Masses and decay widths of $\Xi_{c/b}$ and $\Xi'_{c/b}$ baryons

R. Bijker,[1] H. García-Tecocoatzi,[2] A. Giachino,[3,4] E. Ortiz-Pacheco,[1] and E. Santopinto[3,*]

[1]*Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, 04510 Ciudad de México, México*

[2]*The Center for High Energy Physics, Kyungpook National University, 80 Daehak-ro, Daegu 41566, Korea*

[3]*INFN, Sezione di Genova, Via Dodecaneso 33, 16146 Genova, Italy*

[4]*Institute of Nuclear Physics, Polish Academy of Sciences, Radzikowskiego 152, 31-342 Cracow, Poland*

(Received 15 December 2020; accepted 4 March 2022; published 26 April 2022)

In this article, we present a complete classification of the negative parity $\Xi'_{c/b}$ and $\Xi_{c/b}$ P-wave states: seven belonging to the $SU(3)$ flavor sextet and seven to the flavor antitriplet, the calculation of the $\Xi'_{c/b}$ and $\Xi_{c/b}$ strong partial decay widths into ${}^2\Sigma_c\bar{K}$, ${}^2\Xi'_c\pi$, ${}^4\Sigma_c\bar{K}$, ${}^4\Xi'_c\pi$, $\Lambda'_c\bar{K}$, $\Xi_c\pi$, and $\Xi_c\eta$ channels both within the elementary emission model and the ${}^3P_0$ model, and the calculation of the electromagnetic decay widths for $\Xi'_{c/b}$ and $\Xi_{c/b}$ radiative decays. By means of the equal-spacing mass rule and by the analysis of the strong partial decay widths, we suggest possible assignments for the new LHCb $\Xi_c(2923)^0$, $\Xi_c(2939)^0$, and $\Xi_c(2965)^0$ states, as well as for the Ξ_c's previously reported by Belle and *BABAR*. Our results can be tested by future experiments, at LHCb and Belle, disentangling the remaining missing piece of information, i.e., the quantum numbers. Finally, a comparison is made between a three-quark and a quark-diquark description of Ξ_c states. Very recently the LHCb Collaboration reported the observation of two new Ξ_b states, namely $\Xi_b(6327)^0$ and $\Xi_b(6333)^0$, in the $\Lambda_b^0 K^-\pi^+$ channel with a statistical significance larger than 9 standard deviations. The experimental masses and widths of these two states are consistent with our mass and width predictions for the doublet of D-wave excitations of the Ξ_b system with $J^P_{\Xi_b(6327)^0} = 3/2^+$ and $J^P_{\Xi_b(6333)^0} = 5/2^+$.

DOI: 10.1103/PhysRevD.105.074029

I. INTRODUCTION

The observation of three negative parity Ξ_c^0 charmed baryons by the LHCb Collaboration [1] represents an important milestone in our understanding of the quark structure of hadrons. As the hadron mass patterns carry information on the way the quarks interact with one another, they provide a means of gaining insight into the fundamental binding mechanism of matter at an elementary level. Recent reviews of heavy baryon physics can be found in Refs. [2–6].

The Particle Data Group summary table lists a total of eight neutral single-charm cascade baryons and seven charged ones [7]. The angular momentum and parity of these states have not yet been measured. The assignment of quantum numbers is based on quark model systematics. All ground state single-charm baryons have been identified: the flavor antitriplet with $J^P = 1/2^+$ consists of the Ξ_c^+, Ξ_c^0, and Λ_c^+ baryons; $\Xi_c'^+$, $\Xi_c'^0$, the three charge states of $\Sigma_c(2455)$, and Ω_c^0 form the flavor sextet with $J^P = 1/2^+$; the two charge states of $\Xi_c(2645)$, the three charge states of $\Sigma_c(2520)$, and $\Omega_c(2770)^0$ form the flavor sextet with $J^P = 3/2^+$. Only very recently, the LHCb Collaboration has announced the observation of three negative parity Ξ_c^0 states in the $\Lambda_c^+ K^-$ channel [1]:

$$\begin{aligned}
\Xi_c(2923)^0\colon\ & M = 2923.04 \pm 0.25 \pm 0.20 \pm 0.14\ \text{MeV}, \\
& \Gamma = 7.1 \pm 0.8 \pm 1.8\ \text{MeV}, \\
\Xi_c(2939)^0\colon\ & M = 2938.55 \pm 0.21 \pm 0.17 \pm 0.14\ \text{MeV}, \\
& \Gamma = 10.2 \pm 0.8 \pm 1.1\ \text{MeV}, \\
\Xi_c(2965)^0\colon\ & M = 2964.88 \pm 0.26 \pm 0.14 \pm 0.14\ \text{MeV}, \\
& \Gamma = 14.1 \pm 0.9 \pm 1.3\ \text{MeV}.
\end{aligned}$$

As observed by the LHCb Collaboration, these three states follow an equal-spacing mass rule of around 126 MeV [1] with respect to the excited negative parity Ω_c^0 states [8,9]. This is similar to the equal spacing mass rule for the $SU_f(3)$

*Corresponding author.
elena.santopinto@ge.infn.it

ground states in the Gell-Mann, Okubo, and Gürsey and Radicati mass formulas [10–12]. Therefore, the LHCb Collaboration suggested that the three new negative parity excited $\Xi_c(2923)^0$, $\Xi_c(2939)^0$, and $\Xi_c(2965)^0$ states be assigned to the same flavor $SU_{\rm f}(3)$ multiplet as the negative parity excited $\Omega_c(3050)^0$, $\Omega_c(3065)^0$, and $\Omega_c(3090)^0$, i.e., the $SU_{\rm f}(3)$ flavor sextet (**6**). The Belle [13,14] and *BABAR* [15] Collaborations observed $\Xi_c(2930)^0$ in the same $\Lambda_c^+ K^-$ channel, which could be considered an unresolved combination of two independent states $\Xi_c(2923)^0$ and $\Xi_c(2939)^0$, while the third LHCb state, the $\Xi_c(2965)^0$, could be either the already observed $\Xi_c(2970)^0$ [16] or maybe a completely new state. In the following we work in the hypothesis that the third LHCb state, the $\Xi_c(2965)^0$, is the same state as the already observed $\Xi_c(2970)^0$, and hereafter we denote this state with $\Xi_c(2965)^0$. Moreover, the single-charm cascade baryons of the antitriplet are denoted as Ξ_c, and those of the sextet are indicated by a prime, Ξ'_c.

The new experimental results triggered a large number of theoretical studies mainly on the Ξ_c states of the flavor antitriplet among others using quark-diquark approaches [17–21], molecular states [22], the LQCD approach [23], QCD sum rules [20,24–28], the effective chiral Lagrangian approach [29,30], and the constituent quark model [31–34].

Recently, we introduced an equal-spacing mass formula for heavy baryons which was used to study the negative-parity Ω_c^0 baryons and to predict the corresponding negative parity Ω_b^- states [35], which subsequently were confirmed by the new experimental data from the LHCb Collaboration [36]. The masses and decay widths were found to be in agreement within the experimental errors. The aim of this article is to apply the same model to analyze the properties of all ground state and P-wave Ξ'_Q (sextet) and Ξ_Q (antitriplet) baryons, including the mass spectrum and the decay widths for strong and electromagnetic couplings.

II. HARMONIC OSCILLATOR QUARK MODEL

In the quark model, Ξ_Q baryons are described as usQ or dsQ configurations, i.e., a combination of a nonstrange quark that can be either u or d, a strange quark s, and a heavy quark, $Q = c$ or b. The total wave function that is a product of an orbital, spin, flavor, and color part has to be antisymmetric. Since physical particles form a color singlet, the color part is antisymmetric, and therefore the orbital-spin-flavor part has to be symmetric under the interchange of the light quarks. The flavor part of the two light quarks can be either symmetric (sextet **6**) or antisymmetric (antitriplet $\bar{\mathbf{3}}$); see Fig. 1. Similarly, the spin part can be either symmetric, χ_S with $S = 3/2$ or χ_λ with $S = 1/2$, or antisymmetric, χ_ρ with $S = 1/2$. The states with maximum spin projection ($M_S = S$) are given by

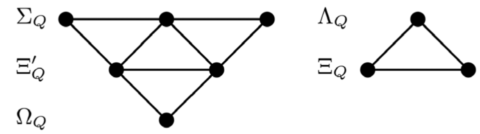

FIG. 1. Heavy baryon sextet (left) and antitriplet (right).

$$
\begin{aligned}
S &= \frac{1}{2} : \chi_\rho = (\uparrow\downarrow\uparrow - \downarrow\uparrow\uparrow)/\sqrt{2}, \\
S &= \frac{1}{2} : \chi_\lambda = (2\uparrow\uparrow\downarrow - \uparrow\downarrow\uparrow - \downarrow\uparrow\uparrow)/\sqrt{6}, \\
S &= \frac{3}{2} : \chi_S = \uparrow\uparrow\uparrow .
\end{aligned}
\tag{1}
$$

The orbital part of the ground state is symmetric, ψ_0 with $L^P = 0_S^+$, and that of the first excited state either symmetric, ψ_λ with $L^P = 1_\lambda^-$ corresponding to a λ-mode excitation, or antisymmetric, ψ_ρ with $L^P = 1_\rho^-$ corresponding to a ρ-mode excitation. Table I shows the wave functions for the Ξ_Q baryons, where we use the notation Ξ'_Q for the sextet and Ξ_Q for the antitriplet. The total angular momentum J satisfies the usual angular momentum coupling rule $|L - S| \le J \le L + S$. All states are isospin doublets with isospin $I = 1/2$. The classification scheme of the negative parity P-wave single-charm and single-bottom cascade baryons in a three-quark description shows that there are in total 14 such states, seven belonging to the flavor sextet (five λ-mode and two ρ-mode) and another seven to the flavor antitriplet (two λ-mode and five ρ-mode).

