Strong decays of low-lying D-wave Ξ_b and Ξ_b' baryons with quark-pair creation model

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For further decoding the inner structure of the two excited Ξ_b states observed by LHCb, we perform a systematical study of the strong decays of the low-lying $1D$-wave Ξ_b and Ξ_b' excitations using the quark pair creation model within the $j-j$ coupling scheme. Combined with the measured masses and decay properties of $\Xi_b(6327)^0$ and $\Xi_b(6327)^0$, the two excited states can be explained as $1D$ λ-mode Ξ_b states $\Xi_b|J^P=\frac{3}{2}^+,2\rangle_{\lambda\lambda}$ and $\Xi_b|J^P=\frac{5}{2}^+,2\rangle_{\lambda\lambda}$, respectively. If such a view is correct, $\Xi_b'\pi$ and $\Xi_b'^*\pi$ could be other interesting channels for experimental exploration of the $\Xi_b(6327)^0$ and $\Xi_b(6327)^0$, respectively. The calculations are good and consistent with the results within the chiral quark model. In addition, for the other missing $1D$-wave Ξ_b and Ξ_b' excitations, our predictions indicate that: (i) the two ρ-mode $1D$ Ξ_b states are likely to be moderate states with a width of $\Gamma\sim 50$ MeV. The $J^P=3/2^+$ state dominantly decays into $\Sigma_b K$ and $\Xi_b'\pi$, while the $J^P=5/2^+$ state decays primarily through $\Sigma_b^* K$ and $\Xi_b'^*\pi$; (ii) The λ-mode $1D$ Ξ_b' states may be moderate states with widths of about several MeV to dozens of MeV. Most of the λ-mode $1D$ Ξ_b' states mainly decay into the $1P$-wave bottomed baryon via the pionic decay processes. Meanwhile, several λ-mode $1D$ Ξ_b' states have significant decay rates into ΛB; (iii) While, the ρ-mode $1D$ Ξ_b' states are predicted to be very broad states with a width of about several hundreds of MeV, it is a great challenge to explore the ρ-mode $1D$ Ξ_b' states in experiments because of their broad widths.

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I. INTRODUCTION

Based on the constituent quark model [1,2], singly bottom baryons contain a b quark and two light quarks. If the two light quarks are u or d quarks, these singly bottom baryons are classified into the Λ_b and Σ_b baryon families with light diquark spin s_ρ being 0 and 1, respectively. When the two light quarks both are s quarks, then these singly bottom baryons form the Ω_b family with the light diquark spin s_ρ being 1. A singly bottom baryon containing one s quark forms the Ξ_b or Ξ_b' family according to whether the light diquark spin s_ρ is 0 or 1. Research of singly bottom baryons gets much attention because the mass of bottom quark m_b is marginally larger than the QCD energy scale. Hence, studies of their various properties can provide valuable validation to the understanding of the nonperturbative energy-region quantum chromodynamics, which features the behavior of strong interactions.

During the past few decades, experimenters have made important progress in establishing and perfecting the singly bottom baryon spectrum. Until now, all the $1S$ singly bottom baryons were well-established in experiments except for Ω_b^* [3]. Meanwhile, there are several higher candidates observed by experiments; nine $1P$ candidates, one $2S$ candidate, and two $1D$ candidates. These observed singly bottom baryons may provide an access point for the study of quantum chromodynamics and have attracted significant attention from the hadron physics community. Their mass spectra and strong decay properties were extensively explored with various theoretical methods and models [4–23]. More detailed information can be found in Refs. [24,25].

Last year, the LHCb Collaboration reported two narrow resonances, $\Xi_b(6327)^0$ and $\Xi_b(6333)^0$, in the $\Lambda_b^0 K^-\pi^+$ mass spectrum [26]. Their masses and decay widths are, respectively,

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TABLE I. Predicted mass of $1D$-wave excited Ξ_b an Ξ_b' baryons in various quark models.

Notation	Quantum number						Mass						Decay channel
$\Xi_b\vert J^P, j\rangle_{\lambda(\rho)}$	l_λ	l_ρ	L	s_ρ	j	J^P	GIM [37]	hCQM [29]	QPM [31]	RQM [4]	hCQM [28]	QCD [32]	
$\Xi_b\vert J^P=\frac{3}{2}^+,2\rangle_{\lambda\lambda}$	2	0	2	0	2	$\frac{3}{2}^+$	6320	6386	6327	6366	6243	6340	$\Xi_b'^{(*)}\pi, \Sigma_b^{(*)}K$
$\Xi_b\vert J^P=\frac{5}{2}^+,2\rangle_{\lambda\lambda}$	2	0	2	0	2	$\frac{5}{2}^+$	6327	6369	6330	6373	6240	6360	
$\Xi_b\vert J^P=\frac{3}{2}^+,2\rangle_{\rho\rho}$	0	2	2	0	2	$\frac{3}{2}^+$						6420	
$\Xi_b\vert J^P=\frac{5}{2}^+,2\rangle_{\rho\rho}$	0	2	2	0	2	$\frac{5}{2}^+$						6430	
$\Xi_b'\vert J^P=\frac{1}{2}^+,1\rangle_{\lambda\lambda}$	2	0	2	1	1	$\frac{1}{2}^+$	6460		6486	6447	6380		$\Xi_b\pi, \Xi_b'^{(*)}\pi, \Xi_b'^{(*)}\eta, \Sigma_b^{(*)}K, \Lambda_b K, \Lambda B, \Sigma B,$
$\Xi_b'\vert J^P=\frac{3}{2}^+,1\rangle_{\lambda\lambda}$	2	0	2	1	1	$\frac{3}{2}^+$	6466		6488	6459	6375		$\vert\Lambda_b P_\lambda\rangle K, \vert\Xi_b(\Xi_b')P_\lambda\rangle\pi$
$\Xi_b'\vert J^P=\frac{3}{2}^+,2\rangle_{\lambda\lambda}$	2	0	2	1	2	$\frac{3}{2}^+$	6460		6456	6431	6377		
$\Xi_b'\vert J^P=\frac{5}{2}^+,2\rangle_{\lambda\lambda}$	2	0	2	1	2	$\frac{5}{2}^+$	6466		6457	6432	6371		
$\Xi_b'\vert J^P=\frac{5}{2}^+,3\rangle_{\lambda\lambda}$	2	0	2	1	3	$\frac{5}{2}^+$	6460		6407	6420	6373		
$\Xi_b'\vert J^P=\frac{7}{2}^+,3\rangle_{\lambda\lambda}$	2	0	2	1	3	$\frac{7}{2}^+$	6467		6408	6414	6368		
$\Xi_b'\vert J^P=\frac{1}{2}^+,1\rangle_{\rho\rho}$	0	2	2	1	1	$\frac{1}{2}^+$							$\Xi_b\pi, \Xi_b'^{(*)}\pi, \Xi_b'^{(*)}\eta, \Sigma_b^{(*)}K, \Lambda_b K,$
$\Xi_b'\vert J^P=\frac{3}{2}^+,1\rangle_{\rho\rho}$	0	2	2	1	1	$\frac{3}{2}^+$							$\vert\Lambda_b P_\lambda\rangle K, \vert\Xi_b(\Xi_b')P_\lambda\rangle\pi$
$\Xi_b'\vert J^P=\frac{3}{2}^+,2\rangle_{\rho\rho}$	0	2	2	1	2	$\frac{3}{2}^+$							
$\Xi_b'\vert J^P=\frac{5}{2}^+,2\rangle_{\rho\rho}$	0	2	2	1	2	$\frac{5}{2}^+$							
$\Xi_b'\vert J^P=\frac{5}{2}^+,3\rangle_{\rho\rho}$	0	2	2	1	3	$\frac{5}{2}^+$							
$\Xi_b'\vert J^P=\frac{7}{2}^+,3\rangle_{\rho\rho}$	0	2	2	1	3	$\frac{7}{2}^+$							

$$m\left[\Xi_b(6327)^0\right] = 6327.28^{+0.23}_{-0.21} \pm 0.12 \pm 0.24 \text{ MeV}, \quad (1)$$

$$\Gamma\left[(\Xi_b(6327)^0)\right] = 0.93^{+0.74}_{-0.60} \text{ MeV}, \quad (2)$$

$$m\left[\Xi_b(6333)^0\right] = 6332.69^{+0.17}_{-0.18} \pm 0.03 \pm 0.22 \text{ MeV}, \quad (3)$$

$$\Gamma\left[(\Xi_b(6333)^0)\right] = 0.25^{+0.58}_{-0.25} \text{ MeV}. \quad (4)$$

Moreover, it is found that the lighter state $\Xi_b(6327)^0$ predominantly decays to $\Sigma_b^+ K^-$, while the heavier state $\Xi_b(6333)^0$ has a significant decay rate into $\Sigma_b^{*+} K^-$. According to the previous study of the $\Xi_b^{(\prime)}$ baryon spectrum [4,10,22,27–39], the two newly observed Ξ_b^0 states [26] may be λ-mode $1D$ Ξ_b states (see Table I). In addition, the few works on strong decay properties also support the two newly states as λ-mode $1D$ Ξ_b states with $J^p = 3/2^+$ and $J^P = 5/2^+$ [31,32,39–42].

