

Radiative decays of the $1P$, $1D$, $2S$, and $2P$ Λ_c and $1D$, $2S$, and $2P$ Ξ_c charmed baryons

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We analyze the radiative decays of the $1P$, $1D$, $2S$, and $2P$ Λ_c and $1D$, $2S$, and $2P$ Ξ_c charmed baryons, belonging to the flavor antitriplet ($\bar{3}_F$), using the constituent quark model. We compute electromagnetic transitions from ground and P -wave states to ground states, as well as from second-shell states to both ground and P -wave final states. Electromagnetic decay widths are especially valuable for identifying resonances when multiple states share similar mass and total decay width. We give branching ratios of several electromagnetic decay widths that can confirm the assignment of the $\Xi_c(3055)$ reported by LHCb. Likewise, we provide branching-ratio predictions that can help guide the assignment of the $\Xi_c(3080)$ states, and discuss their possible interpretation either as $1D$ states with $\mathbf{J}^P = 5/2^+$ or as $2S$ states with $\mathbf{J}^P = 1/2^+$. For the first time, this work provides calculations of electromagnetic decays for D_ρ -wave states, $\rho - \lambda$ mixed configurations, and ρ -mode radially excited states in singly charmed baryons of the flavor antitriplet. Both experimental and model-dependent uncertainties are taken into account throughout our analysis.

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I. INTRODUCTION

The recent observation of numerous excited states in the heavy-baryon sector has considerably improved our

understanding of singly heavy baryons. Charmed baryons, in particular, provide a prominent example of this progress. In addition to the determination of their masses and decay widths, increasing attention has been devoted to measuring their quantum numbers, which play a crucial role in establishing a consistent connection between theoretical predictions and experimental observations. Examples include studies by the BESIII collaboration on the Λ_c^+ state, where its spin was determined to be $\mathbf{J} = 1/2$, with a significance exceeding 6σ [1]; by the Belle collaboration on the $\Xi_c(2970)^+$ state, for which a spin-parity of $\mathbf{J}^P = 1/2^+$ was favored [2]; and more recently by the LHCb

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collaboration in 2025, where the spin-parity for the $\Xi(3055)^{+,0}$ baryon was determined to be $\mathbf{J}^P = 3/2^+$, with a significance greater than 6.5σ [3].

Similarly, the LHCb collaboration excluded the $\mathbf{J} = 1/2$ assignment for the $\Omega_c(3050)^0$ and $\Omega_c(3065)^0$ states with significances of 2.2σ and 3.6σ , respectively [4]. Moreover, the *BABAR* collaboration [5] ruled out the $\mathbf{J} = 3/2$ hypothesis for the $\Sigma_c(2455)^0$ baryon with a significance surpassing 4σ , favoring instead a $\mathbf{J} = 1/2$ assignment, in agreement with quark model expectations.

A brief overview of the most relevant experimental and theoretical developments is presented in Ref. [6], where some of the authors of the present work studied the electromagnetic decay (EMD) widths of the Σ_c , Ξ'_c , and Ω_c charmed baryons belonging to the flavor $\mathbf{6}_F$ multiplet. Further discussions on this topic can be found in the review articles [7–9]. In the present work, we focus on reviewing the main results for singly charmed baryons belonging to the flavor antitriplet.

The first singly charmed baryon was identified as Λ_c^+ in 1975 by the Brookhaven National Laboratory group [10], with a mass of 2426 MeV. In the following years, new states were discovered including Σ_c^{++} [11] and Σ_c^+ [12]. The WA62 Collaboration observed the ground state of the Ξ_c in 1983, with a measured mass of 2460 MeV [13], and in 1985 reported evidence for the Ω_c^0 baryon [14]. In 1993, Ref. [15] reported the observation of a charmed baryon with a mass of 2626.6 MeV (90% CL) in DORIS II at DESY. Theoretical estimates assign this mass to P -wave $\Lambda_c(2630)$ or $\Lambda_c(2640)$ states with $\mathbf{J}^P = 1/2^-$ or $3/2^-$. The $\Lambda_c(2595)^+$ and $\Lambda_c(2625)^+$ baryons, with respective masses of 2593 MeV and 2625 MeV, were observed in 1995 by the CLEO Collaboration [16]. In 1997, Ref. [17] studied and confirmed the existence of the excited charmed baryon $\Lambda_c(2595)^+$. By the end of the 20th century, CLEO introduced the states $\Xi_c(2815)^+$ and $\Xi_c(2815)^0$, with $\mathbf{J}^P = 3/2^-$, which are the charmed-strange analogs of $\Lambda_c(2625)^+$ [18], as well as two excited Λ_c^+ states with masses of about 3105 MeV and 3221 MeV (90% CL) [19]. In 2001, CLEO also provided evidence for the $\mathbf{J}^P = 1/2^-$ $\Xi_c(2790)^0$ and $\Xi_c(2790)^+$ states, analogs of the $\Lambda_c(2595)^+$ [20]. In the first decade of the 21st century, the Belle Collaboration observed two new Ξ_c baryons [21], and confirmed the existence of the $\Xi_c(2815)$ baryon [22].

In 2011 CDF reported the properties of several Λ_c and Σ_c baryons [23], and LHCb discovered in 2017 five Ω_c^0 baryons [24]. Later that year, Belle observed five new resonant states [25] and confirmed four of the states observed previously by LHCb.

More recently, the LHCb Collaboration reported the observation of three excited Ξ_c^0 baryons [26], confirmed four Ω_c^0 states [4], and reported two more Ω_c excited states [27]. In 2025, the same collaboration [3] reported the first determination of the spin-parity of the $\Xi_c(3055)^{+,-}$ baryons, supporting the hypothesis that such baryons

correspond to the first D -wave λ -mode excitation of the Ξ_c flavor antitriplet. Finally, in 2025, LHCb [28] observed four $\Xi_c'^+$ states with high significance.

The spectroscopy of singly charmed baryons has been studied within different theoretical frameworks. In particular, QCD sum rules was employed in Ref. [29], bootstrap quark models in Ref. [30], and heavy-quark symmetry corrections in Ref. [31]. Lattice QCD, chiral perturbation theory, and relativized quark models have also been applied [32–38]. Predictions for the Ξ_c and Ξ_b masses were presented in Ref. [39].

Strong decays of charmed baryons were also analyzed using several techniques, including heavy hadron chiral perturbation theory [40], constituent and light-front quark models [41–43], nonrelativistic quark models with heavy-quark symmetry wave functions [44], combined heavy quark and chiral symmetries [45], Bethe-Salpeter approaches [46], and the $^3P_0$ model [47,48]. Recent works studied the structure and decays of $2P$ -wave charmed baryons like $\Lambda_c(2940)^+$ and $\Xi_c(3123)^+$ [49,50], with extensions to bottom baryons in the $\bar{\mathbf{3}}_F$ representation [51].

Different proposals for the nature of excited charmed baryons can be found in the literature, including molecular interpretations for $\Lambda_c(2593)^+$ [52] and $\Lambda_c(2940)^+$ [53], positive-parity assignments for $\Xi_c(2980)$ and $\Xi_c(3080)$ [54], λ -mode excitations for $\Xi_c(2930)$ [55], $\Xi_c(2923)^0$, $\Xi_c(2939)^0$, $\Xi_c(2965)^0$ [56], systematic patterns among $\bar{\mathbf{3}}_F$ and $\mathbf{6}_F$ states [57], and unquenched quark models applied to $\Lambda_c(2910)^+$ and $\Lambda_c(2940)^+$ [58].

Research on EMDs has progressed significantly over the years, enhancing our understanding of hadronic structure. The first experimental observation of electromagnetic decays from excited charmed baryons, comprising $\Xi_c'^+ \rightarrow \Xi_c^+ \gamma$ and $\Xi_c'^0 \rightarrow \Xi_c^0 \gamma$, was conducted in 1999 by CLEO [59]. In 2006, *BABAR* measured $\Omega_c^{*0} \rightarrow \Omega_c^0 \gamma$ [60], and two years later, Belle verified this result [61]. More recently, Belle announced the first detection of EMDs originating from P -wave Ξ_c states: $\Xi_c(2790)^0 \rightarrow \Xi_c^0 \gamma$ and $\Xi_c(2815)^0 \rightarrow \Xi_c^0 \gamma$, with statistical significances of 3.8σ and 8.6σ , respectively [62].