Following Ref. [35] we consider a harmonic oscillator quark model with a spin, spin-orbit, isospin, and flavor dependent terms

$$
M = H_{\rm ho} + A\vec{S}\cdot\vec{S} + B\vec{L}\cdot\vec{S} + E\vec{I}\cdot\vec{I} + GC_{2SU_{\rm f}(3)} . \tag{2}
$$

TABLE I. Classification of the highest charge state of sextet Ξ'_Q baryons (top) and antitriplet Ξ_Q baryons (bottom). The upper index in the first column denotes the spin degeneracy, $2S + 1$.

State	Wave function	(n_ρ, n_λ)	L^P	J^P
$^2\Xi'_Q$	$\frac{1}{\sqrt{2}}(us+su)Q[\psi_0\chi_\lambda]$	(0,0)	0^+	$\frac{1}{2}^+$
$^4\Xi'_Q$	$\frac{1}{\sqrt{2}}(us+su)Q[\psi_0\chi_S]$	(0,0)	0^+	$\frac{3}{2}^+$
$^2\lambda(\Xi'_Q)_J$	$\frac{1}{\sqrt{2}}(us+su)Q[\psi_\lambda\chi_\lambda]_J$	(0,1)	1^-	$\frac{1}{2}^-, \frac{3}{2}^-$
$^4\lambda(\Xi'_Q)_J$	$\frac{1}{\sqrt{2}}(us+su)Q[\psi_\lambda\chi_S]_J$	(0,1)	1^-	$\frac{1}{2}^-, \frac{3}{2}^-, \frac{5}{2}^-$
$^2\rho(\Xi'_Q)_J$	$\frac{1}{\sqrt{2}}(us+su)Q[\psi_\rho\chi_\rho]_J$	(1,0)	1^-	$\frac{1}{2}^-, \frac{3}{2}^-$
$^2\Xi_Q$	$\frac{1}{\sqrt{2}}(us-su)Q[\psi_0\chi_\rho]$	(0,0)	0^+	$\frac{1}{2}^+$
$^2\lambda(\Xi_Q)_J$	$\frac{1}{\sqrt{2}}(us-su)Q[\psi_\lambda\chi_\rho]_J$	(0,1)	1^-	$\frac{1}{2}^-, \frac{3}{2}^-$
$^2\rho(\Xi_Q)_J$	$\frac{1}{\sqrt{2}}(us-su)Q[\psi_\rho\chi_\lambda]_J$	(1,0)	1^-	$\frac{1}{2}^-, \frac{3}{2}^-$
$^4\rho(\Xi_Q)_J$	$\frac{1}{\sqrt{2}}(us-su)Q[\psi_\rho\chi_S]_J$	(1,0)	1^-	$\frac{1}{2}^-, \frac{3}{2}^-, \frac{5}{2}^-$

The harmonic oscillator quark model for qqQ baryons with two light quarks and one heavy quark is given by [37]

$$H_{\mathrm{ho}} = \sum_i \left(m_i + \frac{p_i^2}{2m_i} \right) + \frac{1}{2} C \sum_{i<j} (\vec{r}_i - \vec{r}_j)^2 = M + \frac{P^2}{2M} + \frac{p_\rho^2}{2m_\rho} + \frac{1}{2} m_\rho \omega_\rho^2 \rho^2 + \frac{p_\lambda^2}{2m_\lambda} + \frac{1}{2} m_\lambda \omega_\lambda^2 \lambda^2, \quad (3)$$

where we have made a change of variables to relative Jacobi coordinates

$$\vec{\rho} = (\vec{r}_1 - \vec{r}_2)/\sqrt{2}, \quad \vec{\lambda} = (\vec{r}_1 + \vec{r}_2 - 2\vec{r}_3)/\sqrt{6}, \quad (4)$$

and the center-of-mass coordinate, and their canonically conjugate momenta. The labels 1 and 2 refer to the light quarks and 3 to the heavy quark.

For Ξ_Q and Ξ'_Q baryons the reduced masses are given by $m_\rho = (m_{u/d} + m_s)/2$, i.e., the average of the strange and nonstrange quark masses, and $m_\lambda = 3m_\rho m_Q/M$ with $M = 2m_\rho + m_Q$. There are two types of radial excitations: the ρ-mode corresponds to an excitation in the relative coordinate between the two light quarks, and the λ-mode to an excitation in the relative coordinate between the two light quarks and the heavy quark. In quark-diquark models, baryons are described as an effective two-body quark-diquark system in which the excitation of the ρ-mode between the two light quarks is not taken into account. As a consequence, the number of excited states is much smaller than in the three-quark picture. Specifically, Table I shows that in a three-quark model there are seven excited states for sextet Ξ'_Q baryons, and another seven for antitriplet Ξ_Q baryons, whereas in quark-diquark models the ρ-mode excitations are absent, leading to five excited Ξ'_Q baryons and two excited Ξ_Q baryons. Therefore, the identification of ρ-mode excitations in the spectrum of heavy-light baryons provides a tool to discriminate between three-quark and quark-diquark descriptions, since the ρ-mode excitations are absent in quark-diquark models, but are allowed in three-quark models of baryons [35].

Whereas in the light-baryon phenomenology, the ρ- and λ-excitations are degenerate in energy, in the heavy-light sector they are decoupled with frequencies, $\omega_\rho = \sqrt{3C/m_\rho}$ and $\omega_\lambda = \sqrt{3C/m_\lambda}$, where C is the spring constant. For qqQ baryons with two light and one heavy quark the frequencies satisfy $\omega_\lambda < \omega_\rho$, whereas for QQq baryons with two heavy and one light quarks the situation is reversed, $\omega_\rho < \omega_\lambda$. For equal masses, as is the case for qqq and QQQ baryons, the two frequencies become the same, $\omega_\rho = \omega_\lambda$.

Since all Ξ'_Q and Ξ_Q baryons are isospin doublets with $I = 1/2$ and have the same quark content, the isospin term and the mass term, $M = m_{u/d} + m_s + m_Q$, give the same contribution to all states. As a consequence, mass differences only depend on the harmonic oscillator frequencies, $\hbar\omega_\rho$ and $\hbar\omega_\lambda$, the spin term A, the spin-orbit term B, and the flavor-dependent term G,

$$M = M(^2\Xi_Q) + \hbar\omega_\rho n_\rho + \hbar\omega_\lambda n_\lambda + A\left[S(S+1) - \frac{3}{4}\right] + B\frac{1}{2}[J(J+1) - L(L+1) - S(S+1)] + G\frac{1}{3}[\mu_1(\mu_1+3) + \mu_2(\mu_2+3) + \mu_1\mu_2 - 4]. \quad (5)$$

The spin-dependent term splits the states with different spin content, such as the $^2\Xi'_Q$ and $^4\Xi'_Q$ configurations in Table I. The spin-orbit interaction, which is small in light baryons [19,38], turns out to be fundamental to describe the heavy-light baryon mass patterns [35]. The effect of the spin-orbit term is to split the states with different J in configurations such as $^2\lambda(\Xi'_Q)_J$. Finally, the mass splittings between different flavor multiplets are given by the eigenvalues of the Casimir operator of the $SU(3)$ flavor algebra [39]. The flavor-dependent term splits the Ξ'_Q baryons belonging to the flavor sextet, **6** labeled by $(\mu_1, \mu_2) = (2, 0)$, from the Ξ_Q baryons of the antitriplet, $\bar{\mathbf{3}}$ characterized by $(\mu_1, \mu_2) = (0, 1)$.

III. MASS SPECTRUM

In the present article we consider single-charm and single-bottom Ξ_Q baryons associated with the ground-state configuration ψ_0 with $(n_\rho, n_\lambda) = (0, 0)$, and with one quantum of excitation, either in the λ mode, ψ_λ, with $(n_\rho, n_\lambda) = (0, 1)$, or in the ρ mode, ψ_ρ, with $(n_\rho, n_\lambda) = (1, 0)$. The allowed configurations are given in Table I.