In our previous work [42], we systematically investigated the strong transitions of the low-lying $1D$-wave Ξ_b/Ξ_b' resonances with the chiral quark model (ChQM) and gave an explanation of the two newly observed Ξ_b states [26]. We noticed that for the low-lying $1D$-wave Ξ_b/Ξ_b' resonances, their masses are large enough to allow the decay channels containing a heavy-light flavor meson. Hence, it is suitable to apply the quark-pair creation (QPC) strong-decay model to discuss those decay channels, which have not been studied systematically. Meanwhile, for further understanding the inner structures of the 1D-wave Ξ_b/Ξ_b' baryons, it is necessary to make a comparison of the theoretical predictions from the QPC model to the results with the chiral quark model [42]. Thus, in this work, we conduct a systematic analysis of the two-body strong decays of the $1D$-wave Ξ_b/Ξ_b' baryons with the QPC model under the $j-j$ coupling scheme, which may provide more information of their strong decays. The quark model classification predicted masses and OZI-allowed decay modes are summarized in Table I.

This paper is organized as follows. In Sec. II, we briefly introduce the mechanism of QPC model and present the parameter values. Then we give our theoretical results and discussions in Sec. III. Finally, we give a summary of our results in Sec. IV.

II. QPC MODEL

The QPC model [43,44], also famous as $^3P_0$ model, plays an important role in studying the strong decay behaviors of the mesons and baryons [23,36,45–58]. The main idea of this model is that strong decays take place via the creation of quark-antiquark pair from the vacuum with quantum number 0^{++}. For baryon decays, one quark of the initial baryon A regroups with the created antiquark to form a meson C and the other two quarks regroup with the created quark to form a daughter baryon B. Here, we adopt this model to study the strong decays of $\Xi_b^{(\prime)}$ baryons. The $\Xi_b^{(\prime)}$ baryon is made of two light flavor quarks (u, s) and a heavy flavor quark b. According to the quark

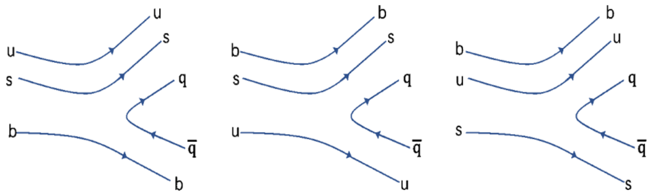

FIG. 1. Decay process of $\Xi_b^{(\prime)}$ in QPC model.

rearrangement process, any of the three quarks in the initial baryon can go into the final meson. Hence, as shown in Fig. 1 there are three possible ways for decay. Meanwhile, the possible final states of Ξ_b and Ξ_b' are listed in Table I.

In the nonrelativistic limit, the transition operator under the QPC model is given by

$$T = -3\gamma\sum_m \langle 1m1-m|00\rangle \int d^3\mathbf{p}_4 d^3\mathbf{p}_5 \delta^3(\mathbf{p}_4+\mathbf{p}_5) \times \mathcal{Y}_1^m\left(\frac{\mathbf{p}_4-\mathbf{p}_5}{2}\right)\chi_{1-m}^{45}\phi_0^{45}\omega_0^{45}a_{4i}^\dagger(\mathbf{p}_4)b_{5j}^\dagger(\mathbf{p}_5), \tag{5}$$

where γ is a parameter of vacuum pair-production strength. $\mathbf{p}_4$ and $\mathbf{p}_5$ present the momenta of the two created quarks, respectively. $\omega_0^{45} = \delta_{ij}$, $\phi_0^{45} = (\mathrm{u\bar{u}} + \mathrm{d\bar{d}} + \mathrm{s\bar{s}})/\sqrt{3}$ and χ_{1-m}^{45} represent the wave function of quark pair flavor singlet, color singlet, and spin triplet state, respectively. The solid harmonic polynomial $\mathcal{Y}_1^m = |\mathbf{p}|\mathrm{Y}_1^m(\theta_p\phi_p)$ reflects the momentum-space distribution and the creation operator $a_{4i}^\dagger d_{5j}^\dagger$ denotes the quark pair creation in the vacuum.

According to the definition of the mock state in the constituent quark model [59], the spatial wave functions of the initial baryon A or final baryon B is

$$\begin{aligned}&|A(N_A^{2S_A+1}L_AJ_AM_{J_A})(\mathbf{p}_A)\rangle \\ &= \sqrt{2E_A}\varphi_A^{123}\omega_A^{123}\sum_{M_{L_A},M_{S_A}}\langle L_AM_{L_A};S_AM_{S_A}|J_A,M_{J_A}\rangle \\ &\times\int d^3\mathbf{p}_1 d^3\mathbf{p}_2 d^3\mathbf{p}_3\delta^3(\mathbf{p}_1+\mathbf{p}_2+\mathbf{p}_3-\mathbf{p}_A) \\ &\times\Psi_{N_AL_AM_{L_A}(\mathbf{p}_1\mathbf{p}_2\mathbf{p}_3)}\chi_{S_AM_{S_A}}^{123}|q_1(\mathbf{p}_1)q_2(\mathbf{p}_2)q_3(\mathbf{p}_3)\rangle.,\end{aligned} \tag{6}$$

Similarly, the spatial wave function of final meson C is

$$\begin{aligned}&|C(N_C^{2S_C+1}L_CJ_CM_{J_C})(\mathbf{p}_C)\rangle \\ &= \sqrt{2E_C}\varphi_C^{ab}\omega_C^{ab}\sum_{M_{L_C}M_{S_C}}\langle L_CM_{L_C};S_CM_{S_C}|J_CM_{J_C}\rangle \\ &\times\int d^3\mathbf{p}_a d^3\mathbf{p}_b\delta^3(\mathbf{p}_a+\mathbf{p}_b-\mathbf{p}_C) \\ &\times\Psi_{N_CL_CM_{L_C}(\mathbf{p}_a\mathbf{p}_b)}\chi_{S_CM_{S_C}}^{ab}|q_a(\mathbf{p}_a)q_b(\mathbf{p}_b)\rangle,\end{aligned} \tag{7}$$

where $\mathbf{p}_i$ (i = 1, 2, 3 and a, b) denotes the momentum of quarks in hadron A and C. $\mathbf{P}_A$ and $\mathbf{P}_C$ are the momenta of initial baryon A and final meson C, respectively. In the present work, the spatial wave function of a baryon or meson is described with a simple harmonic oscillator space wave function. Hence, the spatial wave function of baryon A or B without the radial excitation is

$$\begin{aligned}&\psi(l_\rho,m_\rho,l_\lambda,m_\lambda) \\ &= 3^{\frac{3}{4}}(-i)_\rho^l\left[\frac{2^{l_\rho+2}}{\sqrt{\pi}(2l_\rho+1)!!}\right]^{\frac{1}{2}}\left(\frac{1}{\alpha}\right)^{l_\rho+\frac{3}{2}}\exp\left(-\frac{\mathbf{p}_\rho^2}{2\alpha_\rho^2}\right)\mathcal{Y}_{l_\rho}^{m_\rho}(\mathbf{p}_\rho) \\ &\times(-i)_\lambda^l\left[\frac{2^{l_\lambda+2}}{\sqrt{\pi}(2l_\lambda+1)!!}\right]^{\frac{1}{2}}\left(\frac{1}{\alpha}\right)^{l_\lambda+\frac{3}{2}}\exp\left(-\frac{\mathbf{p}_\lambda^2}{2\alpha_\lambda^2}\right)\mathcal{Y}_{l_\lambda}^{m_\lambda}(\mathbf{p}_\lambda).\end{aligned} \tag{8}$$

The ground-state spatial wave function of meson C is

$$\psi_{0,0} = \left(\frac{R^2}{\pi}\right)^{\frac{3}{4}}\exp\left(-\frac{R^2\mathbf{p}_{ab}^2}{2}\right), \tag{9}$$

where $\mathbf{p}_{ab}$ stands for the relative momentum between the quark and antiquark in the meson. Then, the partial decay amplitude in the center of mass frame can be obtained

$$\begin{aligned}&\mathcal{M}^{M_{J_A}M_{J_B}M_{J_C}}(A\to B+C) \\ &= \gamma\sqrt{8E_AE_BE_C}\prod_{A,B,C}\langle\chi_{S_BM_{S_B}}^{124}\chi_{S_CM_{S_C}}^{35}|\chi_{S_AM_{S_A}}^{123}\chi_{1-m}^{45}\rangle \\ &\times\langle\varphi_B^{124}\varphi_C^{35}|\varphi_A^{123}\varphi_0^{45}\rangle I_{M_{L_B},M_{L_C}}^{M_{L_A},m}(\mathbf{p}),\end{aligned} \tag{10}$$

where $I_{M_{L_B},M_{L_C}}^{M_{L_A},m}(\mathbf{p})$ is the abbreviation of spatial integral. The Clebsch-Gorden coefficients $\prod_{A,B,C}$ can be expanded as

$$\sum\langle L_AM_{L_B};S_BM_{S_B}|J_B,M_{J_B}\rangle\langle L_AM_{L_C};S_CM_{S_C}|J_C,M_{J_C}\rangle \times\langle L_AM_{L_A};S_AM_{S_A}|J_A,M_{J_A}\rangle\langle 1m;1-m|00\rangle. \tag{11}$$

Eventually, the decay width of initial state A to final states B and C can be calculated by the following formula:

$$\Gamma(A\to BC) = \pi^2\frac{|\mathbf{p}|}{M_A^2}\frac{1}{2J_A+1}\sum_{M_{J_A},M_{J_B},M_{J_C}}|\mathcal{M}^{M_{J_A},M_{J_B},M_{J_C}}|^2, \tag{12}$$

where $\mathbf{P}$ is the momentum of the baryon B in the center of mass frame of the baryon A, which can be achieved by

$$|\mathbf{p}| = \frac{\sqrt{[M_A^2-(M_B-M_C)^2][M_A^2-(M_B+M_C)^2]}}{2M_A}. \tag{13}$$