Theoretical advances in EMDs of singly charmed baryons can be found in Refs. [63–94]. Most of these studies focus on ground states [63–79], P -wave states [80–87], and both ground and P -wave states [88–94] using several theoretical frameworks. Specifically, chiral perturbation theory was implemented in Refs. [63–66], while light-cone QCD (LC-QCD) was applied in Refs. [67–73]. A modified bag model was adopted in Ref. [74] to compute the EMDs of heavy baryons. The hypercentral constituent quark model, which was introduced in [95–98], was used in Refs. [75–77], whereas the chiral quark-soliton model was applied in Refs. [78,79]. For P -wave excited Λ_Q baryons, the chiral soliton model was considered in Ref. [80]. Moreover, the coupled-channel approach (CCA) was used in Ref. [81], and LC-QCD was employed in Refs. [82–84]

to examine the EMDs of singly charmed baryons. Another commonly used approach is the constituent quark model (CQM), as seen in Refs. [85–91]. Electromagnetic transitions were also studied using a relativistic three-quark model in Refs. [92,93]. Additionally, heavy quark symmetry was invoked in Ref. [94].

In Ref. [87], the electromagnetic decay widths for the $\Xi_c(2790)^{+,0}$ and $\Xi_c(2815)^{+,0}$ baryons were obtained, employing a nonrelativistic constituent quark model. These theoretical results are in agreement with the recent experimental data reported by the Belle Collaboration [62].

To date, only two studies have examined a subset of second-shell charmed baryon states within the CQM [90,91]. In both works, the Close-Copley replacement [99] was adopted to evaluate the transition amplitudes. In the present study, we calculate the EMD widths of the Λ_c and Ξ_c charmed baryons, with isospin 0 and 1/2, respectively, belonging to the flavor $\bar{\mathbf{3}}_F$ -plet, within the constituent quark model formalism [87,100,101], following the notation and methods of Ref. [6]. We evaluate the transition amplitudes analytically without relying on the Close-Copley replacement. We consider transitions from ground and P -wave states to ground states for the Λ_c baryons, since transitions involving the Ξ_c baryons at this level have been addressed in our previous work [87]. We also analyze transitions from all second-shell Λ_c and Ξ_c states to both ground and P -wave final states. This work presents the first calculation of the EMDs of D_ρ -wave states, ρ - λ mixed states, and radially excited ρ -mode states for singly charmed baryons belonging to the flavor antitriplet. The paper is organized as follows: Sec. II briefly presents the quark model used to determine the mass spectra and outline the formalism used to calculate the EMD widths. Section III addresses our results along with a discussion. Finally, conclusions are summarized in Sec. IV.

II. ELECTROMAGNETIC DECAY WIDTHS

A. Charmed baryon states and mass spectra

First, we establish the masses and quantum states of the charmed baryons, these masses are used to compute the electromagnetic decay widths. Note that the Λ_c and Ξ_c states are part of the flavor $\bar{\mathbf{3}}_F$ -plet (see Fig. 1). We adopt the

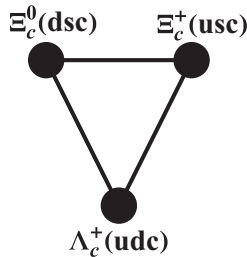


FIG. 1. $SU_f(3)$ flavor antitriplet of the ground-state singly charmed baryons.

masses and assignments of singly charmed baryons obtained in Ref. [102]. This choice is motivated by the excellent agreement between the calculated Ξ_c masses and the available experimental data. For the Λ_c sector, the agreement is also good and reproduces the experimental trend. In Fig. 2, we present the mass predictions of Ref. [102] compared to the experimental values reported by the PDG [103]. These theoretical masses correspond to the eigenvalues of the Hamiltonian introduced in Refs. [104,105], which models a charmed baryon as a three-quark system, given by

$$H = H_{\text{h.o.}} + P_S \mathbf{S}_{\text{tot}}^2 + P_{\text{SL}} \mathbf{S}_{\text{tot}} \cdot \mathbf{L}_{\text{tot}} + P_I \mathbf{I}^2 + P_F \hat{\mathbf{C}}_2, \quad (1)$$

where $H_{\text{h.o.}}$ is the sum of the constituent masses and the harmonic oscillator Hamiltonian. Moreover, the operators $\mathbf{S}_{\text{tot}}$, $\mathbf{L}_{\text{tot}}$, $\mathbf{I}$, and $\hat{\mathbf{C}}_2$ correspond to the spin, orbital angular momentum, isospin, and $SU_f(3)$ flavor degrees of freedom, respectively, with the strength of their contributions encoded in the model parameters P_S , P_{SL} , P_I , and P_F . In Eq. (1), $H_{\text{h.o.}}$ describes the spatial degrees of freedom of the three-quark system using the Jacobi coordinates ρ and λ , which describe the relative motion between the light quarks, and the relative motion of the light-quark pair and the charm quark c , respectively, together with their conjugate momenta $\mathbf{p}_\rho$ and $\mathbf{p}_\lambda$ [100,102,104,105],

$$H_{\text{h.o.}} = \sum_{i=1}^3 m_i + \frac{\mathbf{p}_\rho^2}{2m_\rho} + \frac{\mathbf{p}_\lambda^2}{2m_\lambda} + \frac{1}{2} m_\rho \omega_\rho^2 \rho^2 + \frac{1}{2} m_\lambda \omega_\lambda^2 \lambda^2, \quad (2)$$

where m_i with $i = 1, 2$ are the light quark masses, m_3 is the charm quark mass, $m_\rho = (m_1 + m_2)/2$, and $m_\lambda = 3m_\rho m_3/(2m_\rho + m_3)$. Equation (2) effectively describes the dynamics of two decoupled harmonic oscillators, ρ and λ . These oscillators are characterized with the quantum numbers $n_{\rho(\lambda)} = 2k_{\rho(\lambda)} + l_{\rho(\lambda)}$ where $k_{\rho(\lambda)} = 0, 1, \dots$ is the number of nodes and $l_{\rho(\lambda)} = 0, 1, \dots$ is the orbital angular momentum. We define $N = n_\rho + n_\lambda$ as the n^{th} -energy band. The ρ - and λ -oscillator frequencies are $\omega_{\rho(\lambda)} = \sqrt{\frac{3K_c}{m_{\rho(\lambda)}}}$, where K_c is the harmonic oscillator constant that is a further free parameter of the model. The quark masses and the model parameters are fitted to experimental data [102].

The Λ_c and Ξ_c states, generally referred to as A , are formally described by the state,

$$|\theta_c, \phi_A, k_A, J_A, M_{J_A}\rangle = |\theta_c\rangle \otimes |\phi_A, k_A, J_A, M_{J_A}\rangle, \quad (3)$$

where $|\theta_c\rangle = \frac{1}{\sqrt{6}}(|rgb\rangle - |rbg\rangle + |gbr\rangle - |grb\rangle + |brg\rangle - |bgr\rangle)$ is the $SU_c(3)$ color singlet. $|\phi_A, k_A, J_A, M_{J_A}\rangle$ contains the information related to the flavor, spin, and spatial degrees of freedom, and is given by