The mass formula of Eqs. (2) and (5) is an extension of the Gell-Mann-Okubo and Gürsey-Radicati mass formulas. It was introduced in Ref. [35] to study the recently observed negative parity Ω_c^0 states by the Belle and LHCb Collaborations [8,9]. It was shown that these Ω_c^0 states can be interpreted as λ-mode excitations. In addition, it was used to predict the masses of the corresponding negative parity Ω_b^- baryons which subsequently were measured by the LHCb Collaboration [36]. Here we apply the same mass formula to the Ξ_Q and Ξ'_Q baryons, using the same parameter values as determined in the previous study of Ω_Q baryons [35] without any additional fine-tuning or the introduction of extra parameters.

In this way, the mass spectra of the Ξ_Q and Ξ'_Q baryons are calculated in a parameter-free procedure. The results for ground state and λ- and ρ-mode excitations are reported in

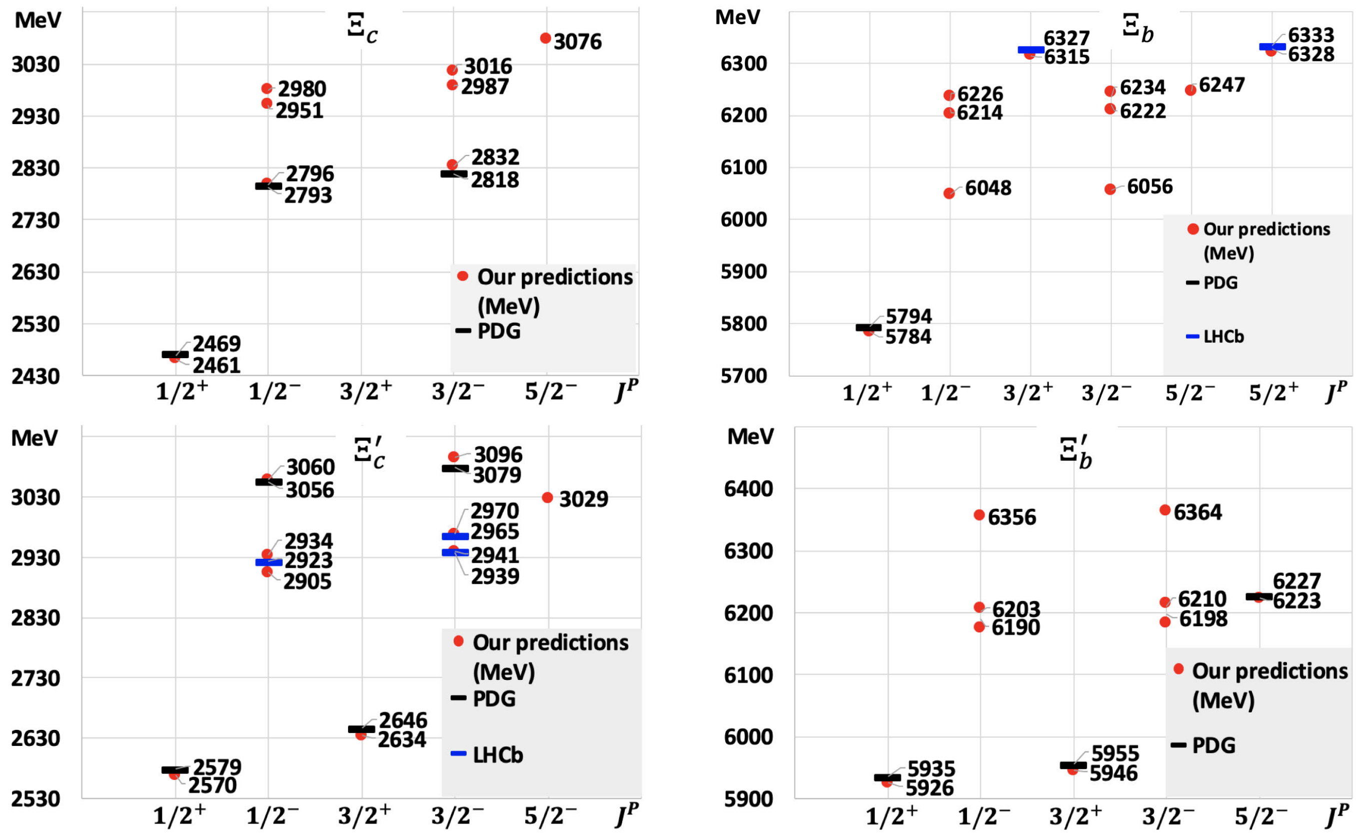

FIG. 2. Mass spectra and tentative quantum number assignments for Ξ_c (top left), Ξ_c' (bottom left), Ξ_b (top right), and Ξ_b' (bottom right). The theoretical predictions (red dots) are compared with the experimental results from the LHCb Collaboration (blue lines) [1,40] and the Particle Data Group compilation (black lines) [7].

Fig. 2 and in Tables II and III. The assignments are mostly based on systematics of mass spectra. For the single-charm baryons, there is no doubt about the identification of the ${}^2\Xi_c'$, ${}^4\Xi_c'$, and ${}^2\Xi_c$ configurations. The masses of the recently measured $\Xi_c(2923)^0$, $\Xi_c(2939)^0$, and $\Xi_c(2965)^0$ resonances [1], together with the observed equal spacing rule [1,10,11] with excited Ω_c^0 baryons

$$\begin{aligned} &M(\Omega_c(3050)^0) - M(\Xi_c(2923)^0) \\ &\simeq M(\Omega_c(3065)^0 - M(\Xi_c(2939)^0) \\ &\simeq M(\Omega_c(3090)^0) - M(\Xi_c(2965)^0) \\ &\simeq 125 \text{ MeV}, \end{aligned} \tag{6}$$

suggest the same assignment as for the Ω_c baryons: λ-mode excitations of flavor sextet configurations ${}^4\lambda(\Xi_c')_{1/2^-}$, ${}^2\lambda(\Xi_c')_{3/2^-}$, and ${}^4\lambda(\Xi_c')_{3/2^-}$, respectively. The $\Xi_c(3055)^+$ and $\Xi_c(3080)^+$ resonances are assigned as ρ-mode excitations of the sextet configuration, ${}^2\rho(\Xi_c')_{J^P}$ with $J^P = 1/2^-$ and $3/2^-$ which would indicate a preference of a three-quark over a quark-diquark description. Finally, the $\Xi_c(2790)$ and $\Xi_c(2815)$ resonances are assigned as λ-mode excitations of the flavor antitriplet.

For the single-bottom Ξ_b baryons the experimental information is scarcer. The ${}^2\Xi_b'$, ${}^4\Xi_b'$, and ${}^2\Xi_b$ configurations can be assigned without problem. The newly observed $\Xi_b(6227)^-$ and $\Xi_b(6227)^0$ resonances [41,42] can be assigned either as a λ-mode excitation of the flavor sextet, ${}^4\lambda(\Xi_b')_{5/2^-}$ (as in Fig. 2 and Table III), or as a ρ-mode excitation of the flavor antitriplet, ${}^2\rho(\Xi_b)_{3/2^-}$ or ${}^4\rho(\Xi_b)_{3/2^-}$.

Very recently the LHCb Collaboration reported the observation of two new Ξ_b states in the $\Lambda_b^0 K^- \pi^+$ channel with a statistical significance larger than 9 standard deviations [40]. Our model suggests to interpret these two states as D-wave excitations of the Ξ_b system with $L = l_\lambda = 2$ and total angular momentum $J^P = 3/2^+$ for $\Xi_b(6327)^0$ and $J^P = 5/2^+$ for $\Xi_b(6333)^0$ (see the top-right panel of Fig. 2). The predicted masses are 6315 MeV and 6328 MeV, respectively, in good agreement with the values measured by the LHCb Collaboration [40]: $m(\Xi_b(6327)^0) = 6327.28^{+0.23}_{-0.21} \pm 0.08 \pm 0.24$ MeV and $m(\Xi_b(6333)^0) = 6332.69^{+0.17}_{-0.18} \pm 0.03 \pm 0.22$ MeV.

IV. DECAY WIDTHS

For the evaluation of strong and electromagnetic decay widths we first discuss the radial wave functions. The

TABLE II. Quantum number assignments, masses, and strong partial decay widths in MeV of sextet Ξ_c' (top) and antitriplet Ξ_c baryons (bottom) for the states reported in Table I. Partial widths denoted by $\cdots$ and 0 are forbidden by phase space and selection rules, respectively.