It should be noted that according to our previous works, the physical properties of the singly heavy baryons tend to be better interpreted in the $j-j$ coupling scheme than the $L-S$ scheme. Thus, in this work we study the strong decay properties of $\Xi_b^{(\prime)}$ resonances within this coupling scheme. In the heavy quark symmetry limit, the states within the $j-j$ coupling scheme are constructed by

$$|J^P, j\rangle = \left|\left\{[(l_\rho l_\lambda)_L s_\rho]_j s_Q\right\}_{J^P}\right\rangle. \tag{14}$$

The states within the $j-j$ coupling scheme can be expressed as linear combinations of the states within the $L-S$ coupling,

$$\begin{aligned}\left|\left\{[(l_\rho l_\lambda)_L s_\rho]_j s_Q\right\}_{J^P}\right\rangle &= (-1)^{L+s_\rho+\frac{1}{2}+J}\sqrt{2J+1}\sum_S\sqrt{2S+1} \\ &\times \begin{pmatrix} L & s_\rho & j \\ s_Q & J & S \end{pmatrix}\left|\left\{[(l_\rho l_\lambda)_L (s_\rho s_Q)_S]_J\right\}\right\rangle. \end{aligned}\tag{15}$$

In the expression, l_ρ and l_λ are the $\rho-$ and λ–modes quantum numbers of the orbital angular, respectively. The total orbital angular momentum $L = |l_\rho - l_\lambda|, \ldots, l_\rho + l_\lambda$. s_ρ is the quantum number of the total spin of the two light quarks and s_Q is the spin of the heavy quark. The total-spin angular momentum $S = |s_\rho - s_Q|, \ldots, s_\rho + s_Q$. J is the total angular momentum. For $1D$ Ξ_b states with $S = 1/2$, the relationship can be expressed as

$$\Xi_b\left|J^P = \frac{3^+}{2}, 2\right\rangle_{\lambda\lambda(\rho\rho)} = \left|\Xi_b{}^2D_{\lambda\lambda(\rho\rho)}\frac{3^+}{2}\right\rangle, \tag{16}$$

$$\Xi_b\left|J^P = \frac{5^+}{2}, 2\right\rangle_{\lambda\lambda(\rho\rho)} = \left|\Xi_b{}^2D_{\lambda\lambda(\rho\rho)}\frac{5^+}{2}\right\rangle. \tag{17}$$

For $1D$ Ξ_b' with $S = 1/2$ or $3/2$, the relationship can be expressed as

$$\Xi_b'\left|J^P = \frac{1^+}{2}, 1\right\rangle_{\lambda\lambda(\rho\rho)} = \left|\Xi_b'{}^4D_{\lambda\lambda(\rho\rho)}\frac{1^+}{2}\right\rangle, \tag{18}$$

$$\begin{aligned}\Xi_b'\left|J^P = \frac{3^+}{2}, 1\right\rangle_{\lambda\lambda(\rho\rho)} &= \sqrt{\frac{1}{2}}\left|\Xi_b'{}^4D_{\lambda\lambda(\rho\rho)}\frac{3^+}{2}\right\rangle \\ &- \sqrt{\frac{1}{2}}\left|\Xi_b'{}^2D_{\lambda\lambda(\rho\rho)}\frac{3^+}{2}\right\rangle, \end{aligned}\tag{19}$$

$$\begin{aligned}\Xi_b'\left|J^P = \frac{3^+}{2}, 2\right\rangle_{\lambda\lambda(\rho\rho)} &= \sqrt{\frac{1}{2}}\left|\Xi_b'{}^4D_{\lambda\lambda(\rho\rho)}\frac{3^+}{2}\right\rangle \\ &+ \sqrt{\frac{1}{2}}\left|\Xi_b'{}^2D_{\lambda\lambda(\rho\rho)}\frac{3^+}{2}\right\rangle, \end{aligned}\tag{20}$$

$$\begin{aligned}\Xi_b'\left|J^P = \frac{5^+}{2}, 2\right\rangle_{\lambda\lambda(\rho\rho)} &= \frac{\sqrt{7}}{3}\left|\Xi_b'{}^4D_{\lambda\lambda(\rho\rho)}\frac{3^+}{2}\right\rangle \\ &- \frac{\sqrt{2}}{3}\left|\Xi_b'{}^2D_{\lambda\lambda(\rho\rho)}\frac{3^+}{2}\right\rangle, \end{aligned}\tag{21}$$

$$\begin{aligned}\Xi_b'\left|J^P = \frac{5^+}{2}, 3\right\rangle_{\lambda\lambda(\rho\rho)} &= \frac{\sqrt{2}}{3}\left|\Xi_b'{}^4D_{\lambda\lambda(\rho\rho)}\frac{3^+}{2}\right\rangle \\ &+ \frac{\sqrt{7}}{3}\left|\Xi_b'{}^2D_{\lambda\lambda(\rho\rho)}\frac{3^+}{2}\right\rangle, \end{aligned}\tag{22}$$

$$\Xi_b'\left|J^P = \frac{7^+}{2}, 3\right\rangle_{\lambda\lambda(\rho\rho)} = \left|\Xi_b'{}^4D_{\lambda\lambda(\rho\rho)}\frac{7^+}{2}\right\rangle. \tag{23}$$

In our calculation, we adopt $m_u = m_d = 330$ MeV, $m_s = 450$ MeV, and $m_b = 5000$ MeV for the constituent quark mass. The value of the harmonic oscillator strength R is 2.5 GeV^{-1} for all light flavor mesons, while it is R = 1.67 GeV^{-1} for the B meson [60]. The parameter α_ρ of the ρ-mode excitation between u/d and s quarks is taken as $\alpha_\rho = 0.42$ GeV. Another harmonic oscillator parameter α_λ is obtained by [61]

$$\alpha_\lambda = \left(\frac{3m_3}{m_1 + m_2 + m_3}\right)^{\frac{1}{4}}\alpha_\rho. \tag{24}$$

The value of vacuum pair-production strength γ is set as 6.95, consistent with our previous work. For the strange quark pair $s\bar{s}$ creation, we use $\gamma_{s\bar{s}} = 6.95/\sqrt{3}$. Additionally, the masses of final baryons and mesons were derived by the Particle Data Group [62].

III. CALCULATIONS AND RESULTS

In this work, we present a systematic study of the $1D$-wave $\Xi_b^{(\prime)}$ baryons' strong decay within the $j-j$ coupling scheme in the framework of the QPC model. Both λ-mode and ρ-mode excitations are taken into consideration. Meanwhile, by comparing the calculated results with experimental information, we also give the possible explanations of the newly observed states $\Xi_b(6327)^0$ and $\Xi_b(6333)^0$. Moreover, we hope the theoretical predictions could provide useful information in searching for the missing $1D$-wave $\Xi_b^{(\prime)}$ states.

A. The 1*D*-wave Ξ_b states

According to the symmetry of wave functions, there are four $1D$-wave Ξ_b baryons (see Table I): two λ-mode states $\Xi_b|J^P = \frac{3}{2}^+, 2\rangle_{\lambda\lambda}$ and $\Xi_b|J^P = \frac{5}{2}^+, 2\rangle_{\lambda\lambda}$, and two ρ-mode states $\Xi_b|J^P = \frac{3}{2}^+, 2\rangle_{\rho\rho}$ and $\Xi_b|J^P = \frac{5}{2}^+, 2\rangle_{\rho\rho}$. In the following we discuss their strong-decay properties carefully.

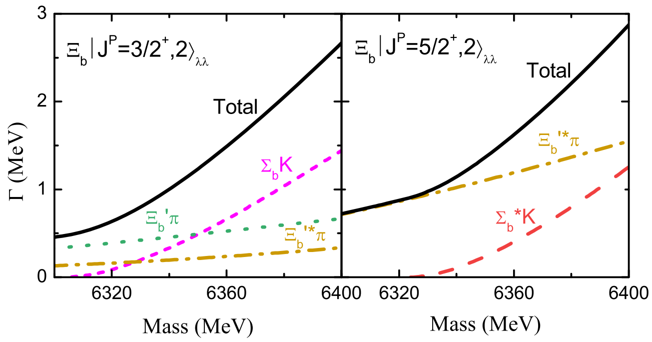

FIG. 2. Partial and total strong decay widths of the λ-mode $1D$ Ξ_b states as a function of the masses. Some decay channels are not shown in the figure for their small partial decay widths.

1. λ-mode excitations

As shown in Table I, the masses of two $1D$ λ-mode Ξ_b baryons $\Xi_b|J^P=\frac{3}{2}^+,2\rangle_{\lambda\lambda}$ and $\Xi_b|J^P=\frac{5}{2}^+,2\rangle_{\lambda\lambda}$ fluctuate around $\sim$6.35 GeV. Considering the uncertainty of the mass predictions, we plot their decay widths as a function of the mass in the range $M\sim(6.30–6.40)$ GeV in Fig. 2. From the figure, we obtain that the two $1D$ λ-mode Ξ_b baryons are likely to be narrow states. As the mass increases within (6.30–6.40) GeV, the partial decay widths increase stably, and the total decay widths vary within the scope of $\Gamma<3$ MeV. Similar results were also obtained in previous works [31,40,42].