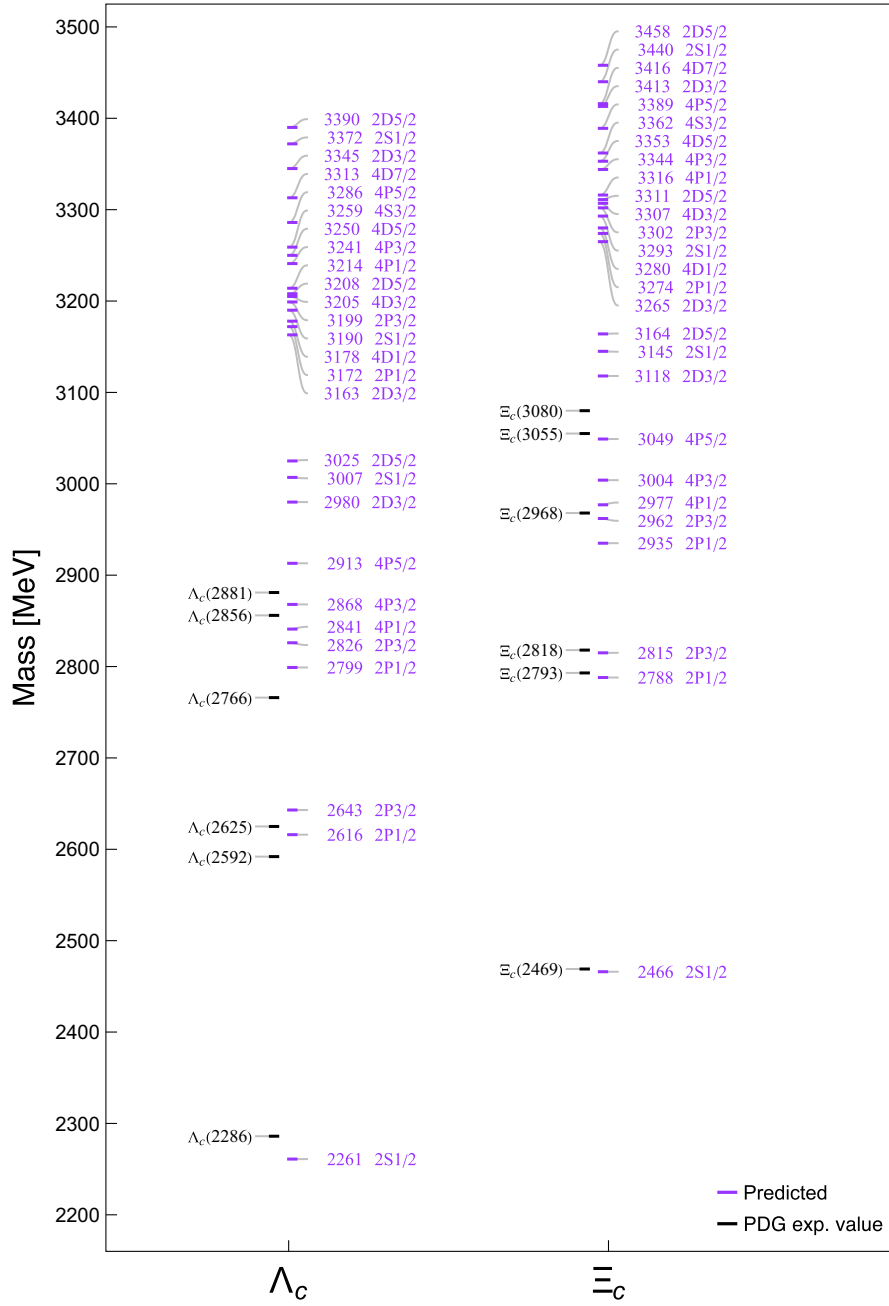


FIG. 2. Comparison between the predicted masses of singly charmed baryon belonging to the $\bar{\mathbf{3}}_F$ -plet, as from Ref. [102], with the experimental data from the PDG [103]. The predicted masses are displayed in purple, while the experimental masses are reported in black [103].

$$\begin{aligned}
 |\phi_{A_I}, k_A, J_A, M_{J_A}\rangle &= |\phi_{A_I}\rangle \otimes \sum_{M_L, M_S} \langle L, M_L; S, M_S | J_A, M_{J_A} \rangle \sum_{m_\lambda, m_{l_\rho}} \langle l_\lambda, m_{l_\lambda}; l_\rho, m_{l_\rho} | L, M_L \rangle \sum_{m_{S_{12}}, m_{S_3}} \langle S_{12}, m_{S_{12}}; S_3, m_{S_3} | S, M_S \rangle \\
 &\times \sum_{m_{S_1}, m_{S_2}} \langle S_1, m_{S_1}; S_2, m_{S_2} | S_{12}, m_{S_{12}} \rangle |S_1, m_{S_1}\rangle \otimes |S_2, m_{S_2}\rangle \otimes |S_3, m_{S_3}\rangle |k_\rho, l_\rho, m_{l_\rho}, k_\lambda, l_\lambda, m_{l_\lambda}\rangle, \quad (4)
 \end{aligned}$$

where $|\phi_{A_I}\rangle$ stands for the flavor wave function defined as $|\phi_{A_I}\rangle \equiv |A, I, M_I\rangle$ for the charmed baryon A with isospin I and isospin projection M_I . For the antitriplet states, Ξ_c , we have two charge states $|\Xi_c^0, 1/2, -1/2\rangle = \frac{1}{\sqrt{2}}(|dsc\rangle - |sdc\rangle)$ and

$|\Xi_c^+, 1/2, 1/2\rangle = \frac{1}{\sqrt{2}}(|usc\rangle - |suc\rangle)$; Λ_c , there is one possible configuration $|\Lambda_c^+, 0, 0\rangle = \frac{1}{\sqrt{2}}(|udc\rangle - |duc\rangle)$. $k_A = k_\rho + k_\lambda$ is the total number of nodes, J_A represents the total angular momentum, and M_{J_A} is the total angular momentum projection. $|S_i, m_{S_i}\rangle$ denote the spin wave function for each quark ($i = 1, 2, 3$), and $|k_\rho, l_\rho, m_{l_\rho}, k_\lambda, l_\lambda, m_{l_\lambda}\rangle$ is the harmonic-oscillator spatial baryon wave function, that are expressed in terms of ω_ρ and ω_λ through the relations $\alpha_{\rho(\lambda)}^2 = \omega_{\rho(\lambda)} m_{\rho(\lambda)}$.

B. Classification of antitriplet states

The Λ_c and Ξ_c states are modeled as three-quark systems that contain two light quarks (indistinguishable) and one heavy charm quark. These states are represented as qqc , where q are the s, u, d quarks and c is the charm quark. We consider the Λ_c and Ξ_c states to belong to the flavor antitriplet, where the light quarks are in an antisymmetric flavor configuration. Moreover, their color wave function is also antisymmetric. Thus the combined spin-orbital wave function of the light-quark pair must be antisymmetric to obtain a total antisymmetric wave function. The allowed baryon states are given by the Hamiltonian in Eq. (1), which defines the total orbital and spin configurations. In this Hamiltonian, $\mathbf{J}_{\text{tot}} = \mathbf{L}_{\text{tot}} + \mathbf{S}_{\text{tot}}$, where $\mathbf{L}_{\text{tot}} = \mathbf{l}_\rho + \mathbf{l}_\lambda$ and $\mathbf{S}_{\text{tot}} = \mathbf{S}_{\text{lt}} + \frac{1}{2}$, $\mathbf{S}_{\text{lt}}$ is the coupled spin of the two light quarks. We study the energy bands $N = 0, 1, 2$.

For $N = 0$, $\mathbf{L}_{\text{tot}} = \mathbf{l}_\lambda = \mathbf{l}_\rho = \mathbf{0}$ and the orbital wave function of the two light quarks is symmetric, hence the spin part must be antisymmetric. This corresponds to $\mathbf{S}_{\text{lt}} = \mathbf{0}$, yielding one ground state.

For $N = 1$, with the $\mathbf{l}_\rho = \mathbf{0}$ and $\mathbf{l}_\lambda = \mathbf{1}$ configuration, the light quark spatial wave function is symmetric and the spin part must be antisymmetric. This implies that $\mathbf{S}_{\text{tot}} = \mathbf{1}/2$ and $\mathbf{L}_{\text{tot}} = \mathbf{l}_\lambda = \mathbf{1}$, giving two P_λ states. For the $\mathbf{l}_\rho = \mathbf{1}$ and $\mathbf{l}_\lambda = \mathbf{0}$ configuration, the light quarks present an antisymmetric spatial wave function and a symmetric spin wave function with two possible values $\mathbf{S}_{\text{tot}} = \mathbf{1}/2, \mathbf{3}/2$. Accordingly, for $\mathbf{L}_{\text{tot}} = \mathbf{l}_\rho = \mathbf{1}$ there are five P_ρ states.

For $N = 2$, in the case of $\mathbf{l}_\rho = \mathbf{0}$ and $\mathbf{l}_\lambda = \mathbf{2}$, the total spatial wave function is symmetric; thus the light quark pair spin function is antisymmetric with $\mathbf{S}_{\text{lt}} = \mathbf{0}$. This yields two D_λ -wave excitations. Likewise, $N = 2$ for two possible radial excited configurations, that is, $k_\rho = 0$ and $k_\lambda = 1$, and $k_\rho = 1$ and $k_\lambda = 0$. These configurations generate symmetric spatial wave functions and hence require light quark pair spin antisymmetric configurations $\mathbf{S}_{\text{lt}} = \mathbf{0}$, producing one λ -radial excitation and one ρ -radial excitation. For the case $\mathbf{l}_\rho = \mathbf{1}$ and $\mathbf{l}_\lambda = \mathbf{1}$ the spatial wave functions are antisymmetric and are coupled to $\mathbf{L}_{\text{tot}} = \mathbf{0}, \mathbf{1}, \mathbf{2}$. Hence, the spin configuration $\mathbf{S}_{\text{tot}} = \mathbf{1}/2, \mathbf{3}/2$, coming from the light quark spin configuration, is $\mathbf{S}_{\text{lt}} = \mathbf{1}$. This produces 13 mixed excited states: six D -wave states, five P -wave states, and two S -wave states.