State	M_{th}	Baryon	M_{exp}	${}^2\Sigma_c\bar{K}$	${}^2\Xi_c'\pi$	${}^4\Sigma_c\bar{K}$	${}^4\Xi_c'\pi$	$\Lambda_c\bar{K}$	${}^2\Xi_c\pi$	${}^2\Xi_c\eta$	Γ_{tot}	Γ_{exp}	References
${}^2\Xi_c'$	2570 ± 2	$\Xi_c'^+$	2578.2 ± 0.5	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	[7]
		$\Xi_c'^0$	2578.7 ± 0.5	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	[7]
${}^4\Xi_c'$	2635 ± 2	$\Xi_c(2645)^+$	2645.10 ± 0.30	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	1.23	$\cdots$	1.23	2.14 ± 0.19	[7]
		$\Xi_c(2645)^0$	2646.16 ± 0.25	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	1.23	$\cdots$	1.23	2.35 ± 0.22	[7]
${}^2\lambda(\Xi_c')_{1/2^-}$	2905 ± 2			$\cdots$	0.18	$\cdots$	0.19	0.03	1.35	$\cdots$	1.75		
${}^4\lambda(\Xi_c')_{1/2^-}$	2934 ± 3	$\Xi_c(2923)^0$	2923.04 ± 0.35	$\cdots$	0.20	$\cdots$	0.18	0.43	4.01	$\cdots$	4.83	7.1 ± 2.0	[1]
${}^2\lambda(\Xi_c')_{3/2^-}$	2941 ± 2	$\Xi_c(2930)^+$	2942.3 ± 4.6	$\cdots$	2.48	$\cdots$	0.22	2.70	6.13	$\cdots$	11.53	14.8 ± 9.1	[7]
		$\Xi_c(2939)^0$	2938.55 ± 0.30	$\cdots$	2.48	$\cdots$	0.22	2.70	6.13	$\cdots$	11.53	10.2 ± 1.4	[1]
${}^4\lambda(\Xi_c')_{3/2^-}$	2970 ± 2	$\Xi_c(2965)^0$	2964.88 ± 0.33	0.00	0.18	$\cdots$	1.34	0.79	1.56	$\cdots$	3.88	14.1 ± 1.6	[1]
${}^4\lambda(\Xi_c')_{5/2^-}$	3030 ± 2			0.66	2.04	0.04	3.46	8.69	14.37	0.01	29.27		
${}^2\rho(\Xi_c')_{1/2^-}$	3060 ± 2	$\Xi_c(3055)^+$	3055.9 ± 0.4	0.02	2.55	0.88	7.28	0	0	0	10.73	7.8 ± 1.9	[7]
${}^2\rho(\Xi_c')_{3/2^-}$	3096 ± 2	$\Xi_c(3080)^+$	3077.2 ± 0.4	7.23	9.24	1.91	7.02	0	0	0	25.39	3.6 ± 1.1	[7]
		$\Xi_c(3080)^0$	3079.9 ± 1.4	7.23	9.24	1.91	7.02	0	0	0	25.39	5.6 ± 2.2	[7]
${}^2\Xi_c$	2461 ± 1	Ξ_c^+	2467.71 ± 0.23	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	[7]
		Ξ_c^0	2470.44 ± 0.28	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	[7]
${}^2\lambda(\Xi_c)_{1/2^-}$	2797 ± 1	$\Xi_c(2790)^+$	2791.9 ± 0.5	$\cdots$	0.01	$\cdots$	0.00	0	0	0	0.01	8.9 ± 1.0	[7]
		$\Xi_c(2790)^0$	2793.9 ± 0.5	$\cdots$	0.01	$\cdots$	0.00	0	0	0	0.01	10.0 ± 1.1	[7]
${}^2\lambda(\Xi_c)_{3/2^-}$	2832 ± 1	$\Xi_c(2815)^+$	2816.51 ± 0.25	$\cdots$	0.24	$\cdots$	0.04	0	0	0	0.28	2.43 ± 0.26	[7]
		$\Xi_c(2815)^0$	2819.79 ± 0.30	$\cdots$	0.24	$\cdots$	0.04	0	0	0	0.28	2.54 ± 0.25	[7]
${}^2\rho(\Xi_c)_{1/2^-}$	2951 ± 1			0.50	0.62	$\cdots$	0.52	0.42	2.52	$\cdots$	4.57		
${}^4\rho(\Xi_c)_{1/2^-}$	2980 ± 2			0.49	0.54	$\cdots$	0.42	1.82	6.93	$\cdots$	10.20		
${}^2\rho(\Xi_c)_{3/2^-}$	2987 ± 1			0.36	4.49	$\cdots$	0.55	4.93	9.12	$\cdots$	19.45		
${}^4\rho(\Xi_c)_{3/2^-}$	3016 ± 2			0.07	0.31	0.63	3.03	1.32	2.25	$\cdots$	7.60		
${}^4\rho(\Xi_c)_{5/2^-}$	3076 ± 2			2.05	3.16	1.28	6.05	12.78	19.54	0.06	44.91		

harmonic oscillator wave functions depend on the two size parameters, one for the ρ coordinate and one for the λ coordinate. The relative wave function for the ground state with $(n_\rho, n_\lambda) = (0,0)$ is given by

$$\psi^{\mathrm{o}}(\vec{\rho},\vec{\lambda}) = \left(\frac{\alpha_\rho\alpha_\lambda}{\pi}\right)^{3/2} \mathrm{e}^{-(\alpha_\rho^2\vec{\rho}^2+\alpha_\lambda^2\vec{\lambda}^2)/2}, \tag{7}$$

with

$$\alpha_\lambda = \alpha_\rho\left(\frac{3m'}{2m+m'}\right)^{1/4}. \tag{8}$$

The oscillator parameters, α_ρ and α_λ, used in the calculation of the strong and electromagnetic decay widths, are related to the frequencies as $\alpha_\rho^2 = \omega_\rho m_\rho = \sqrt{3Cm_\rho}$ and $\alpha_\lambda^2 = \omega_\lambda m_\lambda = \sqrt{3Cm_\lambda}$ to give $\alpha_\rho = 438$ MeV and $\alpha_\lambda = 523$ MeV for Ξ_c and Ξ_c' baryons, and $\alpha_\rho = 403$ MeV and $\alpha_\lambda = 511$ MeV for Ξ_b and Ξ_b' baryons.

A. Strong couplings

Strong couplings provide an important test of baryon wave functions, and can be used to distinguish between different models of baryon structure. Here we consider strong decays of baryons by the emission of a pseudoscalar meson

$$B \to B' + M. \tag{9}$$

Several forms have been suggested for the form of the operator inducing the strong transition [43]. In this article we consider the strong decays of Ξ_Q and Ξ_Q' baryons by the emission of a pseudoscalar meson as calculated in the elementary emission model (EEM), as well as in the ${}^3P_0$ model.

In the EEM the corresponding operator is given by [44–46]

$$\mathcal{H}_s = \frac{1}{(2\pi)^{3/2}(2k_0)^{1/2}}\sum_{j=1}^{3} X_j^M[2g(\vec{s}_j\cdot\vec{k})\mathrm{e}^{-i\vec{k}\cdot\vec{r}_j} + h\vec{s}_j\cdot(\vec{p}_j\mathrm{e}^{-i\vec{k}\cdot\vec{r}_j} + \mathrm{e}^{-i\vec{k}\cdot\vec{r}_j}\vec{p}_j)], \tag{10}$$

TABLE III. As in Table II, but for sextet Ξ_b' (top) and antitriplet Ξ_b baryons (bottom).

State	Assignment	$M_{\rm th}$	$M_{\rm exp}$	$^2\Sigma_b\bar{K}$	$^2\Xi_b'\pi$	$^4\Sigma_b\bar{K}$	$^4\Xi_b'\pi$	$\Lambda_b\bar{K}$	$^2\Xi_b\pi$	$^2\Xi_b\eta$	$\Gamma_{\rm tot}$	$\Gamma_{\rm exp}$	References
$^2\Xi_b'$	$\Xi_b'(5935)^-$	5926 ± 2	5935.02 ± 0.05	···	···	···	···	···	···	···	···	<0.08	[7]
$^4\Xi_b'$	$\Xi_b(5945)^0$	5946 ± 6	5952.3 ± 0.6	···	···	···	···	···	0.48	···	0.48	0.90 ± 0.18	[7]
	$\Xi_b(5955)^-$		5955.33 ± 0.13	···	···	···	···	···	0.48	···	0.48	1.65 ± 0.33	[7]
$^2\lambda(\Xi_b')_{1/2^-}$		6190 ± 2		···	0.00	···	0.19	0.04	1.55	···	1.78		
$^4\lambda(\Xi_b')_{1/2^-}$		6203 ± 7		···	0.01	···	0.14	0.00	3.84	···	3.99		
$^2\lambda(\Xi_b')_{3/2^-}$		6198 ± 2		···	0.81	···	0.12	1.37	6.00	···	8.30		
$^4\lambda(\Xi_b')_{3/2^-}$		6210 ± 6		···	0.05	···	0.54	0.38	1.37	···	2.33		
$^4\lambda(\Xi_b')_{5/2^-}$	$\Xi_b(6227)^0$	6223 ± 6	$6226.8^{+1.5}_{-1.6}$	···	0.42	···	0.96	3.06	9.36	···	13.80	$18.6^{+5.2}_{-4.3}$	[41]
	$\Xi_b(6227)^-$		6227.9 ± 0.9	···	0.42	···	0.96	3.06	9.36	···	13.80	19.9 ± 2.6	[42]
$^2\rho(\Xi_b')_{1/2^-}$		6356 ± 2		0.55	1.66	0.40	8.32	0	0	0	10.93		
$^2\rho(\Xi_b')_{3/2^-}$		6364 ± 2		1.14	5.59	1.18	5.92	0	0	0	13.83		
$^2\Xi_b$	Ξ_b^0	5784 ± 2	5791.9 ± 0.5	···	···	···	···	···	···	···	···	···	[7]
	Ξ_b^-		5797.0 ± 0.6	···	···	···	···	···	···	···	···	···	[7]
$^2\lambda(\Xi_b)_{1/2^-}$		6048 ± 2		···	···	···	···	0	0	0	···		
$^2\lambda(\Xi_b)_{3/2^-}$		6056 ± 2		···	···	···	···	0	0	0	···		
$^2\rho(\Xi_b)_{1/2^-}$		6214 ± 2		···	0.04	···	0.26	0.01	1.63	···	1.94		
$^4\rho(\Xi_b)_{1/2^-}$		6226 ± 6		···	0.04	···	0.17	0.12	3.87	···	4.21		
$^2\rho(\Xi_b)_{3/2^-}$		6222 ± 2		···	0.99	···	0.16	1.78	5.51	···	8.44		
$^4\rho(\Xi_b)_{3/2^-}$		6234 ± 6		···	0.06	···	0.71	0.46	1.24	···	2.47		
$^4\rho(\Xi_b)_{5/2^-}$		6247 ± 6		···	0.47	···	1.14	3.46	8.38	···	13.45		