For the $J^P=3/2^+$ state $\Xi_b|J^P=\frac{3}{2}^+,2\rangle_{\lambda\lambda}$, the main decay channels are $\Xi_b'\pi$, $\Xi_b'^*\pi$ and Σ_bK. Combining the predicted mass and decay properties, $\Xi_b|J^P=\frac{3}{2}^+,2\rangle_{\lambda\lambda}$ may be a candidate of the newly observed state $\Xi_b(6327)^0$. Hence, we fix the mass of $\Xi_b|J^P=\frac{3}{2}^+,2\rangle_{\lambda\lambda}$ at $M=6327$ MeV, and collect its decays in Table II. It is found that the total decay width is about

$$\Gamma_{\rm total}\simeq 0.74\ \text{MeV}. \tag{25}$$

This value is consistent with the observation and is about 3.4 times less than the value in Ref. [42]. Meanwhile, $\Xi_b|J^P=\frac{3}{2}^+,2\rangle_{\lambda\lambda}$ has a significant decay rate into Σ_bK, which is predicted to be

$$\frac{\Gamma[\Xi_b|J^P=3/2^+,2\rangle_{\lambda\lambda}\to\Sigma_bK]}{\Gamma_{\rm total}}\sim 22\%. \tag{26}$$

This result is in good agreement with the predictions in Ref. [42]. In addition, this state has large decay rates into the $\Xi_b'\pi$ and $\Xi_b'^*\pi$ channels with branching fractions of

$$\frac{\Gamma[\Xi_b|J^P=3/2^+,2\rangle_{\lambda\lambda}\to\Xi_b'\pi]}{\Gamma_{\rm total}}\sim 55\%, \tag{27}$$

$$\frac{\Gamma[\Xi_b|J^P=3/2^+,2\rangle_{\lambda\lambda}\to\Xi_b'^*\pi]}{\Gamma_{\rm total}}\sim 23\%. \tag{28}$$

Those results are good agreement with the ratios in Ref. [42] as well.

If the newly observed $\Xi_b(6327)^0$ state corresponds to $\Xi_b|J^P=\frac{3}{2}^+,2\rangle_{\lambda\lambda}$. Indeed, besides the $\Lambda_bK\pi$ final state by the intermediate channel Σ_bK, the $\Xi_b\pi\pi$ final state by the intermediate channels $\Xi_b'\pi$ and $\Xi_b'^{*\pi}$ may be another interesting channel for observing $\Xi_b(6327)^0$ in forthcoming experiments.

The $J^P=5/2^+$ state $\Xi_b|J^P=5/2^+,2\rangle_{\lambda\lambda}$ mainly decays into the $\Xi_b'^*\pi$ and Σ_b^*K channels. The $\Xi_b|J^P=5/2^+,2\rangle_{\lambda\lambda}$ may be an assignment of the newly observed state $\Xi_b(6333)^0$, since the Σ_b^*K mode has a significant contribution to the decay. Fixing the mass of $\Xi_b|J^P=5/2^+,2\rangle_{\lambda\lambda}$ at $M=6333$ MeV, we also collect its decay properties in Table II. From the table, we find that the total decay width

$$\Gamma_{\rm Total}\simeq 1.02\ \text{MeV}, \tag{29}$$

is about 2 times less than the result in Ref. [42] and close to the upper limit of the observed one. The branching fractions for the dominant decay channels are

TABLE II. The comparison of the partial decay widths of the 1D-wave Ξ_b states from the QPC model and the chiral quark model [42]. $\Gamma_{\rm Total}$ represent the total decay width and Expt. stands for the experimental value. The unit is MeV.

	$\Xi_b\vert J^P=\frac{3}{2}^+,2\rangle_{\lambda\lambda}$		$\Xi_b\vert J^P=\frac{5}{2}^+,2\rangle_{\lambda\lambda}$		$\Xi_b\vert J^P=\frac{3}{2}^+,2\rangle_{\rho\rho}$		$\Xi_b\vert J^P=\frac{5}{2}^+,2\rangle_{\rho\rho}$	
	$\Xi_b(6327)^0$		$\Xi_b(6333)^0$		$M=6420$		$M=6430$	
Decay width	QPC	ChQM [42]	QPC	ChQM [42]	QPC	ChQM [42]	QPC	ChQM [42]
$\Gamma[\Sigma_bK]$	0.16	0.59	…	…	17.7	8.59	0.67	0.34
$\Gamma[\Sigma_b^*K]$	…	…	0.04	0.11	2.91	1.56	18.2	9.25
$\Gamma[\Xi_b'\pi]$	0.41	1.30	0.02	0.41	21.6	4.63	1.57	0.95
$\Gamma[\Xi_b'^*\pi]$	0.17	0.67	0.96	1.64	6.02	1.97	27.0	5.87
Γ[Total]	0.74	2.56	1.02	2.16	48.3	16.75	47.5	16.42
Expt.	$0.93^{+0.74}_{-0.60}$		$0.25^{+0.58}_{-0.25}$					

$$\frac{\Gamma[\Xi_b|J^P=5/2^+,2\rangle_{\lambda\lambda}\to\Sigma_b^*K]}{\Gamma_{\text{total}}}\sim 4\%,$$
$$\frac{\Gamma[\Xi_b|J^P=5/2^+,2\rangle_{\lambda\lambda}\to\Xi_b'^*\pi]}{\Gamma_{\text{total}}}\sim 94\%. \quad (30)$$

According to our calculations, the $\Xi_b|J^P=5/2^+,2\rangle_{\lambda\lambda}$ state is almost saturated by the $\Xi_b'^*\pi$ decay channel. Hence, to further decode the nature of $\Xi_b(6333)^0$, the $\Xi_b\pi\pi$ final state by the intermediate channel $\Xi_b'^*\pi$ is worth attention. This result is highly in agreement with the calculation in Ref. [42].

2. ρ-mode excitations

Discussions on ρ-mode excitation spectrum roughly estimates the mass of the ρ-mode excitation to be about 100 MeV heavier that those of the λ-mode excitation [34]. Thus, we discuss the decay properties of the two ρ-mode $1D$ Ξ_b states as a function of the mass within the possible range $M\sim(6.40\text{–}6.50)$ GeV in Fig. 3. As shown in the figure the two states, $\Xi_b|J^P=3/2^+,2\rangle_{\rho\rho}$ and $\Xi_b|J^P=5/2^+,2\rangle_{\rho\rho}$, are probably moderate states with a width of dozens of MeV. The $\Xi_b|J^P=3/2^+,2\rangle_{\rho\rho}$ state dominantly decays into the $\Xi_b'\pi$, Σ_bK and $\Xi_b'^*\pi$ channels while the $\Xi_b|J^P=5/2^+,2\rangle_{\rho\rho}$ state mainly decays into the Σ_b^*K and $\Xi_b'^*\pi$ channels.

To show the decay properties of the two ρ-mode $1D$ Ξ_b states in a more comprehensible way, we further fix their masses to be the predicted masses in Ref. [32] and collect their decays in Table II. We also give the results from Ref. [42] in Table II for comparison.

With the mass of $\Xi_b|J^P=3/2^+,2\rangle_{\rho\rho}$ fixed on $M=6420$ MeV, the total decay width

$$\Gamma_{\text{Total}}\simeq 48.3\ \text{MeV}, \quad (31)$$

is about 3 times larger than the result in Ref. [42]. The predicted partial width ratio between the main decay channels Σ_bK and $\Xi_b'\pi$ is

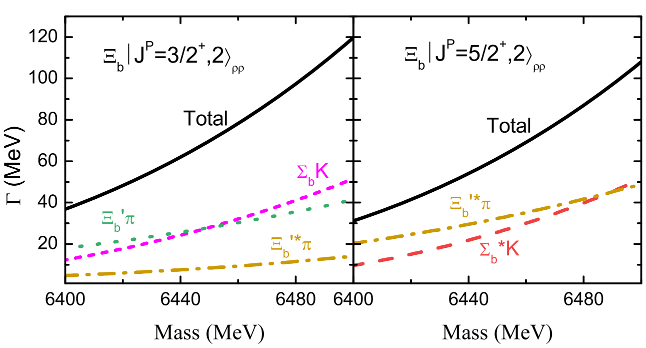

FIG. 3. Partial and total strong decay widths of the ρ-mode $1D$ Ξ_b states as a function of the masses. Some decay channels are not shown in the figure because of their small partial decay widths.

$$\frac{\Gamma[\Xi_b|J^P=3/2^+,2\rangle_{\rho\rho}\to\Sigma_bK]}{\Gamma[\Xi_b|J^P=3/2^+,2\rangle_{\rho\rho}\to\Xi_b'\pi]}\simeq 0.82. \quad (32)$$

The other ρ-mode $1D$ Ξ_b state $\Xi_b|J^P=5/2^+,2\rangle_{\rho\rho}$ has a comparative decay width with $\Xi_b|J^P=3/2^+,2\rangle_{\rho\rho}$ when we fix the mass to be $M=6430$ MeV. While the main decay channels of the $\Xi_b|J^P=5/2^+,2\rangle_{\rho\rho}$ are Σ_b^*K and $\Xi_b'^*\pi$ and the predicted partial width ratio is

$$\frac{\Gamma[\Xi_b|J^P=5/2^+,2\rangle_{\rho\rho}\to\Sigma_b^*K]}{\Gamma[\Xi_b|J^P=3/2^+,2\rangle_{\rho\rho}\to\Xi_b'^*\pi]}\simeq 0.67. \quad (33)$$

Different dominant decay channels can be used to distinguish the two ρ-mode $1D$ Ξ_b states.