TABLE I. Classification of the symmetry properties of the two-light-quark spatial and spin wave functions of the antitriplet states. The states are organized by energy bands $N = n_\rho + n_\lambda$. The first column contains the spatial wave state $|k_\lambda, k_\rho, l_\lambda, l_\rho\rangle$ where $l_{\lambda,\rho}$ are the orbital angular momenta and $k_{\lambda,\rho}$ are the number of nodes of the λ and ρ oscillators. The second column, “Orbital symmetry,” indicates the symmetry of the two-light-quark spatial wave function under exchange of the light quarks, with S (A) denoting symmetric (antisymmetric) configurations. $\mathbf{S}_{\text{lt}}$ represents the total spin of the two-light-quark subsystem, while “spin symmetry” specifies the corresponding symmetry of the two-light-quark spin wave function. The fifth column contains the total baryon spin $\mathbf{S}_{\text{tot}}$. The sixth column contains the total angular momentum $\mathbf{L}_{\text{tot}}$. The last column lists all possible total spin-parity quantum numbers $\mathbf{J}^P$.

$ k_\lambda, k_\rho, l_\lambda, l_\rho\rangle$	Orbital symmetry	$\mathbf{S}_{\text{lt}}$	Spin symmetry	$\mathbf{S}_{\text{tot}}$	$\mathbf{L}_{\text{tot}}$	$\mathbf{J}^P$
$N = 0$						
$ 0, 0, 0, 0\rangle$	S	0	A	$\frac{1}{2}$	0	$\frac{1}{2}^+$
$N = 1$						
$ 0, 0, 1, 0\rangle$	S	0	A	$\frac{1}{2}$	1	$\frac{1}{2}^-, \frac{3}{2}^-$
				$\frac{1}{2}$	1	$\frac{1}{2}^-, \frac{3}{2}^-$
$ 0, 0, 0, 1\rangle$	A	1	S	$\frac{3}{2}$	1	$\frac{1}{2}^-, \frac{3}{2}^-, \frac{5}{2}^-$
$N = 2$						
$ 0, 0, 0, 2\rangle$	S	0	A	$\frac{1}{2}$	2	$\frac{3}{2}^+, \frac{5}{2}^+$
$ 0, 1, 0, 0\rangle$	S	0	A	$\frac{1}{2}$	0	$\frac{1}{2}^+$
$ 1, 0, 0, 0\rangle$	S	0	A	$\frac{1}{2}$	0	$\frac{1}{2}^+$
				$\frac{1}{2}$	0	$\frac{1}{2}^+$
$ 0, 0, 1, 1\rangle$	A	1	S	$\frac{1}{2}$	1	$\frac{1}{2}^-, \frac{3}{2}^-$
				$\frac{1}{2}$	2	$\frac{3}{2}^+, \frac{5}{2}^+$
				$\frac{3}{2}$	0	$\frac{3}{2}^+$
$ 0, 0, 1, 1\rangle$	A	1	S	$\frac{3}{2}$	1	$\frac{1}{2}^-, \frac{3}{2}^-, \frac{5}{2}^-$
				$\frac{3}{2}$	2	$\frac{1}{2}^+, \frac{3}{2}^+, \frac{5}{2}^+, \frac{7}{2}^+$
$ 0, 0, 2, 0\rangle$	S	0	A	$\frac{1}{2}$	2	$\frac{3}{2}^+, \frac{5}{2}^+$

Finally, the symmetric configuration $\mathbf{l}_\rho = \mathbf{2}$ and $\mathbf{l}_\lambda = \mathbf{0}$, combined with the light quark antisymmetric spin configuration, $\mathbf{S}_{\text{lt}} = \mathbf{0}$, gives two D_ρ excited states.

It is worth emphasizing that, although the ground state Ξ_c baryons have a light quark pair spin configuration $\mathbf{S}_{\text{lt}} = \mathbf{0}$, this assignment does not hold for all excited states. For the excited baryon Ξ_c , the light-quark pair can also have total spin $\mathbf{S}_{\text{lt}} = \mathbf{1}$, provided that the spatial wave function is antisymmetric to maintain the overall antisymmetry of the total light-quark wave function. The previous considerations and the state constructions are summarized in Table I.

C. Electromagnetic decay widths

At this point we compute the electromagnetic decay widths of Λ_c and Ξ_c states in accordance to the formalism developed in Refs. [87,100,101,106]. The formalism treats the emission of left-handed photons in radiative transitions

of the form $A \rightarrow A'\gamma$, where A and A' denote the initial and final baryon states, respectively. The interaction Hamiltonian describing the electromagnetic decays is

$$\mathcal{H}_{\text{em}} = 2\sqrt{\frac{\pi}{k}} \sum_{j=1}^3 \mu_j \left[\mathbf{k} \mathbf{s}_{j,-} e^{-i\mathbf{k} \cdot \mathbf{r}_j} - \frac{1}{2} (\mathbf{p}_{j,-} e^{-i\mathbf{k} \cdot \mathbf{r}_j} + e^{-i\mathbf{k} \cdot \mathbf{r}_j} \mathbf{p}_{j,-}) \right], \quad (5)$$

where μ_j , $\mathbf{s}_{j,-} = s_{j,x} - i s_{j,y}$, and $\mathbf{p}_{j,-} = p_{j,x} - i p_{j,y}$ are the magnetic moment, spin-ladder, and momentum-ladder operators of the j th quark, respectively. The electromagnetic transition amplitude, $A_{M_{JA}}$, of the radiative decay $A \rightarrow A'\gamma$, is computed as,

$$A_{M_{JA}} = \langle \phi_{A'}, k_{A'}, J_{A'}, M_{J_{A'}} | -1 | \mathcal{H}_{\text{em}} | \phi_A, k_A, J_A, M_{J_A} \rangle, \quad (6)$$

where A' is the final charmed baryon. Utilizing this transition amplitude, we obtain the partial decay width

$$\Gamma_{\text{em}} = \frac{\Phi}{(2\pi)^2} \frac{2}{2J_A + 1} \sum_{M_{J_A} > 0} |A_{M_{JA}}|^2, \quad (7)$$

where $\Phi = 4\pi(E_{A'}/m_A)k^2$ is the phase-space factor, with $k = (m_A^2 - m_{A'}^2)/(2m_A)$ and $E_{A'} = \sqrt{m_{A'}^2 + k^2}$. These baryon states are eigenstates of the Hamiltonian given in Eq. (1), and are denoted by $|l_\lambda, l_\rho, k_\lambda, k_\rho\rangle$, which represents a compact form of the state $|\phi_{A'}, k_{A'}, J_{A'}, M_{J_{A'}}\rangle$. This notation is adopted to emphasize the spatial degrees of freedom, since the novelty of this work resides in the calculation of electromagnetic decays of spatially excited D_ρ -wave, ρ - λ mixed, and radially excited ρ mode of the Λ_c and Ξ_c states.

Electromagnetic decays are allowed between different flavor multiplets. That is, for decays of antitriplet excited states, the final flavor wave functions $|\phi_{A'}\rangle$ may belong to either the anti-triplet or the sextet multiplet. $|\phi_{A'}\rangle$, for the antitriplet configurations Ξ_c and Λ_c , are defined as in Sec. II A. Moreover, $|\phi_{A'}\rangle$ for the sextet configurations can represent a Ξ'_c or Σ_c charmed baryon. The flavor wave functions of the final states Ξ'_c have two charge states, $|\Xi_c^0, 1/2, -1/2\rangle = \frac{1}{\sqrt{2}}(|dsc\rangle + |sdc\rangle)$ and $|\Xi_c^+, 1/2, 1/2\rangle = \frac{1}{\sqrt{2}}(|usc\rangle + |suc\rangle)$, while for the Σ_c states, the flavor wave functions of the final states have three possible charge configurations, $|\Sigma_c^{++}, 1, 1\rangle = |uuc\rangle$, $|\Sigma_c^0, 1, -1\rangle = |ddc\rangle$, and $|\Sigma_c^+, 1, 0\rangle = \frac{1}{\sqrt{2}}(|udc\rangle + |duc\rangle)$.