where $\vec{r}_j$, $\vec{p}_j$, and $\vec{s}_j$ are the coordinate, momentum, and spin of the jth constituent, respectively; k_0 is the meson energy; and $\vec{k} = k\hat{z}$ denotes the momentum carried by the outgoing meson. The flavor operator X_j^M corresponds to the emission of an elementary meson by the jth constituent: $q_j \to q_j' + M$. The coefficients g and h are fitted to two strong decays of Ω_c baryons

$$\Gamma(\Omega_c(3050) \to \Xi_c + \bar{K}) = 0.8 \pm 0.2 \text{ MeV},$$
$$\Gamma(\Omega_c(3066) \to \Xi_c + \bar{K}) = 3.5 \pm 0.4 \text{ MeV}, \quad (11)$$

to obtain $g = 3.410\ \text{GeV}^{-1}$ and $h = -0.521\ \text{GeV}^{-1}$ in qualitative agreement with values used in the light baryon sector [44,46].

A comparison between the experimental data and the predicted mass spectra and strong partial decay widths calculated within EEM are shown in Tables II and III. The zeros in the tables are consequences of the spin-flavor symmetry of the configurations $^2\rho(\Xi_Q')_J$ and $^2\lambda(\Xi_Q)_J$. The calculated values are of the order of 0–15 MeV in qualitative agreement with the experimental data.

In the $^3P_0$ model the transition operator is given by [43,47–51]

$$T^\dagger = -3\gamma_0 \int d\vec{p}_4\, d\vec{p}_5 \delta(\vec{p}_4 + \vec{p}_5) C_{45} F_{45} \times [\chi_{45} \times \mathcal{Y}_1(\vec{p}_4 - \vec{p}_5)]_0^{(0)} b_4^\dagger(\vec{p}_4) d_5^\dagger(\vec{p}_5). \quad (12)$$

Here, γ_0 is the pair-creation strength, and $b_4^\dagger(\vec{p}_4)$ and $d_5^\dagger(\vec{p}_5)$ are the creation operators for a quark and an antiquark with momenta $\vec{p}_4$ and $\vec{p}_5$, respectively. The $q\bar{q}$ pair is characterized by a color-singlet wave function C_{45}, a flavor-singlet wave function F_{45}, a spin-triplet wave function χ_{45} with spin $S = 1$, and a solid spherical harmonic $\mathcal{Y}_1(\vec{p}_4 - \vec{p}_5)$, since the quark and antiquark are in a relative P-wave. We fit $\gamma_0 = 6.52$ to the isospin channel $\Xi_c\bar{K}$.

In Tables II and III we show the two-body decay widths calculated in the elementary emission model. A comparison of the mass spectrum and the strong decay widths with experimental results suggests that the $\Xi_c(2923)^0$, $\Xi_c(2939)^0$, and $\Xi_c(2965)^0$ baryons are negative parity P-wave states of Ξ_c' and/or Ξ_c states. In fact, we can summarize the emerging possible identification of the three new Ξ_c states observed by LHCb [1] and the $\Xi_b(6227)^-$ reported in [42] as negative parity P-wave Ξ_Q' λ-excitation states of the flavor sextet **6**

$$
\begin{aligned}
&{}^4\lambda(\Xi_c')_{1/2^-} \to \Xi_c(2923)^0,\\
&{}^2\lambda(\Xi_c')_{3/2^-} \to \Xi_c(2939)^0,\\
&{}^4\lambda(\Xi_c')_{3/2^-} \to \Xi_c(2965)^0,\\
&{}^4\lambda(\Xi_b')_{5/2^-} \to \Xi_b(6227)^-,
\end{aligned} \tag{13}
$$

and/or as negative parity P-wave Ξ_Q ρ-excitation states of the flavor anti-triplet $\bar{\mathbf{3}}$

$$
\begin{aligned}
&{}^2\rho(\Xi_c)_{1/2^-} \to \Xi_c(2939)^0,\\
&{}^4\rho(\Xi_c)_{1/2^-} \to \Xi_c(2965)^0,\\
&{}^2\rho(\Xi_b)_{3/2^-} \to \Xi_b(6227)^-.
\end{aligned} \tag{14}
$$

Each of those states satisfies the equal spacing rules with the Ω_c or Ω_b states: the P-wave Ξ_Q λ-excitation states since they belong to the same **6**-plet, while the P-wave Ξ_Q ρ-excitation states that belong to a $\bar{\mathbf{3}}$-plet due to accidental degeneration in the spectrum. We cannot exclude *a priori* that the states seen by LHCb correspond to all of them, also because each of those states can decay into the $\Lambda_c\bar{K}$ channel. LHCb, BELLE, and *BABAR* can do new analysis to test if the P-wave Ξ_Q' and Ξ_Q are 14 states or not. The future amplitude analysis and the subsequent measurement of their J^P quantum numbers will be crucial in order to disentangle the correct identification of those states. The fact that in our model $\Xi_c(3055)^+$ and $\Xi_c(3080)^+$ resonances are assigned as ρ-mode excitations of the sextet configuration, ${}^2\rho(\Xi_c')_{J^P}$ with $J^P = 1/2^-$ and $3/2^-$ indicates a preference of a three-quark over a quark-diquark description. However, this assignment is mainly based on the predicted mass spectrum, and we cannot exclude that all the five states, $\Xi_c(2923)^0$, $\Xi_c(2939)^0$, $\Xi_c(2965)^0$, $\Xi_c(3055)^+$, and $\Xi_c(3080)^+$ are instead λ-mode excitations

$$
\begin{aligned}
&{}^2\lambda(\Xi_c')_{1/2^-} \to \Xi_c(2923)^0,\\
&{}^4\lambda(\Xi_c')_{1/2^-} \to \Xi_c(2939)^0,\\
&{}^2\lambda(\Xi_c')_{3/2^-} \to \Xi_c(2965)^0,\\
&{}^4\lambda(\Xi_c')_{3/2^-} \to \Xi_c(3055)^+,\\
&{}^4\lambda(\Xi_c')_{5/2^-} \to \Xi_c(3080)^+.
\end{aligned} \tag{15}
$$

In Tables IV and V we present the total strong decay widths calculated in the EEM and the ${}^3P_0$ models for the harmonic oscillator quark model. We show a comparison between our results with the available experimental data and also with the chiral quark model approach (χQM) [29]. As can be seen, most of our results about the strong decays are consistently below the total experimental widths, since the latter always have the complete information of the scattering processes. On the other hand, as one can observe, the values obtained in the χQM [29] are in general larger than the experimental widths.

TABLE IV. Comparison of the strong decay widths of Ξ_c and Ξ_c' baryons in MeV calculated in the elementary emission model (EEM) and the ${}^3P_0$ model with the values obtained in the chiral quark model (χQM) [29] and the available experimental data (Exp).