B. The 1D-wave Ξ_b' states

Based on the classification of the quark model, there are six ρ-mode $1D$-wave Ξ_b' states and six λ-mode D-wave Ξ_b' states. According to the theoretical predictions by various quark models (see Table I), the masses of the λ-mode $1D$ Ξ_b' vary in the range of $M\sim(6.40\text{–}6.50)$ GeV. Meanwhile, we notice that the mass predictions for the ρ-mode $1D$-wave Ξ_b' states are less, which may be ∼100 MeV heavier than those of the λ-mode excitations. Hence, the masses of the ρ-mode $1D$-wave Ξ_b' states may be in the scope of $M\sim(6.50\text{–}6.60)$ GeV. Because of the high masses of the $1D$ Ξ_b' excitations, there are many new decay channels available compared to the $1D$ Ξ_b baryons, such as the decay channels containing a $1P$-wave bottom baryon or B meson. It should be noted that the $\Lambda/\Sigma B$ decay channel for ρ-mode excitations is forbidden due to the orthogonality of the spatial wave function. Thus, for the ρ-mode $1D$-wave Ξ_b' excitations, we only focus on the decay channels containing light K and π mesons.

1. λ-mode excitations

The six $1D$-wave λ-mode excited Ξ_b' states within $j-j$ coupling scheme are $\Xi_b'|J^P=1/2^+,1\rangle_{\lambda\lambda}$, $\Xi_b'|J^P=3/2^+,1\rangle_{\lambda\lambda}$, $\Xi_b'|J^P=3/2^+,2\rangle_{\lambda\lambda}$, $\Xi_b'|J^P=5/2^+,2\rangle_{\lambda\lambda}$, $\Xi_b'|J^P=5/2^+,3\rangle_{\lambda\lambda}$, and $\Xi_b'|J^P=7/2^+,3\rangle_{\lambda\lambda}$. First, we fix their masses on the predictions within the QCD-motivated relative quark model in Ref. [4], and collect the decay properties in Table III.

The $J^P=1/2^+$ state $\Xi_b'|J^P=1/2^+,1\rangle_{\lambda\lambda}$ may be a moderate state with a width of $\Gamma_{\text{Total}}\simeq 136.7$ MeV, which is about 2 times greater than the value in Ref. [42]. Furthermore, we find that this state mainly decays into $\Xi_b|J^P=1/2^-,1\rangle_\lambda\pi$, $\Lambda_b|J^P=1/2^-,1\rangle_\lambda K$ and $\Xi_b'|J^P=1/2^-,1\rangle_\lambda\pi$. The predicted partial width ratios are

TABLE III. The comparison of the partial decay widths of the $1D$-wave Ξ_b' states from the QPC model and the chiral quark model [42]. The masses of λ-mode excitations are taken from the predictions in Ref. [4]. While, the masse of the ρ-mode excitations are fixed on the values which are 100 MeV heavier than the corresponding masses of the λ-mode excitations. $\Gamma_{\rm Total}$ represents the total decay width and the unit is MeV.

	$\Xi_b'\lvert J^P=\frac{1}{2}^+,1\rangle_{\lambda\lambda}$		$\Xi_b'\lvert J^P=\frac{3}{2}^+,1\rangle_{\lambda\lambda}$		$\Xi_b'\lvert J^P=\frac{3}{2}^+,2\rangle_{\lambda\lambda}$		$\Xi_b'\lvert J^P=\frac{5}{2}^+,2\rangle_{\lambda\lambda}$		$\Xi_b'\lvert J^P=\frac{5}{2}^+,3\rangle_{\lambda\lambda}$		$\Xi_b'\lvert J^P=\frac{7}{2}^+,3\rangle_{\lambda\lambda}$	
	$M=6447$		$M=6459$		$M=6431$		$M=6432$		$M=6420$		$M=6414$	
Decay width	QPC	ChQM [42]	QPC	ChQM [42]	QPC	ChQM [42]	QPC	ChQM [42]	QPC	ChQM [42]	QPC	ChQM [42]
$\Gamma[\Lambda_b K]$	2.8	2.4	2.8	2.1	⋯	⋯	1.3	⋯	2.0	5.8	0.5	5.4
$\Gamma[\Sigma_b^* K]$	0.7	1.8	1.9	4.9	0.5	1.8	3.1	6.8	⋯	0.8	⋯	0.1
$\Gamma[\Sigma_b K]$	1.6	4.1	0.4	1.1	3.1	8.4	1.0	0.5	3.6	0.4	⋯	0.2
$\Gamma[\Xi_b \eta]$	0.4	0.4	0.5	0.1	⋯	0.1	0.1	0.9	0.2	0.2	⋯	⋯
$\Gamma[\Xi_b \pi]$	4.6	2.2	4.6	2.0	⋯	⋯	2.0	⋯	3.2	9.6	0.5	9.1
$\Gamma[\Xi_b' \pi]$	1.1	1.3	0.3	0.3	2.3	2.9	0.8	1.3	3.2	1.2	⋯	0.6
$\Gamma[\Xi_b'^* \pi]$	0.5	0.6	1.3	1.6	0.5	2.3	2.6	4.1	0.1	2.1	0.1	0.6
$\Gamma[\Lambda B]$	10.7		0.9		3.8		⋯		⋯		⋯	
$\Gamma[\Lambda_b\lvert J^P=1/2^-,1\rangle_\lambda K]$	34.7	32.3	⋯	0.2	⋯	1.1	⋯	2.6	⋯	0.1	⋯	⋯
$\Gamma[\Lambda_b\lvert J^P=3/2^-,1\rangle_\lambda K]$	⋯	0.1	36.0	15.8	⋯	1.4	⋯	⋯	⋯	0.2		⋯
$\Gamma[\Xi_b\lvert J^P=1/2^-,1\rangle_\lambda \pi]$	52.0	13.8	⋯	1.1	0.1	0.4	⋯	0.6	0.3	0.5	⋯	⋯
$\Gamma[\Xi_b\lvert J^P=3/2^-,1\rangle_\lambda \pi]$	⋯	0.4	52.3	10.2	0.1	1.0	0.1	0.2	0.1	0.1	0.2	1.5
$\Gamma[\Xi_b'\lvert J^P=1/2^-,0\rangle_\lambda \pi]$	⋯	1.0	⋯	0.1	11.2	0.2	⋯	0.1	⋯	⋯	⋯	⋯
$\Gamma[\Xi_b'\lvert J^P=1/2^-,1\rangle_\lambda \pi]$	21.4	9.0	⋯	⋯	⋯	0.1	⋯	0.1	0.1	0.1	0.2	⋯
$\Gamma[\Xi_b'\lvert J^P=3/2^-,1\rangle_\lambda \pi]$	⋯	0.9	3.0	0.3	1.3	0.6	0.7	⋯	0.7	⋯	0.8	⋯
$\Gamma[\Xi_b'\lvert J^P=3/2^-,2\rangle_\lambda \pi]$	⋯	0.3	1.9	⋯	18.0	6.2	0.2	⋯	0.2	⋯	0.2	⋯
$\Gamma[\Xi_b'\lvert J^P=5/2^-,2\rangle_\lambda \pi]$	6.1	0.6	1.6	0.2	1.8	0.1	3.3	1.3	2.4	⋯	0.5	⋯
$\Gamma_{\rm Total}$	136.7	71.2	107.6	40.0	42.6	26.6	15.3	18.5	16.0	21.0	3.0	17.5