D. Uncertainties

Uncertainties are reported for each electromagnetic decay width and arise from the masses of the charmed baryons involved in the transition $A \rightarrow A'\gamma$, taken from PDG measurements [103], together with a model uncertainty associated with the mass description in Eq. (1). Error

propagation is performed through a Monte Carlo procedure in which baryon masses are sampled from Gaussian distributions centered on either the PDG values or the theoretical predictions of Ref. [102], with widths given by the combined experimental and model uncertainties. For each sampled set, the decay width is computed and the procedure is repeated 10^3 times. The mean value defines the central result, while the 68% confidence interval is obtained from quantiles. Fits and uncertainty propagation are performed using MINUIT [107] and NumPy [108].

III. RESULTS AND DISCUSSION

A. Results

This Section presents our numerical results for the electromagnetic decay widths of the singly charmed baryons Λ_c and Ξ_c , shown in Tables II–V. The baryon names and their predicted masses are taken from Ref. [102]. Additionally, we provide the total angular momentum and parity $\mathbf{J}^P$, the internal configuration of the baryon state given by $|l_\lambda, l_\rho, k_\lambda, k_\rho\rangle$, and the corresponding spectroscopic notation $^{2S+1}L_{x,J}$ for the initial states, where L denotes the total orbital angular momentum, S the total spin, the subscript x the type of orbital excitation, and the subscript J the total angular momentum. Here, x can take the values λ , $\lambda\lambda$, ρ , $\rho\rho$, and $\lambda\rho$. The value λ corresponds to a single λ -mode excitation, while ρ corresponds to a single ρ -mode excitation. The $\lambda\lambda$ and $\rho\rho$ configurations represent double excitations in their respective modes. Finally, $\lambda\rho$ denotes a mixed excitation of both the λ and ρ modes.

In Tables II–V, the predictions obtained in this work are displayed starting from the fifth column. Each column represents a particular decay channel, with the corresponding final-state baryon identified in the table header. The second row specifies the spectroscopic notation $^{2S+1}L_{x,J}$ associated with each final state as defined before. Moreover, our predictions are compared with previous theoretical results, including those obtained using LC-QCD [84] and CQMs [86,89]. Results from Ref. [63–82,85,92–94] are not included, since those studies considered only a limited number of decay channels.

In this paper, we present results for the Λ_c charmed baryons with initial states belonging to the energy bands $N = 0, 1, 2$ in the decay process. In contrast, for the Ξ_c baryons, we present electromagnetic decay widths only for initial states in the $N = 2$ energy band, since the lower-energy bands were previously discussed in Ref. [87]. For $N = 0$, we compute S -wave to S -wave transitions, which are presented in Table II for the Λ_c baryons. For the energy band $N = 1$, we evaluate P -wave to S -wave transitions, also shown in Table II. Finally, for $N = 2$, we consider the decays of the S -, P -, and D -wave states to the S -, and P -wave final states, which are presented in Tables III–V for the Λ_c and Ξ_c baryons, respectively. Tables III–V are

TABLE II. Predicted electromagnetic decay widths (in keV) for $\Lambda_c(nnc)^+$ states with isospin 0 belonging to the flavor antitriplet. The first column denotes the baryon name along with its predicted mass in both S -wave and P -wave configurations, taken from Ref. [102], corresponding to the $N = 0$ and $N = 1$ energy bands, respectively, where $N = n_\rho + n_\lambda$. The second column indicates the spin-parity $\mathbf{J}^P$, while the third column shows the internal configuration of the state in the three-quark model, written as $|l_\lambda, l_\rho, k_\lambda, k_\rho\rangle$, where $l_{\lambda,\rho}$ are the orbital angular momenta and $k_{\lambda,\rho}$ are the number of nodes of the λ and ρ oscillators. The fourth column provides the spectroscopic notation $^{2S+1}L_{x,J}$ associated with each initial state, where L is the total orbital angular momentum, S is the total spin, $x = \lambda$ or ρ denotes the mode in which the orbital excitation occurs, and the subscript J is the total angular momentum. From the fifth column onward, the predicted electromagnetic decay widths are presented for each decay channel, computed using Eq. (7). The decay products are listed at the top of each column, together with the spectroscopic notation $^{2S+1}L_{x,J}$ of the final states. Zero values correspond to electromagnetic decays that are either forbidden by phase space or have widths too small to be displayed at this scale. Our results are compared with those from Refs. [89,86,84]. The “...” symbol indicates that no prediction is available for that particular state in previous studies.

$\Lambda_c(nnc)$	$\mathbf{J}^P$	$ l_\lambda, l_\rho, k_\lambda, k_\rho\rangle$	$^{2S+1}L_{x,J}$	$\frac{\Lambda_c^+\gamma}{^2S_{1/2}}$	$\frac{\Sigma_c^+\gamma}{^2S_{1/2}}$	$\frac{\Sigma_c^{*+}\gamma}{^4S_{3/2}}$	
$N = 0$							
$\Lambda_c(2261)$	$\frac{1}{2}^+$	$ 0, 0, 0, 0\rangle$	$^2S_{1/2}$	0	0	0	
$N = 1$							
$\Lambda_c(2616)$	$\frac{1}{2}^-$	$ 1, 0, 0, 0\rangle$	$^2P_{\lambda,1/2}$	$3.5^{+3.2}_{-2.9}$ 0.26 0.1 ...	$1.5^{+1.5}_{-1.0}$ 0.45 1.0 2800^{+2400}_{-1700}	$0.1^{+0.1}_{-0.1}$ 0.05 0 640^{+860}_{-480}	[89] [86] [83]
$\Lambda_c(2643)$	$\frac{3}{2}^-$	$ 1, 0, 0, 0\rangle$	$^2P_{\lambda,3/2}$	$1.2^{+1.8}_{-0.8}$ 0.3 0.7 ...	$3.1^{+2.7}_{-1.7}$ 1.17 2.5 1900^{+1400}_{-950}	$0.2^{+0.3}_{-0.1}$ 0.26 0.2 71^{+80}_{-47}	[89] [86] [83]
$\Lambda_c(2800)$	$\frac{1}{2}^-$	$ 0, 1, 0, 0\rangle$	$^2P_{\rho,1/2}$	19^{+7}_{-7} 1.59 9.6	584^{+51}_{-49} 41.6 97.3	$2.6^{+2.0}_{-1.5}$ 0.02 1.5	[89] [86]
$\Lambda_c(2842)$	$\frac{1}{2}^-$	$ 0, 1, 0, 0\rangle$	$^4P_{\rho,1/2}$	12^{+4}_{-4} 0.8 5.8	10^{+6}_{-5} 0.08 5.3	90^{+21}_{-26} 6.81 6.0	[89] [86]
$\Lambda_c(2827)$	$\frac{3}{2}^-$	$ 0, 1, 0, 0\rangle$	$^2P_{\rho,3/2}$	22^{+7}_{-7} 2.35 11.8	1299^{+213}_{-232} 48.0 447.0	$3.8^{+2.6}_{-2.0}$ 0.09 2.5	[89] [86]
$\Lambda_c(2869)$	$\frac{3}{2}^-$	$ 0, 1, 0, 0\rangle$	$^4P_{\rho,3/2}$	37^{+11}_{-12} 3.29 19.4	35^{+20}_{-16} 0.55 21.1	434^{+37}_{-37} 17.4 79.1	[89] [86]
$\Lambda_c(2914)$	$\frac{5}{2}^-$	$ 0, 1, 0, 0\rangle$	$^4P_{\rho,5/2}$	28^{+8}_{-8} ... 16.1 ...	32^{+16}_{-14} ... 22.2 ...	1341^{+229}_{-249} ... 362.8 130^{+1000}_{-130}	[89] [86] [83]

organized according to the electric charge of the baryons. Our predictions are compared with some of the results in Refs. [90,91], however, a one-to-one comparison is not possible due to the fact that those works use different basis quantum states.

B. Discussion

Electromagnetic decay widths are generally smaller than the dominant strong decay widths. Nevertheless, they can serve as powerful tools since they allow the estimation of

observable branching ratios in collider experiments, particularly when resonances exhibit similar masses and strong decay widths.

