D(2750)$, and $D(2760)$. *Phys. Rev. D* **82**, 114014 (2010)
42. L. Y. Xiao, X. H. Zhong, Strong decays of higher excited heavy-light mesons in a chiral quark model. *Phys. Rev. D* **90**, 074029 (2014)
43. A. Manohar, H. Georgi, Chiral quarks and the nonrelativistic quark model. *Nucl. Phys. B* **234**, 189 (1984)
44. Q. Zhao, J. S. Al-Khalili, Z. P. Li, R. L. Workman, Pion photoproduction on the nucleon in the quark model. *Phys. Rev. C* **65**, 065204 (2002)
45. Z. P. Li, The Threshold pion photoproduction of nucleons in the chiral quark model. *Phys. Rev. D* **50**, 5639 (1994)
46. Z. P. Li, H. X. Ye, M. H. Lu, An Unified approach to pseudoscalar meson photoproductions off nucleons in the quark model. *Phys. Rev. C* **56**, 1099 (1997)
47. H. Y. Cheng, Charmed baryons circa 2015. *Front. Phys.* **10**, 101406 (2015). (Beijing)
48. C. Patrignani et al., [Particle Data Group], Review of particle physics. *Chin. Phys. C* **40**, 100001 (2016)