	$\Xi_b'\lvert J^P=\frac{1}{2}^+,1\rangle_{\rho\rho}$		$\Xi_b'\lvert J^P=\frac{3}{2}^+,1\rangle_{\rho\rho}$		$\Xi_b'\lvert J^P=\frac{3}{2}^+,2\rangle_{\rho\rho}$		$\Xi_b'\lvert J^P=\frac{5}{2}^+,2\rangle_{\rho\rho}$		$\Xi_b'\lvert J^P=\frac{5}{2}^+,3\rangle_{\rho\rho}$		$\Xi_b'\lvert J^P=\frac{7}{2}^+,3\rangle_{\rho\rho}$	
	$M=6547$		$M=6559$		$M=6531$		$M=6532$		$M=6520$		$M=6514$	
Decay width	QPC	ChQM [42]	QPC	ChQM [42]	QPC	ChQM [42]	QPC	ChQM [42]	QPC	ChQM [42]	QPC	ChQM [42]
$\Gamma[\Lambda_b K]$	192.1	7.6	203.7	7.2	⋯	⋯	⋯	⋯	22.9	6.7	21.7	6.5
$\Gamma[\Sigma_b^* K]$	1.1	4.4	20.9	13.8	22.8	7.2	108.1	21.1	3.5	5.3	4.2	2.0
$\Gamma[\Sigma_b K]$	54.5	11.1	15.1	2.8	105.9	24.2	4.3	1.8	4.0	1.7	2.0	0.9
$\Gamma[\Xi_b \pi]$	259.9	11.0	275.9	10.6	⋯	⋯	⋯	⋯	26.8	10.5	25.4	10.1
$\Gamma[\Xi_b' \pi]$	38.4	4.3	5.2	1.1	77.5	9.6	4.0	2.0	3.9	2.0	2.1	1.1
$\Gamma[\Xi_b'^* \pi]$	0.3	2.1	45.9	5.4	19.3	4.8	195.6	11.4	11.0	5.3	9.3	2.7
$\Gamma[\Xi_b \eta]$	14.4	0.8	16.2	0.6	⋯	1.0	⋯	2.6	0.4	0.6	0.4	⋯
$\Gamma[\Xi_b' \eta]$	0.5	0.6	0.2	0.7	0.7	0.2	⋯	0.2	⋯	⋯	⋯	⋯
$\Gamma[\Xi_b'^* \eta]$	0.1	0.1	0.6	0.8	0.1	0.4	2.3	0.2	0.1	0.1	⋯	⋯
$\Gamma[\Lambda_b\lvert J^P=1/2^-,1\rangle_\lambda K]$	6.4	0.5	0.6	0.6	⋯	⋯	⋯	⋯	0.4	⋯	⋯	⋯
$\Gamma[\Lambda_b\lvert J^P=3/2^-,1\rangle_\lambda K]$	0.8	0.9	7.2	1.9	⋯	0.1	⋯	⋯	0.1	⋯	0.5	⋯
$\Gamma[\Xi_b\lvert J^P=1/2^-,1\rangle_\lambda \pi]$	9.8	0.5	0.9	0.5	⋯	⋯	⋯	⋯	0.8	0.1	⋯	0.1
$\Gamma[\Xi_b\lvert J^P=3/2^-,1\rangle_\lambda \pi]$	1.3	0.8	10.8	1.9	⋯	0.1	⋯	⋯	0.2	0.1	1.0	0.1
$\Gamma[\Xi_b'\lvert J^P=1/2^-,0\rangle_\lambda \pi]$	0.1	⋯	0.3	⋯	1.6	⋯	⋯	⋯	⋯	⋯	⋯	⋯
$\Gamma[\Xi_b'\lvert J^P=1/2^-,1\rangle_\lambda \pi]$	4.4	⋯	0.1	0.1	⋯	⋯	⋯	⋯	⋯	⋯	⋯	⋯
$\Gamma[\Xi_b'\lvert J^P=3/2^-,1\rangle_\lambda \pi]$	0.6	⋯	1.0	⋯	0.5	⋯	⋯	⋯	⋯	⋯	⋯	⋯
$\Gamma[\Xi_b'\lvert J^P=3/2^-,2\rangle_\lambda \pi]$	⋯	0.1	⋯	0.2	2.4	⋯	⋯	⋯	⋯	⋯	⋯	⋯
$\Gamma[\Xi_b'\lvert J^P=5/2^-,2\rangle_\lambda \pi]$	0.8	⋯	0.4	⋯	0.4	⋯	1.1	0.1	⋯	⋯	0.1	⋯
$\Gamma_{\rm Total}$	585.6	44.8	604.7	48.2	231.2	47.6	312.8	39.4	74.3	32.4	66.8	23.5

$$\frac{\Gamma[\Xi_b'|J^P=1/2^+,1\rangle_{\lambda\lambda}\to\Lambda_b|J^P=1/2^-,1\rangle_\lambda K]}{\Gamma[\Xi_b'|J^P=1/2^+,1\rangle_{\lambda\lambda}\to\Xi_b|J^P=1/2^-,1\rangle_\lambda \pi]}\simeq 0.67, \tag{34}$$

$$\frac{\Gamma[\Xi_b'|J^P=1/2^+,1\rangle_{\lambda\lambda}\to\Xi_b'|J^P=1/2^-,1\rangle_\lambda \pi]}{\Gamma[\Xi_b'|J^P=1/2^+,1\rangle_{\lambda\lambda}\to\Xi_b|J^P=1/2^-,1\rangle_\lambda \pi]}\simeq 0.41. \tag{35}$$

Hence, the $\Xi_b'|J^P=1/2^+,1\rangle_{\lambda\lambda}$ state are likely to be observed in the $\Xi_b\pi\pi\pi$ and $\Sigma_b\pi K$ final state via the decay chains $\Xi_b'|J^P=1/2^+,1\rangle_{\lambda\lambda}\to\Xi_b(\Xi_b')|J^P=1/2^-,1\rangle_\lambda\pi\to\Xi_b'\pi\pi\to\Xi_b\pi\pi\pi$ and $\Xi_b'|J^P=1/2^+,1\rangle_{\lambda\lambda}\to\Lambda_b|J^P=1/2^-,1\rangle_\lambda K\to\Lambda_b\pi\pi K$.

Meanwhile, the partial decay width of ΛB is sizable, and the predicted partial width ratio between ΛB and $\Xi_b|J^P=1/2^-,1\rangle_\lambda\pi$ is

$$\frac{\Gamma[\Xi_b'|J^P=1/2^+,1\rangle_{\lambda\lambda}\to\Lambda B]}{\Gamma[\Xi_b'|J^P=1/2^+,1\rangle_{\lambda\lambda}\to\Xi_b|J^P=1/2^-,1\rangle_\lambda \pi]}\simeq 0.21. \tag{36}$$

ΛB may be another good channel for looking for the missing state $\Xi_b'|J^P=1/2^+,1\rangle_{\lambda\lambda}$.

For the $J^P=3/2^+$ state $\Xi_b'|J^P=3/2^+,1\rangle_{\lambda\lambda}$, the width is predicted to be $\Gamma\simeq 107.6$ MeV. The dominant decay channels are $\Xi_b|J^P=3/2^-,1\rangle_\lambda\pi$ and $\Lambda_b|J^P=3/2^-,1\rangle_\lambda K$, and the partial width ratio is

$$\frac{\Gamma[\Xi_b'|J^P=3/2^+,1\rangle_{\lambda\lambda}\to\Lambda_b|J^P=3/2^-,1\rangle_\lambda K]}{\Gamma[\Xi_b'|J^P=3/2^+,1\rangle_{\lambda\lambda}\to\Xi_b|J^P=3/2^-,1\rangle_\lambda \pi]}\simeq 0.69. \tag{37}$$

This state has good potential to be discovered in the $\Xi_b\pi\pi\pi$ and $\Lambda_b\pi\pi K$ final states via the decay chains $\Xi_b'|J^P=3/2^+,1\rangle_{\lambda\lambda}\to\Xi_b|J^P=3/2^-,1\rangle_\lambda\pi\to\Xi_b'^*\pi\pi\to\Xi_b\pi\pi\pi$ and $\Xi_b'|J^P=3/2^+,1\rangle_{\lambda\lambda}\to\Lambda_b|J^P=3/2^-,1\rangle_\lambda K\to\Lambda_b\pi\pi K$. The predicted dominant decay channels are consistent with the results within the ChQM.

The other $J^P=3/2^+$ state, $\Xi_b'|J^P=3/2^+,2\rangle_{\lambda\lambda}$, has a width of $\Gamma\simeq 42.6$ MeV and mainly decays into $\Xi_b'|J^P=3/2^-,2\rangle_\lambda\pi$ and $\Xi_b'|J^P=1/2^-,0\rangle_\lambda\pi$ with a partial width ratio

$$\frac{\Gamma[\Xi_b'|J^P=3/2^+,2\rangle_{\lambda\lambda}\to\Xi_b'|J^P=1/2^-,0\rangle_\lambda \pi]}{\Gamma[\Xi_b'|J^P=3/2^+,1\rangle_{\lambda\lambda}\to\Xi_b'|J^P=3/2^-,2\rangle_\lambda \pi]}\simeq 0.62. \tag{38}$$

Since the predicted width of $\Xi_b'|J^P=3/2^+,2\rangle_{\lambda\lambda}$ is not broad, this resonance might be observed via the decays chains $\Xi_b'|J^P=3/2^+,2\rangle_{\lambda\lambda}\to\Xi_b'|J^P=3/2^-,2\rangle_\lambda\pi\to\Xi_b\pi\pi$ and $\Xi_b'|J^P=3/2^+,2\rangle_{\lambda\lambda}\to\Xi_b'|J^P=1/2^-,0\rangle_\lambda\pi\to\Xi_b\pi\pi$.

Furthermore, $\Xi_b'|J^P=3/2^+,2\rangle_{\lambda\lambda}$ may have a sizeable decay rate into ΛB, and predicted branching fractions is

$$\frac{\Gamma[\Xi_b'|J^P=3/2^+,2\rangle_{\lambda\lambda}\to\Lambda B]}{\Gamma_{\mathrm{Total}}}\sim 9\%. \tag{39}$$

Thus, ΛB may be another interesting channel for experimental exploration.

The two $J^P=5/2^+$ states $\Xi_b'|J^P=5/2^+,2\rangle_{\lambda\lambda}$ and $\Xi_b'|J^P=5/2^+,3\rangle_{\lambda\lambda}$ have a comparable narrow width of $\Gamma\simeq(15\text{–}16)$ MeV. Meanwhile, both of the two states have significant partial widths of the $\Xi_b'|J^P=5/2^-,2\rangle_\lambda\pi$ and $\Xi_b\pi$ channels, and the corresponding branching fractions are

$$\frac{\Gamma[\Xi_b'|J^P=5/2^+,2/3\rangle_{\lambda\lambda}\to\Xi_b'|J^P=5/2^-,2\rangle_\lambda \pi]}{\Gamma_{\mathrm{Total}}}\sim 22/15\%, \tag{40}$$

$$\frac{\Gamma[\Xi_b'|J^P=5/2^+,2/3\rangle_{\lambda\lambda}\to\Xi_b\pi]}{\Gamma_{\mathrm{Total}}}\sim 13/20\%. \tag{41}$$

In addition, the $\Xi_b'|J^P=5/2^+,2\rangle_{\lambda\lambda}$ has sizeable decay rates into Σ_b^*K and $\Xi_b'^{*\pi}$, which are

$$\frac{\Gamma[\Xi_b'|J^P=5/2^+,2\rangle_{\lambda\lambda}\to\Sigma_b^*K/\Xi_b'^*\pi]}{\Gamma_{\mathrm{Total}}}\sim 20/17\%. \tag{42}$$

The $\Xi_b'|J^P=5/2^+,3\rangle_{\lambda\lambda}$ has sizeable decay rates into $\Sigma_b K$ and $\Xi_b'\pi$, and the predicted branching fractions are

$$\frac{\Gamma[\Xi_b'|J^P=5/2^+,3\rangle_{\lambda\lambda}\to\Sigma_b K/\Xi_b'\pi]}{\Gamma_{\mathrm{Total}}}\sim 23/20\%. \tag{43}$$

Thanks to the huge difference in branching ratios, those strong decay channels can be used to distinguish the two $J^P=5/2^+$ states.