In particular, we focus on the electromagnetic decay widths of the $\Xi_c(3055)^{+,0}$ and $\Xi_c(3080)^{+,0}$ states. In Ref. [102], these resonances were interpreted as members of the flavor sextet. These assignments were proposed in a context where angular-distribution measurements were unavailable and several nearby resonances had been reported in the literature, making their identification

TABLE III. Predicted electromagnetic decay widths (in keV) for transitions from second shell $\Lambda_c^+(snc)$ states with isospin 0 belonging to the flavor antitriplet. The first column lists the baryon name along with its predicted mass in the $N = 2$ energy band, where $N = n_\rho + n_\pi$, as calculated in Ref. [102]. The second column displays the spin-parity $\mathbf{J}^P$, while the third column shows the internal configuration $|I_\lambda, I_\rho, k_\lambda, k_\rho\rangle$ in the three-quark model, where $I_{\lambda,\rho}$ are the orbital angular momenta and $k_{\lambda,\rho}$ denote the number of radial nodes of the λ and ρ oscillators. The fourth column presents the spectroscopic notation $2S+1L_{x,J}$ associated with each initial state, where L is the total orbital angular momentum, S is the total spin, the subscript x specifies the orbital excitation and can take the values $x = \lambda, 2\lambda, \rho, \rho\rho$, or $\lambda\rho$, and the subscript J is the total angular momentum. From the fifth column onward, the electromagnetic decay widths are shown, computed using Eq. (7). Each column corresponds to a specific decay channel; the final-state particles are indicated at the top of each column, and their spectroscopic notation $2S+1L_{x,J}$ is provided in the second row. Zero values correspond to decay widths that are either forbidden by phase space or too small to be shown at this scale. Our results are compared with those in Refs. [90,91]. The symbol “...” indicates that no prediction is available for the corresponding state in Refs. [90,91].

[illegible]

TABLE IV. Same as Table III, but for Ξ_c^+ states with isospin $1/2$.

$\Xi_c^+(snc)$	$\mathbf{J}^P$	$ l_s, l_p, k_s, k_p\rangle$	$2S_{1/2}$	$2S_{1/2}$	$4S_{3/2}$	$2P_{\lambda,1/2}$	$2P_{\lambda,3/2}$	$2P_{\rho,1/2}$	$P_{\rho,1/2}$	$4P_{\rho,3/2}$	$4P_{\rho,5/2}$	$2P_{\lambda,1/2}$	$2P_{\lambda,3/2}$	$2P_{\lambda,5/2}$	$4P_{\lambda,3/2}$	$4P_{\lambda,5/2}$	$2P_{\rho,1/2}$	$2P_{\rho,3/2}$	$2P_{\rho,5/2}$	$\Xi_c^+\gamma$	$\Xi_c^+\gamma$	$\Xi_c^+\gamma$	$\Xi_c^+\gamma$	$\Xi_c^+\gamma$	$\Xi_c^+\gamma$
$N=2$																									
$\Xi_c(3118)$	$\frac{3}{2}^+$	$ 2, 0, 0, 0\rangle$	49^{+9}_{-8}	10^{+5}_{-4}	$2.5^{+1.4}_{-1.0}$	34^{+22}_{-21}	7^{+4}_{-4}	0	0	0	0	0	0	0	$2.0^{+1.4}_{-0.9}$	$2.5^{+3.1}_{-1.7}$	$1.5^{+1.2}_{-0.8}$	$0.3^{+0.4}_{-0.2}$	0	0	0	0	0	0	0
$\Xi_c(3163)$	$\frac{5}{2}^+$	$ 2, 0, 0, 0\rangle$	61^{+8}_{-7}	14^{+7}_{-6}	$4.0^{+2.0}_{-1.7}$	$0.2^{+0.1}_{-0.1}$	31^{+22}_{-22}	0	0	0	0	0	0	0	8^{+4}_{-3}	$0.5^{+0.5}_{-0.3}$	$4.7^{+2.9}_{-2.1}$	$1.7^{+1.2}_{-0.8}$	$0.6^{+0.6}_{-0.4}$	0	0	0	0	0	0
$\Xi_c(3145)$	$\frac{1}{2}^+$	$ 0, 0, 1, 0\rangle$	27^{+1}_{-1}	1.6	2.0	0.1	0.6	0	0	0	0	0	0	0	0.26	0.21	0.42	0.63	1.24	0	0	0	0	0	0
$\Xi_c(3440)$	$\frac{1}{2}^+$	$ 0, 0, 0, 1\rangle$	0	176^{+49}_{-51}	67^{+21}_{-21}	$4.1^{+1.6}_{-1.6}$	$1.9^{+0.8}_{-0.7}$	0.1	0	0	0	0	0	0	19^{+16}_{-16}	$0.1^{+0.1}_{-0.1}$	40^{+33}_{-33}	$0.2^{+0.2}_{-0.2}$	$4.3^{+4.6}_{-4.6}$	0	0	0	0	0	0
$\Xi_c(3265)$	$\frac{3}{2}^+$	$ 1, 1, 0, 0\rangle$	28^{+13}_{-11}	130^{+10}_{-11}	6^{+3}_{-3}	$4.5^{+1.8}_{-1.5}$	$4.3^{+1.6}_{-1.4}$	5^{+4}_{-4}	$1.3^{+0.2}_{-0.2}$	$0.3^{+0.2}_{-0.2}$	0	486^{+33}_{-35}	5^{+2}_{-2}	60^{+6}_{-6}	$1.2^{+0.3}_{-0.3}$	$1.2^{+0.3}_{-0.3}$	$0.1^{+0.1}_{-0.1}$	$0.1^{+0.1}_{-0.1}$	$0.1^{+0.1}_{-0.1}$	0	0	0	0	0	0
$\Xi_c(3311)$	$\frac{1}{2}^+$	$ 1, 1, 0, 0\rangle$	34^{+14}_{-13}	663^{+146}_{-153}	9^{+4}_{-3}	12^{+4}_{-4}	8^{+2}_{-2}	13^{+8}_{-8}	$0.2^{+0.2}_{-0.1}$	$0.8^{+0.6}_{-0.4}$	$0.4^{+0.4}_{-0.3}$	60^{+27}_{-22}	$0.8^{+0.5}_{-0.4}$	863^{+81}_{-90}	$3.0^{+1.6}_{-1.6}$	$1.6^{+0.9}_{-0.7}$	$3.8^{+2.8}_{-1.9}$	$2.3^{+1.8}_{-1.3}$	0	0	0	0	0	0	0