	Our work				
State	EEM	${}^3P_0$	χQM [29]	Experimental data [1,7]	Baryon
${}^4\Xi_c'$	1.23	0.02		2.14 ± 0.19	$\Xi_c(2645)^+$
	1.23	0.02		2.35 ± 0.22	$\Xi_c(2645)^0$
${}^2\lambda(\Xi_c')_{1/2^-}$	1.75	0.79	21.67		
${}^4\lambda(\Xi_c')_{1/2^-}$	4.83	0.53	37.05	7.1 ± 2.0	$\Xi_c(2923)^0$
${}^2\lambda(\Xi_c')_{3/2^-}$	11.53	3.08	20.89	14.8 ± 9.1	$\Xi_c(2930)^+$
	11.53	3.08		10.2 ± 1.4	$\Xi_c(2939)^0$
${}^4\lambda(\Xi_c')_{3/2^-}$	3.88	2.04	12.33	14.1 ± 1.6	$\Xi_c(2965)^0$
${}^4\lambda(\Xi_c')_{5/2^-}$	29.27	5.43	20.20		
${}^2\rho(\Xi_c')_{1/2^-}$	10.73	6.26		7.8 ± 1.9	$\Xi_c(3055)^+$
${}^2\rho(\Xi_c')_{3/2^-}$	25.39	3.70		3.6 ± 1.1	$\Xi_c(3080)^+$
	25.39	3.70		5.6 ± 2.2	$\Xi_c(3080)^0$
${}^2\lambda(\Xi_c)_{1/2^-}$	0.01	0.41	3.61	8.9 ± 1.0	$\Xi_c(2790)^+$
	0.01	0.41		10.0 ± 1.1	$\Xi_c(2790)^0$
${}^2\lambda(\Xi_c)_{3/2^-}$	0.28	0.54	2.11	2.43 ± 0.26	$\Xi_c(2815)^+$
	0.28	0.54		2.54 ± 0.25	$\Xi_c(2815)^0$
${}^2\rho(\Xi_c)_{1/2^-}$	4.57	0.70			
${}^4\rho(\Xi_c)_{1/2^-}$	10.20	0.45			
${}^2\rho(\Xi_c)_{3/2^-}$	19.45	3.76			
${}^4\rho(\Xi_c)_{3/2^-}$	7.60	2.51			
${}^4\rho(\Xi_c)_{5/2^-}$	44.91	4.55			

The predicted widths for the recently observed $\Xi_b(6327)^0$ and $\Xi_b(6333)^0$ baryons are 0.19 MeV and 0.10 MeV, respectively, in good agreement with the experimental width measured by the LHCb Collaboration [40]: $\Gamma(\Xi_b(6327)^0) = 0.93^{+0.74}_{-0.60}$ MeV and $\Gamma(\Xi_b(6333)^0) = 0.25^{+0.58}_{-0.25}$ MeV; see Table V.

It is worth noting that there is not a single model which is capable of providing a completely satisfactory description of baryon open-flavor strong decay widths [52], but effective models can describe the trend of the data. The uncertainty in the theoretical widths can be related to the values of the oscillator widths, α_λ and α_ρ, which are determined from the effective masses and the frequencies. We used a single set of values of α_λ and α_ρ, but the effective masses can have a large error; the correct propagation of the error is outside of the scope of the present article.

B. Electromagnetic couplings

In constituent models, electromagnetic couplings arise from the coupling of the (pointlike) constituent parts to the electromagnetic field [53–56]. We discuss here the case of the emission of a left-handed photon

$$B \to B' + \gamma, \tag{16}$$

for which the nonrelativistic part of the transverse electromagnetic coupling is given by

$$\mathcal{H}_{em} = 2\sqrt{\frac{\pi}{k_0}} \sum_{j=1}^{3} \mu_j e_j \left[k s_{j,-} \mathrm{e}^{-i\vec{k}\cdot\vec{r}_j} + \frac{1}{2g_j} \left(p_{j,-} \mathrm{e}^{-i\vec{k}\cdot\vec{r}_j} + \mathrm{e}^{-i\vec{k}\cdot\vec{r}_j} p_{j,-} \right) \right], \tag{17}$$

where $\vec{r}_j$, $\vec{p}_j$, and $\vec{s}_j$ are the coordinate, momentum, and spin of the jth constituent, respectively; k_0 is the photon energy; and $\vec{k} = k\hat{z}$ denotes the momentum carried by the outgoing photon. The photon is emitted by the jth constituent: $q_j \to q'_j + \gamma$.

Table VI shows a comparison of the radiative decay widths of ground state Ξ'_Q and Ξ_Q baryons with the results of light-cone QCD sum rules (LCQSR) [57–59], the bag model (BM) [60], vector meson dominance (VMD) [61], the chiral quark model (χQM) [29], the nonrelativistic quark model (NRQM) [62], heavy-baryon chiral perturbation theory (HBχPT) [63], the relativistic quark model (RQM) [64], and the hypercentral quark model (hCQM) [34]. Tables VII and VIII show the radiative decay widths of excited P-wave Ξ'_c and Ξ_c baryons, and excited P-wave Ξ'_b and Ξ_b baryons, respectively. Recently, the electromagnetic decay widths of the $\Xi_c(2790)$ and $\Xi_c(2815)$ baryons were measured by the Belle Collaboration [65]. The decay widths of the neutral states were found to be large and of the order of several hundreds of keV; for the charged states only an upper limit could be established. Inspection of Table VII shows that this behavior is in agreement only with an interpretation in terms of a λ-mode excitation of the flavor antitriplet $^2\lambda(\Xi_c)_J$. A similar result was found in the χQM [29]. The results are summarized in Table IX. In addition, Table VII shows that there are several other decay widths that are expected to be large, for example,

TABLE V. As in Table IV, but for Ξ_b and Ξ'_b baryons.

State	Our work EEM	Our work $^3P_0$	χQM [29]	Experimental data [7,40–42]	Baryon
$^2\Xi'_b$	$\cdots$	$\cdots$	0.08	< 0.08	
$^4\Xi'_b$	0.48	0.02	0.98	0.90 ± 0.18	$\Xi_b(5945)^0$
	0.48	0.02		1.65 ± 0.33	$\Xi_b(5955)^-$
$^2\lambda(\Xi'_b)_{1/2^-}$	1.78	0.86	27.05		
$^4\lambda(\Xi'_b)_{1/2^-}$	3.99	0.65	32.24		
$^2\lambda(\Xi'_b)_{3/2^-}$	8.30	2.92	24.15		
$^4\lambda(\Xi'_b)_{3/2^-}$	2.33	1.83	15.83		
$^4\lambda(\Xi'_b)_{5/2^-}$	13.80	3.36	24.39	$18.6^{+5.2}_{-4.3}$	$\Xi_b(6227)^0$
	13.80	3.36		19.9 ± 2.6	$\Xi_b(6227)^-$
$^2\rho(\Xi'_b)_{1/2^-}$	10.93	5.88			
$^2\rho(\Xi'_b)_{3/2^-}$	13.83	3.08			
$^2\lambda(\Xi_b)_{1/2^-}$	$\cdots$	$\cdots$	2.88		
$^2\lambda(\Xi_b)_{3/2^-}$	$\cdots$	$\cdots$	2.95		
$^2\rho(\Xi_b)_{1/2^-}$	1.94	0.55			
$^4\rho(\Xi_b)_{1/2^-}$	4.21	0.36			
$^2\rho(\Xi_b)_{3/2^-}$	8.44	1.90			
$^4\rho(\Xi_b)_{3/2^-}$	2.47	1.90			
$^4\rho(\Xi_b)_{5/2^-}$	13.45	2.16			
D-wave					
$^2\lambda(\Xi_b)_{3/2^+}$		0.19		$0.93^{+0.74}_{-60}$	$\Xi_b(6327)^0$
$^2\lambda(\Xi_b)_{5/2^+}$		0.10		$0.25^{+0.58}_{-25}$	$\Xi_b(6333)^0$

TABLE VI. Radiative decay widths of ground state S-wave sextet Ξ'_Q baryons in keV.

Decay	Our work	LCQSR [57–59]	BM [60]	VMD [61]	χQM [29]	NRQM [62]	HBχPT [63]	RQM [64]	hCQM [34]
$^2\Xi'^+_c \to {}^2\Xi^+_c + \gamma$	15.1	8.5 ± 2.5	10.2		42.3		5.43 ± 0.33	12.7 ± 1.5	
$^2\Xi'^0_c \to {}^2\Xi^0_c + \gamma$	0.3	0.27 ± 0.06	0.0015		0.00		0.46	0.17 ± 0.002	
$^4\Xi'^+_c \to {}^2\Xi^+_c + \gamma$	59.8	52 ± 32	44.3	152.4	139	63.32	21.6 ± 1	54 ± 3	17.48
$^4\Xi'^0_c \to {}^2\Xi^0_c + \gamma$	1.3	0.66 ± 0.41	0.908	1.318	0.00	0.30	1.84	0.68 ± 0.04	0.45
$^4\Xi'^+_c \to {}^2\Xi'^+_c + \gamma$	0.0	0.274	0.011	0.485	0.004		0.07 ± 0.03		
$^4\Xi'^0_c \to {}^2\Xi'^0_c + \gamma$	0.9	2.142	1.03	1.317	3.03		0.42 ± 0.16		
$^2\Xi'^0_b \to {}^2\Xi^0_b + \gamma$	33.2	47.0 ± 21.0	14.7		84.6		13.0 ± 0.8		
$^2\Xi'^-_b \to {}^2\Xi^-_b + \gamma$	0.7	3.3 ± 1.3	0.118		0.00		1.0		
$^4\Xi'^0_b \to {}^2\Xi^0_b + \gamma$	49.5	135 ± 85	24.7	270.8	104	18.79	17.2 ± 0.1		
$^4\Xi'^-_b \to {}^2\Xi^-_b + \gamma$	1.0	1.50 ± 0.95	0.278	2.246	0.00	0.09	1.4		
$^4\Xi'^0_b \to {}^2\Xi'^0_b + \gamma$	0.0	0.131	0.004	0.281	5.19		$(1.5 \pm 0.5) \times 10^{-3}$		
$^4\Xi'^-_b \to {}^2\Xi'^-_b + \gamma$	0.0	0.303	0.005	0.702	15.0		$(8.2 \pm 4) \times 10^{-3}$		

TABLE VII. Radiative decay widths of excited P-wave Ξ_c' and Ξ_c baryons in keV. The second line in the heading denotes the electric charge of the initial and final baryons.