For the $J^P=7/2^+$ state $\Xi_b'|J^P=7/2^+,3\rangle_{\lambda\lambda}$, it may be a fairly narrow state with a width of $\Gamma\simeq 3$ MeV, which is significantly smaller than the results within the ChQM. Furthermore, the strong decay is mainly contributed by $\Lambda_b K$, $\Xi_b'\pi$, $\Xi_b'|J^P=3/2^-,1\rangle\pi$ and $\Xi_b'|J^P=5/2^-,2\rangle\pi$, and each channel takes over about 17–27%, so this state has a good chance of being observed in the $\Lambda_b K$, $\Xi_b\pi\pi$ and $\Xi_b\pi\pi\pi$ final states in future experiments.

Then, accounting for the uncertainty of the predicted masses, we plot the decay properties of the $1D$ λ-mode Ξ_b' as functions of masses within the range of $M=(6.40\text{–}6.50)$ GeV, as shown in Fig. 4. We can easily find that partial decay widths of these states are sensitive to masses, especially for the final states containing a P-wave baryons.

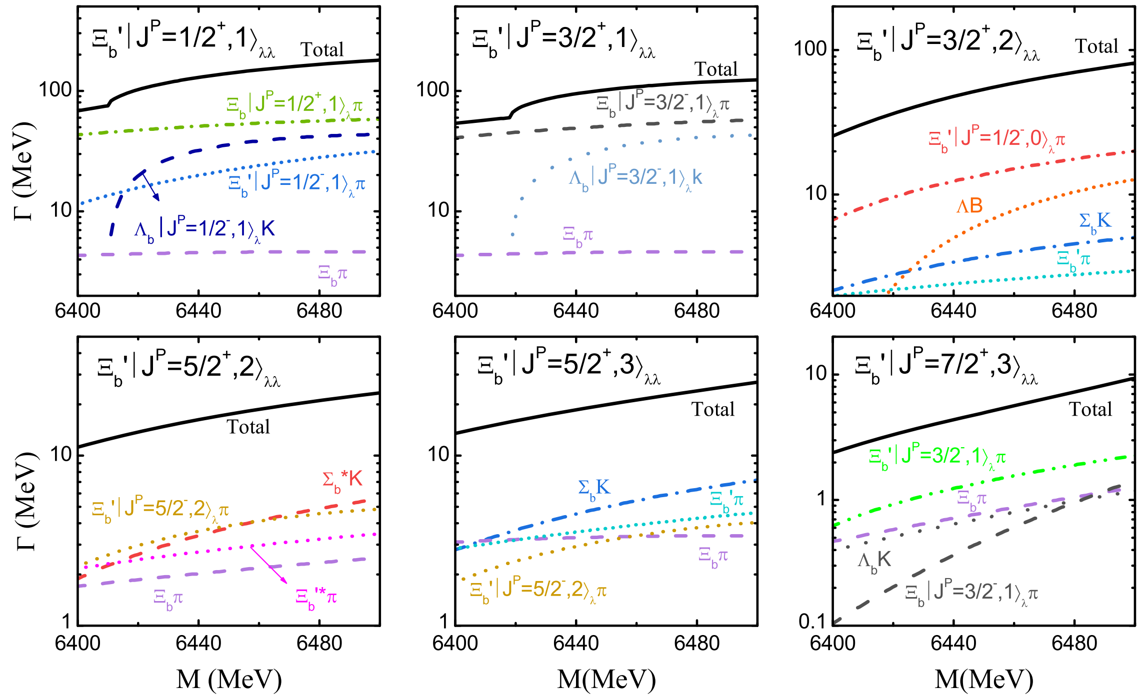

FIG. 4. Partial and total strong decay widths of the λ-mode $1D$ Ξ_b' states as a function of the masses. Some decay channels are not shown in the figure because of their small partial decay widths.

2. ρ-mode excitations

Discussions about the decay and spectrum of the ρ-mode excitations are scarce. The masses of the ρ-mode excitations are about 70–150 MeV higher than the λ-mode excitations, hence we fix the masses of the $1D$-wave ρ-mode excitations on the values which are 100 MeV higher than the predicted masses of the corresponding λ-mode excitations in Ref. [4]. Then we comprehensively analyze their decay properties and collect in Table III.

From the table, it is found that the two states $\Xi_b'|J^P = 1/2^+, 1\rangle_{\rho\rho}$ and $\Xi_b'|J^P = 3/2^+, 1\rangle_{\rho\rho}$ may be very broad states with a comparable width of $\Gamma \sim 600$ MeV, and both mainly decay into the $\Lambda_b K$ and $\Xi_b\pi$ channels. The predicted branching fractions are

$$\frac{\Gamma[\Xi_b'|J^P = 1/2^+, 1\rangle_{\rho\rho} \to \Xi_b\pi/\Lambda_b K]}{\Gamma_{\text{total}}} \sim 44/33\%, \quad (44)$$

$$\frac{\Gamma[\Xi_b'|J^P = 3/2^+, 1\rangle_{\rho\rho} \to \Xi_b\pi/\Lambda_b K]}{\Gamma_{\text{total}}} \sim 46/34\%. \quad (45)$$

We notice that the total decay widths of the two states in QPC are much larger than the predictions ($\Gamma \sim 50$ MeV) using the ChQM, while the main decay channels are grossly consistent within the two models.

Meanwhile, the partial decay widths of $\Xi_b'|J^P = 1/2^+, 1\rangle_{\rho\rho}$ decaying into $\Sigma_b K$ and $\Xi_b'|J^P = 1/2^+, 1\rangle_{\rho\rho}$ decaying into $\Xi_b'^{*\pi}$ are sizable, and the branching fractions are

$$\frac{\Gamma[\Xi_b'|J^P = 1/2^+, 1\rangle_{\rho\rho} \to \Sigma_b K]}{\Gamma_{\text{total}}} \sim 9\%, \quad (46)$$

$$\frac{\Gamma[\Xi_b'|J^P = 3/2^+, 1\rangle_{\rho\rho} \to \Xi_b'^{*}\pi]}{\Gamma_{\text{total}}} \sim 8\%. \quad (47)$$

However, it is hard to observe the two states $\Xi_b'|J^P = 1/2^+, 1\rangle_{\rho\rho}$ and $\Xi_b'|J^P = 3/2^+, 1\rangle_{\rho\rho}$ because of their broad decay widths. Meanwhile, since they have very similar decay properties, it will be a great challenge to distinguish them from each other.

The two states $\Xi_b'|J^P = 3/2^+, 2\rangle_{\rho\rho}$ and $\Xi_b'|J^P = 5/2^+, 2\rangle_{\rho\rho}$ may be broad states as well, and have a comparable width of about $\Gamma \sim (230–320)$ MeV. However, our calculations indicate that their dominant decay channels are drastically different. The state $\Xi_b'|J^P = 3/2^+, 2\rangle_{\rho\rho}$ mainly decays into $\Sigma_b K$ and $\Xi_b'\pi$ channels while $\Xi_b'|J^P = 5/2^+, 2\rangle_{\rho\rho}$ decays primarily through the $\Sigma_b^* K$ and $\Xi_b'^{*\pi}$ channels. The predicted branching fractions are

$$\frac{\Gamma[\Xi_b'|J^P = 3/2^+, 2\rangle_{\rho\rho} \to \Sigma_b K/\Xi_b'\pi]}{\Gamma_{\text{total}}} \sim 46/33\%, \quad (48)$$

$$\frac{\Gamma[\Xi_b'|J^P = 5/2^+, 2\rangle_{\rho\rho} \to \Sigma_b^* K/\Xi_b'^{*}\pi]}{\Gamma_{\text{total}}} \sim 35/63\%. \quad (49)$$

Comparing this to the results within ChQM, we also get that the total decay widths of the two states $\Xi_b'|J^P = 3/2^+, 2\rangle_{\rho\rho}$