$\Xi_c(3281)$	$\frac{1}{2}^+$	$ 1, 1, 0, 0\rangle$	15^{+6}_{-6}	11^{+4}_{-4}	61^{+9}_{-9}	10^{+5}_{-5}	0	$1.6^{+0.8}_{-0.8}$	$2.0^{+2.0}_{-2.0}$	$3.4^{+3.2}_{-3.2}$	$0.3^{+0.3}_{-0.3}$	5^{+3}_{-3}	388^{+58}_{-68}	0	62^{+15}_{-15}	$2.5^{+2.6}_{-1.5}$	$2.5^{+1.7}_{-1.7}$	0	0	0	0	0	0	0	0
$\Xi_c(3308)$	$\frac{3}{2}^+$	$ 1, 1, 0, 0\rangle$	34^{+16}_{-16}	26^{+12}_{-12}	94^{+16}_{-16}	26^{+11}_{-11}	$1.5^{+0.9}_{-0.8}$	$4.7^{+3.1}_{-3.1}$	8^{+7}_{-7}	$1.6^{+2.0}_{-1.8}$	$0.9^{+0.8}_{-0.7}$	15^{+8}_{-8}	304^{+21}_{-21}	$0.8^{+0.4}_{-0.3}$	193^{+19}_{-18}	16^{+6}_{-6}	16^{+6}_{-6}	8^{+8}_{-8}	$0.4^{+0.4}_{-0.4}$	0	0	0	0	0	0
$\Xi_c(3353)$	$\frac{1}{2}^+$	$ 1, 1, 0, 0\rangle$	55^{+21}_{-21}	44^{+9}_{-9}	186^{+35}_{-35}	11^{+4}_{-4}	23^{+8}_{-8}	$2.6^{+1.3}_{-1.3}$	7^{+4}_{-4}	11^{+7}_{-7}	$1.5^{+1.2}_{-1.0}$	8^{+3}_{-3}	36^{+18}_{-18}	15^{+5}_{-5}	556^{+57}_{-57}	104^{+9}_{-9}	6^{+3}_{-3}	10^{+5}_{-5}	10^{+5}_{-5}	0	0	0	0	0	0
$\Xi_c(3416)$	$\frac{1}{2}^+$	$ 1, 1, 0, 0\rangle$	42^{+15}_{-15}	36^{+13}_{-13}	724^{+157}_{-165}	$1.5^{+1.4}_{-0.9}$	32^{+10}_{-10}	$0.1^{+0.1}_{-0.1}$	$1.2^{+0.7}_{-0.7}$	$0.9^{+0.8}_{-0.8}$	$0.1^{+0.1}_{-0.1}$	591^{+60}_{-68}	7^{+4}_{-4}	63^{+5}_{-5}	$3.7^{+2.1}_{-1.5}$	$0.5^{+0.3}_{-0.3}$	$0.2^{+0.2}_{-0.1}$	0	0	0	0	0	0	0	0
$\Xi_c(3275)$	$\frac{1}{2}^+$	$ 1, 1, 0, 0\rangle$	0	18^{+5}_{-5}	0	17^{+7}_{-7}	7^{+3}_{-3}	22^{+14}_{-14}	$0.8^{+0.6}_{-0.6}$	$0.5^{+0.5}_{-0.5}$	$0.2^{+0.2}_{-0.2}$	307^{+35}_{-35}	$3.0^{+1.7}_{-1.7}$	412^{+32}_{-32}	$3.1^{+1.6}_{-1.6}$	$0.7^{+0.5}_{-0.5}$	$4.4^{+3.5}_{-3.5}$	$1.4^{+1.1}_{-1.1}$	0	0	0	0	0	0	0
$\Xi_c(3302)$	$\frac{1}{2}^+$	$ 1, 1, 0, 0\rangle$	0	0	$4.4^{+1.2}_{-1.4}$	28^{+11}_{-11}	12^{+6}_{-6}	$4.7^{+2.6}_{-2.6}$	$4.3^{+2.8}_{-2.8}$	$1.7^{+1.2}_{-1.2}$	$0.4^{+0.3}_{-0.3}$	16^{+8}_{-8}	148^{+17}_{-17}	6^{+3}_{-3}	72^{+16}_{-16}	$1.1^{+0.6}_{-0.6}$	8^{+8}_{-8}	$2.8^{+2.8}_{-2.8}$	0	0	0	0	0	0	0
$\Xi_c(3317)$	$\frac{1}{2}^+$	$ 1, 1, 0, 0\rangle$	0	0	0	17^{+8}_{-8}	8^{+3}_{-3}	$3.3^{+2.6}_{-2.6}$	25^{+16}_{-16}	$1.2^{+0.8}_{-0.8}$	$0.4^{+0.3}_{-0.3}$	10^{+5}_{-5}	555^{+88}_{-88}	$4.2^{+1.9}_{-1.9}$	58^{+5}_{-5}	30^{+7}_{-7}	7^{+4}_{-4}	$2.3^{+1.9}_{-1.3}$	0	0	0	0	0	0	0
$\Xi_c(3344)$	$\frac{1}{2}^+$	$ 1, 1, 0, 0\rangle$	0	0	13^{+4}_{-4}	17^{+8}_{-8}	8^{+3}_{-3}	$1.8^{+0.9}_{-0.9}$	$1.9^{+1.7}_{-1.7}$	$0.5^{+0.5}_{-0.5}$	$0.6^{+0.5}_{-0.5}$	6^{+2}_{-2}	$4.8^{+2.2}_{-1.8}$	25^{+9}_{-9}	477^{+87}_{-84}	282^{+23}_{-21}	$4.4^{+2.9}_{-2.3}$	18^{+9}_{-9}	0	0	0	0	0	0	0
$\Xi_c(3389)$	$\frac{1}{2}^+$	$ 1, 1, 0, 0\rangle$	0	0	18^{+5}_{-5}	8^{+3}_{-3}	40^{+16}_{-16}	$2.2^{+0.8}_{-0.8}$	20^{+14}_{-14}	$1.3^{+0.8}_{-0.8}$	$0.6^{+0.5}_{-0.5}$	5^{+1}_{-1}	331^{+61}_{-61}	9^{+2}_{-2}	295^{+48}_{-48}	47^{+5}_{-5}	5^{+3}_{-3}	8^{+5}_{-5}	0	0	0	0	0	0	0
$\Xi_c(3362)$	$\frac{1}{2}^+$	$ 1, 1, 0, 0\rangle$	0	0	0	6^{+1}_{-1}	12^{+2}_{-2}	36^{+22}_{-22}	$0.4^{+0.3}_{-0.3}$	$0.1^{+0.0}_{-0.0}$	$0.2^{+0.2}_{-0.2}$	572^{+102}_{-102}	$1.3^{+0.6}_{-0.6}$	84^{+8}_{-8}	$0.2^{+0.1}_{-0.1}$	$1.0^{+0.6}_{-0.6}$	$2.1^{+1.4}_{-1.4}$	$2.6^{+2.2}_{-1.8}$	0	0	0	0	0	0	0
$\Xi_c(3293)$	$\frac{1}{2}^+$	$ 1, 1, 0, 0\rangle$	0	0	0	5^{+1}_{-1}	9^{+3}_{-3}	11^{+5}_{-5}	26^{+12}_{-12}	7^{+4}_{-4}	$0.5^{+0.3}_{-0.3}$	$0.9^{+0.9}_{-0.9}$	$0.3^{+0.3}_{-0.3}$	$1.3^{+0.8}_{-0.8}$	0	$0.1^{+0.1}_{-0.1}$	$0.3^{+0.3}_{-0.3}$	1357^{+128}_{-153}	211^{+28}_{-30}	0	0	0	0	0	0
$\Xi_c(3413)$	$\frac{3}{2}^+$	$ 0, 2, 0, 0\rangle$	63^{+7}_{-7}	63^{+19}_{-19}	24^{+9}_{-9}	17^{+8}_{-8}	11^{+6}_{-6}	11^{+5}_{-5}	26^{+13}_{-13}	14^{+8}_{-8}	9^{+6}_{-6}	$1.6^{+0.9}_{-0.9}$	$0.5^{+0.5}_{-0.5}$	$2.4^{+2.1}_{-1.4}$	$0.1^{+0.1}_{-0.1}$	$0.3^{+0.3}_{-0.3}$	6^{+3}_{-3}	1563^{+143}_{-169}	0	0	0	0	0	0	0
$\Xi_c(3458)$	$\frac{5}{2}^+$	$ 0, 2, 0, 0\rangle$	60^{+6}_{-6}	75^{+20}_{-20}	29^{+9}_{-9}	8^{+3}_{-3}	25^{+10}_{-10}	26^{+11}_{-11}	$3.4^{+2.3}_{-1.7}$	20^{+9}_{-8}	14^{+7}_{-7}	0	0	0	0	0	0	0	0	0	0	0	0	0	0