	$^2\Xi_c'+\gamma$		$^4\Xi_c'+\gamma$		$^2\Xi_c+\gamma$		
	+	0	+	0	+	0	
$^2\lambda(\Xi_c')_{1/2^-}$	0.4	183.5	0.4	0.2	42.9	0.9	
	0.0	472.0	1.6	1.0	46.4	0.0	[29]
$^2\lambda(\Xi_c')_{3/2^-}$	17.0	401.7	0.7	0.3	57.5	1.2	
	12.1	302.0	1.6	1.0	46.1	0.0	[29]
$^4\lambda(\Xi_c')_{1/2^-}$	1.5	0.7	0.3	20.3	27.2	0.6	
	0.3	0.2	0.2	125.0	14.5	0.0	[29]
$^4\lambda(\Xi_c')_{3/2^-}$	6.5	2.8	0.5	122.4	99.4	2.1	
	2.1	1.2	1.6	187.0	54.6	0.0	[29]
$^4\lambda(\Xi_c')_{5/2^-}$	7.3	2.9	12.0	293.2	92.9	2.0	
	1.6	0.9	2.3	192.0	32.0	0.0	[29]
$^2\rho(\Xi_c')_{1/2^-}$	16.3	26.6	4.7	7.7	731.2	15.5	
$^2\rho(\Xi_c')_{3/2^-}$	20.9	34.3	6.4	10.5	783.4	16.6	
$^2\lambda(\Xi_c)_{1/2^-}$	2.3	0.0	0.2	0.0	5.4	239.3	
	1.4	0.0	0.4	0.0	4.6	263.0	[29]
$^2\lambda(\Xi_c)_{3/2^-}$	4.6	0.1	0.6	0.0	2.4	344.6	
	2.3	0.0	1.0	0.0	2.8	292.0	[29]
$^2\rho(\Xi_c)_{1/2^-}$	157.2	3.3	1.8	0.0	16.0	26.2	
	128.0	0.0	0.2	0.0	1.4	5.6	[29]
$^2\rho(\Xi_c)_{3/2^-}$	585.1	12.4	2.8	0.1	20.6	33.7	
	110.0	0.0	0.5	0.0	1.9	7.5	[29]
$^4\rho(\Xi_c)_{1/2^-}$	5.4	0.1	12.5	0.3	9.8	16.1	
	0.4	0.0	43.4	0.0	0.7	3.0	[29]
$^4\rho(\Xi_c)_{3/2^-}$	21.2	0.4	122.4	2.6	34.6	56.6	
	1.8	0.0	58.1	0.0	2.8	11.2	[29]
$^4\rho(\Xi_c)_{5/2^-}$	21.7	0.5	445.5	9.5	30.8	50.5	

TABLE VIII. As Table VII, but for Ξ_b' and Ξ_b baryons.

	$^2\Xi_b'+\gamma$		$^4\Xi_b'+\gamma$		$^2\Xi_b+\gamma$		
	0	−	0	−	0	−	
$^2\lambda(\Xi_b')_{1/2^-}$	48.2	46.4	0.3	0.5	53.7	1.1	
	76.3	190.0	0.9	3.5	72.2	0.0	[29]
$^2\lambda(\Xi_b')_{3/2^-}$	101.2	116.0	0.3	0.5	57.9	1.2	
	43.9	92.3	0.9	3.6	72.8	0.0	[29]
$^4\lambda(\Xi_b')_{1/2^-}$	0.5	0.8	6.5	5.3	30.3	0.6	
	0.3	1.5	69.5	164.0	34.0	0.0	[29]
$^4\lambda(\Xi_b')_{3/2^-}$	1.4	2.5	35.6	35.4	90.2	1.9	
	0.7	2.0	47.5	104.0	94.0	0.0	[29]
$^4\lambda(\Xi_b')_{5/2^-}$	1.1	1.9	64.1	76.1	64.8	1.4	
	0.4	1.9	41.5	88.2	47.7	0.0	[29]
$^2\rho(\Xi_b')_{1/2^-}$	12.3	20.2	5.2	8.6	698.5	14.8	
$^2\rho(\Xi_b')_{3/2^-}$	13.2	21.6	5.6	9.2	705.7	15.0	
$^2\lambda(\Xi_b)_{1/2^-}$	0.2	0.0	0.0	0.0	72.8	80.0	
	1.3	0.0	2.0	0.0	63.6	135.0	[29]
$^2\lambda(\Xi_b)_{3/2^-}$	0.3	0.0	0.1	0.0	79.3	85.6	
	1.7	0.0	2.6	0.0	68.3	147.0	[29]
$^2\rho(\Xi_b)_{1/2^-}$	120.9	2.6	1.2	0.0	11.9	19.5	
	94.3	0.0	0.6	0.0	1.9	7.2	[29]
$^2\rho(\Xi_b)_{3/2^-}$	296.9	6.3	1.3	0.0	12.9	21.1	
	69.4	0.0	0.8	0.0	2.1	8.1	[29]
$^4\rho(\Xi_b)_{1/2^-}$	1.9	0.0	13.7	0.3	6.7	10.9	
	0.2	0.0	80.0	0.0	0.9	3.6	[29]
$^4\rho(\Xi_b)_{3/2^-}$	5.9	0.1	91.5	1.9	19.9	32.5	
	0.8	0.0	78.0	0.0	2.9	11.4	[29]
$^4\rho(\Xi_b)_{5/2^-}$	4.6	0.1	193.9	4.1	14.1	23.1	

TABLE IX. Radiative decay widths of $\Xi_c(2790)$ and $\Xi_c(2815)$ baryons in keV.

Decay	Our work	χQM [29]	MB [66]	LCQSR [67]	Experimental data [65]
$\Xi_c(2790)^+ \to {}^2\Xi_c^+ + \gamma$	5.4	4.6	249.6 ± 41.9	265 ± 106	< 350
$\Xi_c(2790)^0 \to {}^2\Xi_c^0 + \gamma$	239.3	263.0	119.3 ± 21.7	2.7 ± 0.8	800 ± 320
$\Xi_c(2815)^+ \to {}^2\Xi_c^+ + \gamma$	2.4	2.8			< 80
$\Xi_c(2815)^0 \to {}^2\Xi_c^0 + \gamma$	344.6	292.0			$320 \pm 45^{+45}_{-80}$

$$
\begin{aligned}
&{}^2\lambda(\Xi_c'^0)_J \to {}^2\Xi_c'^0 + \gamma, \\
&{}^4\lambda(\Xi_c'^0)_J \to {}^4\Xi_c'^0 + \gamma, \\
&{}^2\rho(\Xi_c'^+)_J \to {}^2\Xi_c^+ + \gamma, \\
&{}^2\rho(\Xi_c^+)_J \to {}^2\Xi_c'^+ + \gamma, \\
&{}^4\rho(\Xi_c^+)_J \to {}^4\Xi_c'^+ + \gamma,
\end{aligned} \tag{18}
$$

as well as the corresponding decay widths in Table VIII for the beauty Ξ_b' and Ξ_b baryons.

V. SUMMARY AND CONCLUSIONS

This work was motivated by recent LHCb measurements of Ξ_c^0 baryons and the observation of the equal spacing rules with Ω_c resonances. We presented a quark model calculation of ground state and excited heavy Ξ_Q baryons with $Q = c$ and b involving both sextet (Ξ_Q') and antitriplet (Ξ_Q) states. According to the quark model analysis there are 14 negative parity P-wave states divided evenly between the sextet (five λ-mode and two ρ-mode) and the antitriplet (two λ-mode and five ρ-mode).

The mass spectrum was obtained in a harmonic oscillator quark model with spin, spin-orbit, isospin, and flavor dependent terms. The parameters were taken from a previous study of Ω_c and Ω_b baryons. The assignments of quantum numbers were based on systematics of the mass spectrum as well as on the strong and electromagnetic decay widths. Just as in the case of the masses, the parameters in the elementary emission model and the $^3P_0$ model for strong decays were taken from a study of Ω_c baryons. No attempt was made to fine-tune the parameter values to the spectroscopic properties of the Ξ_c and Ξ_c' baryons.