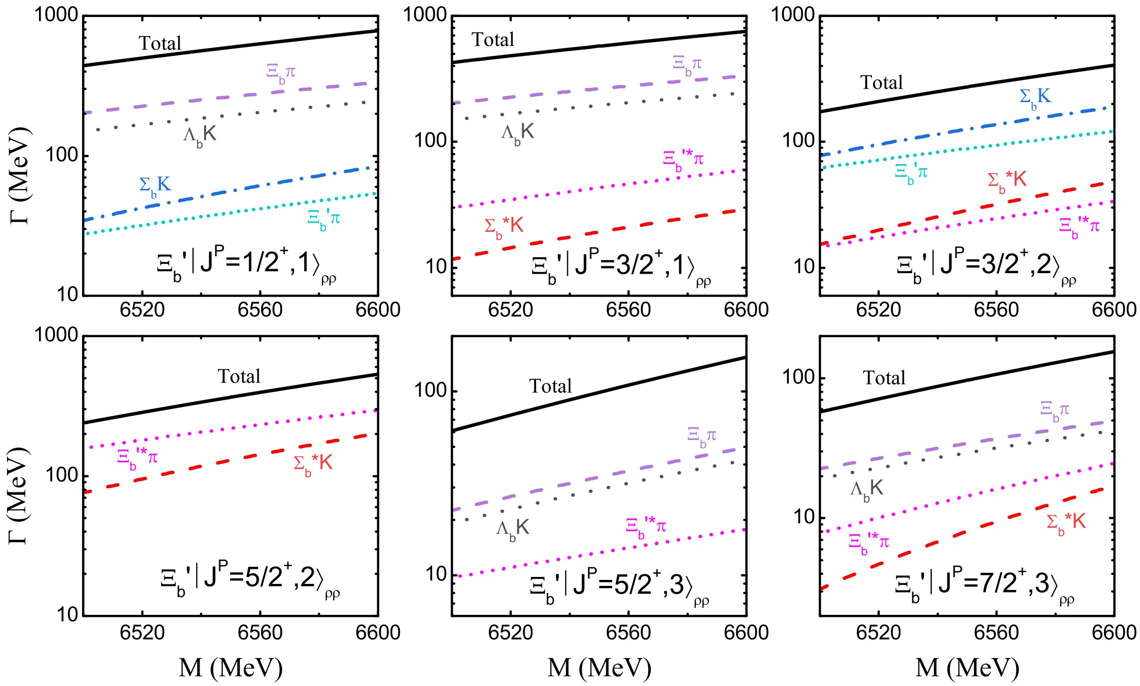

FIG. 5. Partial and total strong decay widths of the ρ-mode $1D$ Ξ_b' states as a function of the masses. Some decay channels are not shown in the figure because of their small partial decay widths.

and $\Xi_b'|J^P=5/2^+,2\rangle_{\rho\rho}$ using QPC are significant larger, while the main decay channels predicted by the two models are consistent.

As for the states $\Xi_b'|J^P=5/2^+,3\rangle_{\rho\rho}$ and $\Xi_b'|J^P=7/2^+,3\rangle_{\rho\rho}$, they have extremely similar decay properties. Both of them are probably two moderate states with a width of $\Gamma\sim(65\text{–}75)$ MeV and predominantly decay into $\Xi_b\pi$, Λ_bK and $\Xi_b'^*\pi$. The branching fractions are

$$\frac{\Gamma[\Xi_b'|J^P=5/2^+,3\rangle_{\rho\rho}\to\Xi_b\pi/\Lambda_bK/\Xi_b'^*\pi]}{\Gamma_{\text{total}}}\sim 36/31/15\%, \tag{50}$$

$$\frac{\Gamma[\Xi_b'|J^P=7/2^+,3\rangle_{\rho\rho}\to\Xi_b\pi/\Lambda_bK/\Xi_b'^*\pi]}{\Gamma_{\text{total}}}\sim 38/32/14\%. \tag{51}$$

The results can be tested in future experiments. Meanwhile, thanks to the width not being very wide, $\Xi_b'|J^P=5/2^+,3\rangle_{\rho\rho}$ and $\Xi_b'|J^P=7/2^+,3\rangle_{\rho\rho}$ can possibly be searched for in the $\Xi_b\pi,\Lambda_bK$ and $\Xi_b'^*\pi$ decay channels.

Similarly, the predicted masses of the ρ-mode Ξ_b' excitations certainly have a large uncertainty, which may bring uncertainties to our theoretical results. To investigate this effect, we plot the partial decay widths of the ρ-mode excitations as functions of the masses in the range of $M=(6.50\text{–}6.60)$ GeV, as shown in Fig. 5.

IV. SUMMARY

To decode the inner structures of the newly observed single bottom states, $\Xi_b(6327)^0$ and $\Xi_b(6333)^0$, we perform a systematical study of the $1D$-wave Ξ_b and Ξ_b' baryons in the framework of the QPC model within the $j-j$ coupling scheme. Both the λ-mode and ρ-mode excitations are taken into account. Our main results are summarized as follows.

For the two $1D$ λ-mode Ξ_b baryons, $\Xi_b|J^P=\frac{3}{2}^+,2\rangle_{\lambda\lambda}$ and $\Xi_b|J^P=\frac{5}{2}^+,2\rangle_{\lambda\lambda}$, they should be very narrow states with a width of $\Gamma\sim 1.0$ MeV. Combined with the observations, $\Xi_b|J^P=\frac{3}{2}^+,2\rangle_{\lambda\lambda}$ may be a good candidate of the $\Xi_b(6327)^0$ and $\Xi_b|J^P=\frac{5}{2}^+,2\rangle_{\lambda\lambda}$ could be a good candidate of the $\Xi_b(6333)^0$. If the assignment is true, another interesting channel for observation of $\Xi_b(6327)^0$ in future experiments is $\Xi_b'\pi$ and that of $\Xi_b(6333)^0$ is $\Xi_b'^*\pi$.

The $1D$ ρ-mode Ξ_b baryons, $\Xi_b|J^P=\frac{3}{2}^+,2\rangle_{\rho\rho}$ and $\Xi_b|J^P=\frac{5}{2}^+,2\rangle_{\rho\rho}$, have a comparable decay width of about $\Gamma\sim 50$ MeV. Menawhile, $\Xi_b|J^P=\frac{3}{2}^+,2\rangle_{\rho\rho}$ mainly decays into Σ_bK and $\Xi_b'\pi$, while $\Xi_b|J^P=\frac{5}{2}^+,2\rangle_{\rho\rho}$ decays dominantly via Σ_b^*K and $\Xi_b'^*\pi$. Such moderate states have good potential to be observed in their corresponding dominant decay channels in future experiments.

The three $1D$ λ-mode Ξ_b' baryons, $\Xi_b'|J^P=\frac{1}{2}^+,1\rangle_{\lambda\lambda}$, $\Xi_b'|J^P=\frac{3}{2}^+,1\rangle_{\lambda\lambda}$, and $\Xi_b'|J^P=\frac{3}{2}^+,2\rangle_{\lambda\lambda}$ are predicted to be moderate states with a width of dozens of MeV to a hundred MeV, and mainly decay into the $1P$-wave bottomed baryon via the pionic-decay processes. Meanwhile, $\Xi_b'|J^P = \frac{1}{2}^+, 1\rangle_{\lambda\lambda}$ and $\Xi_b'|J^P = \frac{3}{2}^+, 2\rangle_{\lambda\lambda}$ have significant decay rates into ΛB, which is likely to be an interesting channel for experimental exploration. The other two $1D$ λ-mode Ξ_b' baryons, $\Xi_b'|J^P = \frac{5}{2}^+, 2\rangle_{\lambda\lambda}$ and $\Xi_b'|J^P = \frac{5}{2}^+, 3\rangle_{\lambda\lambda}$, have a comparable narrow width of $\Gamma \simeq (15\text{–}16)$ MeV, and their decays are dominated by the $\Xi_b'|J^P = 5/2^-, 2\rangle_\lambda \pi$ and $\Xi_b \pi$ channels. $\Xi_b'|J^P = \frac{7}{2}^+, 3\rangle_{\lambda\lambda}$ is predicted to be a fairly narrow state with a width of $\Gamma \simeq 3$ MeV. The main decay channels are $\Lambda_b K$, $\Xi_b' \pi$, $\Xi_b'|J^P = 3/2^-, 1\rangle \pi$ and $\Xi_b'|J^P = 5/2^-, 2\rangle \pi$.

For the $1D$ ρ-mode Ξ_b' baryons, the two states $\Xi_b'|J^P = \frac{5}{2}^+, 3\rangle_{\rho\rho}$ and $\Xi_b'|J^P = \frac{7}{2}^+, 3\rangle_{\rho\rho}$ show the possibility to be observed in their dominant decay channels $\Lambda_b K$, $\Xi_b \pi$, and $\Xi_b'^* \pi$ because of their narrow widths. It will be a great challenge to observe the other four states $\Xi_b'|J^P = \frac{1}{2}^+, 1\rangle_{\rho\rho}$, $\Xi_b'|J^P = \frac{3}{2}^+, 1\rangle_{\rho\rho}$, $\Xi_b'|J^P = \frac{3}{2}^+, 2\rangle_{\rho\rho}$, and $\Xi_b'|J^P = \frac{5}{2}^+, 2\rangle_{\rho\rho}$ because of their very broad width of several hundreds of MeV.

Finally, it should be pointed out that some states, especially the $1D$-wave Ξ_b' states, have very different predictions within the QPC model and ChQM. In fact, as discussed in our previous work [63], these two phenomenological models have some obvious differences from each other. Within the QPC model, strong decay takes place via the creation of quark-antiquark pairs from the vacuum with quantum numbers 0^{++}. Meanwhile, all the hadrons in the final and initial states are taken as particles containing internal structures. Furthermore, the chiral symmetry of the interactions for the pseudoscalar mesons with the quarks are not considered. While in the ChQM, the coupling of the light pseudoscalar mesons with the quarks are described by the chiral Lagrangian, which satisfies the spirit of QCD. In addition, those light-emitting pseudoscalar mesons are considered to be structureless Goldstone bosons. Moreover, the quantum numbers of the quark-antiquark pairs created in the vacuum are not defined in the ChQM. Hence, the predictions presented in this work await forthcoming experimental verification.

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