Overall, there is a reasonable agreement with the available experiment. In particular, it was found that the electromagnetic decay widths of the neutral and charged $\Xi_c(2790)$ and $\Xi_c(2815)$ baryons are compatible only with an assignment as a λ-mode excitation of the $^2\lambda(\Xi_c)_J$ configuration of the flavor antitriplet. At the moment, not for all states can such an unambiguous assignment be made. We have identified several large electromagnetic decay widths of the order of several hundreds of keV which may help future experimental studies of charm and bottom baryons. The future measurement of the J^P quantum numbers is crucial to determine the correct assignment of those states. Moreover, the identification of the negative parity P-wave states of the ρ-mode excitation is important to distinguish between an interpretation in terms of a three-quark or a quark-diquark structure, since in a quark-diquark model the ρ-mode excitations are frozen [35]. In the bottom sector our model is able to reproduce the masses and widths of the two new Ξ_b states by LHCb [40], which have been identified as positive parity D-wave excitations of the Ξ_b system with the following quantum number assignment: $J^P_{\Xi_b(6327)^0} = 3/2^+$ and $J^P_{\Xi_b(6333)^0} = 5/2^+$. In the charm sector by providing results for the spectrum of both Ξ_c and Ξ_c' baryons and combining them with predictions for their $\Lambda_c^+ K^-$ decays and their total decay widths, we can suggest assignments that can be tested by further experimental amplitude analysis.

ACKNOWLEDGMENTS

This work was supported by INFN and by Grant No. IN101320 from UNAM-PAPIIT. H. G. T. acknowledges support from National Research Foundation (NRF) of Korea (Grants No. 2020R1I1A1A01066423 and No. 2019R1I1A3A01058933).

[1] R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. Lett. **124**, 222001 (2020).
[2] W. Roberts and M. Pervin, Int. J. Mod. Phys. A **23**, 2817 (2008).
[3] V. Crede and W. Roberts, Rep. Prog. Phys. **76**, 076301 (2013).
[4] H. Y. Cheng, Front. Phys. (Beijing) **10**, 101406 (2015).
[5] H. X. Chen, W. Chen, X. Liu, Y. R. Liu, and S. L. Zhu, Rep. Prog. Phys. **80**, 076201 (2017).
[6] Y. S. Amhis *et al.* (HFLAV Collaboration), Eur. Phys. J. C **81**, 226 (2021).
[7] P. A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020).
[8] R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. Lett. **118**, 182001 (2017).
[9] J. Yelton *et al.* (Belle Collaboration), Phys. Rev. D **97**, 051102 (2018).
[10] M. Gell-Mann, Phys. Rev. **125**, 1067 (1962).
[11] S. Okubo, Prog. Theor. Phys. **27**, 949 (1962).
[12] F. Gürsey and L. A. Radicati, Phys. Rev. Lett. **13**, 173 (1964).
[13] Y. B. Li *et al.* (Belle Collaboration), Eur. Phys. J. C **78**, 252 (2018).
[14] Y. B. Li *et al.* (Belle Collaboration), Eur. Phys. J. C **78**, 928 (2018).
[15] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. D **77**, 031101 (2008).
[16] T. J. Moon *et al.* (Belle Collaboration), Phys. Rev. D **103**, L111101 (2021).
[17] Y. Yamaguchi, S. Ohkoda, A. Hosaka, T. Hyodo, and S. Yasui, Phys. Rev. D **91**, 034034 (2015).
[18] D. Ebert, R. N. Faustov, and V. O. Galkin, Phys. Rev. D **84**, 014025 (2011).
[19] D. Ebert, R. N. Faustov, and V. O. Galkin, Phys. Lett. B **659**, 612 (2008).
[20] H. M. Yang, H. X. Chen, and Q. Mao, Phys. Rev. D **102**, 114009 (2020).
[21] Q. F. Lü, Eur. Phys. J. C **80**, 921 (2020).
[22] HongQiang Zhu, NaNa Ma, and Yin Huang, Eur. Phys. J. C **80**, 1184 (2020).
[23] H. Bahtiyar, K. U. Can, G. Erkol, P. Gubler, M. Oka, and T. T. Takahashi, Phys. Rev. D **102**, 054513 (2020).
[24] J. R. Zhang and M. Q. Huang, Phys. Rev. D **78**, 094015 (2008).
[25] H. X. Chen, W. Chen, Q. Mao, A. Hosaka, X. Liu, and S. L. Zhu, Phys. Rev. D **91**, 054034 (2015).
[26] S. S. Agaev, K. Azizi, and H. Sundu, Eur. Phys. J. A **57**, 201 (2021).
[27] H. M. Yang and H. X. Chen, Phys. Rev. D **101**, 114013 (2020); **102**, 079901(E) (2020).
[28] Z. G. Wang, Eur. Phys. J. A **47**, 81 (2011).

[29] K. L. Wang, Y. X. Yao, X. H. Zhong, and Q. Zhao, Phys. Rev. D **96**, 116016 (2017).
[30] K. L. Wang, L. Y. Xiao, and X. H. Zhong, Phys. Rev. D **102**, 034029 (2020).
[31] B. Chen, K. W. Wei, X. Liu, and T. Matsuki, Eur. Phys. J. C **77**, 154 (2017).
[32] T. Yoshida, E. Hiyama, A. Hosaka, M. Oka, and K. Sadato, Phys. Rev. D **92**, 114029 (2015).
[33] Z. Shah, K. Thakkar, A. K. Rai, and P. C. Vinodkumar, Chin. Phys. C **40**, 123102 (2016).
[34] K. Gandhi, Z. Shah, and A. K. Rai, Eur. Phys. J. Plus **133**, 512 (2018).
[35] E. Santopinto, A. Giachino, J. Ferretti, H. García-Tecocoatzi, M. A. Bedolla, R. Bijker, and E. Ortiz-Pacheco, Eur. Phys. J. C **79**, 1012 (2019).
[36] R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. Lett. **124**, 082002 (2020).
[37] N. Isgur and G. Karl, Phys. Rev. D **18**, 4187 (1978).
[38] S. Capstick and N. Isgur, Phys. Rev. D **34**, 2809 (1986).
[39] J. J. de Swart, Rev. Mod. Phys. **35**, 916 (1963).
[40] R. Aaij *et al.* (LHCb Collaboration), arXiv:2110.04497.
[41] R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. D **103**, 012004 (2021).
[42] R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. Lett. **121**, 072002 (2018).
[43] A. Le Yaouanc, L. Oliver, O. Pène, and J.-C. Raynal, *Hadron Transitions in the Quark Model* (Gordon and Breach, New York, 1988).
[44] R. Bijker, F. Iachello, and A. Leviatan, Ann. Phys. (N.Y.) **284**, 89 (2000).
[45] R. Koniuk and N. Isgur, Phys. Rev. D **21**, 1868 (1980).
[46] R. Bijker, F. Iachello, and A. Leviatan, Phys. Rev. D **55**, 2862 (1997).
[47] L. Micu, Nucl. Phys. **B10**, 521 (1969).
[48] A. Le Yaouanc, L. Oliver, O. Pene, and J. C. Raynal, Phys. Rev. D **8**, 2223 (1973).
[49] W. Roberts and B. Silvestre-Brac, Phys. Rev. D **57**, 1694 (1998).
[50] C. Chen, X. L. Chen, X. Liu, W. Z. Deng, and S. L. Zhu, Phys. Rev. D **75**, 094017 (2007).
[51] R. Bijker, J. Ferretti, G. Galatà, H. García-Tecocoatzi, and E. Santopinto, Phys. Rev. D **94**, 074040 (2016).
[52] S. Capstick and W. Roberts, Prog. Part. Nucl. Phys. **45**, S241 (2000).
[53] L. A. Copley, G. Karl, and E. Obryk, Phys. Lett. **29B**, 117 (1969).
[54] L. A. Copley, G. Karl, and E. Obryk, Nucl. Phys. **B13**, 303 (1969).
[55] R. Bijker, F. Iachello, and A. Leviatan, Ann. Phys. (N.Y.) **236**, 69 (1994).
[56] R. Bijker, F. Iachello, and A. Leviatan, Phys. Rev. C **54**, 1935 (1996).
[57] T. M. Aliev, K. Azizi, and A. Ozpineci, Phys. Rev. D **79**, 056005 (2009).
[58] T. M. Aliev, K. Azizi, and H. Sunda, Eur. Phys. J. C **75**, 14 (2015).
[59] T. M. Aliev, T. Barakat, and M. Savci, Phys. Rev. D **93**, 056007 (2016).
[60] A. Bernotas and V. Simonis, Phys. Rev. D **87**, 074016 (2013).
[61] T. M. Aliev, M. Savc, and V. S. Zamiralov, Mod. Phys. Lett. A **27**, 1250054 (2012).
[62] A. Majethiya, B. Patel, and P. C. Vinodkumar, Eur. Phys. J. C **42**, 213 (2009).
[63] G.-J. Wang, L. Meng, and S.-L. Zhu, Phys. Rev. D **99**, 034021 (2019).
[64] M. A. Ivanov, J. G. Körner, V. E. Lyubovitskij, and A. G. Rusetsky, Phys. Rev. D **60**, 094002 (1999).
[65] J. Yelton *et al.* (Belle Collaboration), Phys. Rev. D **102**, 071103(R) (2020).
[66] D. Gamermann, C. E. Jiménez-Tejero, and A. Ramos, Phys. Rev. D **83**, 074018 (2011).
[67] T. M. Aliev, T. Barakat, and M. Savc, Eur. Phys. J. C **79**, 437 (2019).