TABLE V. Same as Table III, but for Ξ_c^0 states with isospin 1/2.

$\Xi_c^0(snc)$	$\mathbf{J}^P$	$ l_\lambda, l_\rho, k_\lambda, k_\rho\rangle$	$2S+1L_{\lambda J}$	$2S_{1/2}$	$2S_{1/2}$	$4S_{3/2}$	$2P_{\lambda,1/2}$	$2P_{\lambda,3/2}$	$2P_{\rho,1/2}$	$4P_{\rho,1/2}$	$2P_{\rho,3/2}$	$4P_{\rho,3/2}$	$4P_{\rho,3/2}$	$2P_{\lambda,1/2}$	$2P_{\lambda,3/2}$	$4P_{\lambda,3/2}$	$4P_{\lambda,3/2}$	$2P_{\lambda,5/2}$	$4P_{\lambda,5/2}$	$2P_{\rho,1/2}$	$2P_{\rho,3/2}$
$N=2$																					
$\Xi_c(3118)$	$\frac{3}{2}^+$	$ 2, 0, 0, 0\rangle$	$2D_{\lambda,3/2}$	22^{+8}_{-8}	$0.2^{+0.2}_{-0.1}$	$0.1^{+0.0}_{-0.0}$	543^{+31}_{-32}	74^{+5}_{-5}	0	0	0	0	0	0	0	0	0	0	0	0	0
	$\frac{1}{2}^+$	$ 1, 1, 0, 0\rangle$	$2D_{\lambda,3/2}$	17^8	0	0	270.4	46.0	...	...	...	...	...	...	...	...	...	...	...	...	...
$\Xi_c(3163)$	$\frac{5}{2}^+$	$ 2, 0, 0, 0\rangle$	$2D_{\lambda,5/2}$	18^{+7}_{-8}	$0.3^{+0.2}_{-0.2}$	$0.1^{+0.1}_{-0.0}$	673^{+41}_{-42}	74^{+5}_{-5}	0	0	0	0	0	0	0	0	0	0	0	0	0
	$\frac{3}{2}^+$	$ 1, 1, 0, 0\rangle$	$2D_{\lambda,5/2}$	...	...	...	7.62	85.1	...	...	...	...	...	...	...	...	...	...	...	...	...
$\Xi_c(3145)$	$\frac{1}{2}^+$	$ 0, 0, 1, 0\rangle$	$2S_{1/2}$	21.4	0	0	0.6	298.8	...	...	...	...	...	...	...	...	...	...	...	...	...
	$\frac{3}{2}^+$	$ 1, 1, 0, 0\rangle$	$2S_{1/2}$	$0.4^{+0.2}_{-0.1}$	$0.7^{+0.5}_{-0.4}$	$0.2^{+0.1}_{-0.1}$	327^{+30}_{-29}	94^{+10}_{-11}	...	...	...	...	...	...	...	...	...	...	...	...	...
$\Xi_c(3440)$	$\frac{1}{2}^+$	$ 0, 0, 0, 1\rangle$	$2S_{1/2}$	0	$3.7^{+1.9}_{-1.7}$	$1.4^{+0.8}_{-0.7}$	6^{+2}_{-2}	$2.5^{+0.8}_{-0.8}$	124^{+39}_{-38}	$0.7^{+0.3}_{-0.3}$	313^{+111}_{-104}	$2.6^{+1.2}_{-1.2}$	65^{+39}_{-30}	$0.4^{+0.5}_{-0.3}$	$0.9^{+1.0}_{-0.6}$	$0.9^{+1.0}_{-0.6}$	0	$0.1^{+0.1}_{-0.1}$	16^{+6}_{-6}	8^{+3}_{-3}	0
$\Xi_c(3265)$	$\frac{3}{2}^+$	$ 1, 1, 0, 0\rangle$	$2D_{\rho,3/2}$	39^{+14}_{-12}	$2.7^{+0.8}_{-0.8}$	$0.1^{+0.1}_{-0.1}$	6^{+2}_{-2}	6^{+2}_{-2}	212^{+11}_{-11}	$0.7^{+0.3}_{-0.3}$	27^{+1}_{-1}	$0.2^{+0.1}_{-0.1}$	0	10^{+3}_{-3}	$0.1^{+0.1}_{-0.1}$	$1.3^{+0.4}_{-0.4}$	0	0	0	0	0
$\Xi_c(3311)$	$\frac{5}{2}^+$	$ 1, 1, 0, 0\rangle$	$2D_{\rho,5/2}$	47^{+15}_{-15}	14^{+6}_{-6}	$0.2^{+0.1}_{-0.1}$	16^{+4}_{-4}	11^{+3}_{-3}	15^{+9}_{-9}	$0.1^{+0.1}_{-0.1}$	342^{+23}_{-25}	$0.4^{+0.4}_{-0.3}$	$0.2^{+0.2}_{-0.1}$	$1.3^{+0.9}_{-0.7}$	0	18^{+6}_{-6}	$0.1^{+0.0}_{-0.0}$	0	0	0	0
$\Xi_c(3281)$	$\frac{1}{2}^+$	$ 1, 1, 0, 0\rangle$	$4D_{\rho,1/2}$	21^{+8}_{-8}	$0.2^{+0.2}_{-0.1}$	$1.3^{+0.4}_{-0.3}$	13^{+5}_{-5}	0	$0.8^{+0.7}_{-0.7}$	166^{+17}_{-29}	0	23^{+8}_{-8}	$0.4^{+0.5}_{-0.3}$	$0.1^{+0.1}_{-0.1}$	8^{+2}_{-2}	0	$1.3^{+0.7}_{-0.6}$	$0.1^{+0.1}_{-0.1}$	$0.1^{+0.1}_{-0.1}$	$0.1^{+0.1}_{-0.1}$	$0.1^{+0.1}_{-0.1}$
$\Xi_c(3308)$	$\frac{3}{2}^+$	$ 1, 1, 0, 0\rangle$	$4D_{\rho,3/2}$	46^{+7}_{-7}	$0.6^{+0.4}_{-0.4}$	$2.0^{+0.8}_{-0.8}$	35^{+12}_{-12}	$2.1^{+1.0}_{-0.9}$	$2.3^{+0.8}_{-0.8}$	123^{+8}_{-8}	$0.1^{+0.1}_{-0.1}$	81^{+3}_{-3}	5^{+2}_{-2}	$0.3^{+0.2}_{-0.1}$	$0.1^{+0.1}_{-0.1}$	0	$4.0^{+1.2}_{-1.1}$	$0.3^{+0.2}_{-0.2}$	$0.1^{+0.1}_{-0.1}$	0	0
$\Xi_c(3353)$	$\frac{5}{2}^+$	$ 1, 1, 0, 0\rangle$	$4D_{\rho,5/2}$	75^{+23}_{-23}	$0.9^{+0.6}_{-0.6}$	$3.9^{+1.5}_{-1.5}$	16^{+4}_{-4}	32^{+9}_{-9}	$1.2^{+0.8}_{-0.8}$	13^{+7}_{-7}	$2.2^{+1.3}_{-1.3}$	223^{+14}_{-17}	44^{+2}_{-2}	$0.2^{+0.1}_{-0.1}$	$0.8^{+0.6}_{-0.6}$	$0.3^{+0.2}_{-0.2}$	12^{+4}_{-4}	$2.2^{+0.6}_{-0.6}$	$0.1^{+0.1}_{-0.1}$	$0.2^{+0.2}_{-0.1}$	0
$\Xi_c(3416)$	$\frac{7}{2}^+$	$ 1, 1, 0, 0\rangle$	$4D_{\rho,7/2}$	58^{+17}_{-17}	$0.8^{+0.5}_{-0.5}$	15^{+7}_{-6}	$2.1^{+1.7}_{-1.2}$	45^{+10}_{-11}	$0.1^{+0.1}_{-0.1}$	$1.6^{+1.3}_{-1.3}$	$3.7^{+1.9}_{-1.9}$	22^{+10}_{-10}	386^{+36}_{-40}	0	$0.2^{+0.2}_{-0.1}$	$0.5^{+0.2}_{-0.2}$	$1.4^{+1.0}_{-0.8}$	$2.0^{+0.6}_{-0.6}$	$0.1^{+0.1}_{-0.1}$	$0.5^{+0.4}_{-0.3}$	0
$\Xi_c(3275)$	$\frac{1}{2}^+$	$ 1, 1, 0, 0\rangle$	$2P_{\rho,1/2}$	0	$0.4^{+0.2}_{-0.2}$	0	0	0	258^{+23}_{-23}	$0.9^{+0.6}_{-0.6}$	34^{+4}_{-4}	$0.5^{+0.5}_{-0.5}$	$0.1^{+0.1}_{-0.1}$	12^{+4}_{-4}	$0.1^{+0.1}_{-0.1}$	$1.3^{+0.4}_{-0.4}$	$0.1^{+0.1}_{-0.1}$	0	0	0	0
$\Xi_c(3302)$	$\frac{3}{2}^+$	$ 1, 1, 0, 0\rangle$	$2P_{\rho,3/2}$	0	$0.4^{+0.2}_{-0.2}$	0	23^{+8}_{-8}	10^{+3}_{-3}	116^{+22}_{-22}	$0.4^{+0.4}_{-0.4}$	199^{+13}_{-13}	$0.4^{+0.4}_{-0.4}$	$0.1^{+0.1}_{-0.1}$	6^{+3}_{-3}	$0.1^{+0.1}_{-0.1}$	9^{+3}_{-3}	$0.1^{+0.1}_{-0.1}$	0	$0.1^{+0.1}_{-0.1}$	0	0
$\Xi_c(3317)$	$\frac{5}{2}^+$	$ 1, 1, 0, 0\rangle$	$4P_{\rho,1/2}$	0	0	$0.1^{+0.0}_{-0.0}$	38^{+14}_{-14}	16^{+3}_{-3}	$2.4^{+0.9}_{-0.9}$	65^{+7}_{-7}	$0.9^{+0.4}_{-0.4}$	35^{+8}_{-8}	$0.7^{+0.5}_{-0.5}$	$0.3^{+0.3}_{-0.3}$	$0.1^{+0.1}_{-0.1}$	$1.5^{+0.4}_{-0.4}$	$0.1^{+0.1}_{-0.1}$	0	$0.2^{+0.2}_{-0.2}$	$0.1^{+0.1}_{-0.1}$	0
$\Xi_c(3344)$	$\frac{3}{2}^+$	$ 1, 1, 0, 0\rangle$	$4P_{\rho,3/2}$	0	0	$0.3^{+0.1}_{-0.1}$	24^{+8}_{-8}	10^{+3}_{-3}	$1.6^{+0.9}_{-0.9}$	237^{+46}_{-46}	$0.6^{+0.3}_{-0.3}$	25^{+1}_{-1}	18^{+2}_{-2}	$0.2^{+0.2}_{-0.2}$	$0.1^{+0.1}_{-0.1}$	$1.2^{+0.4}_{-0.4}$	$0.6^{+0.2}_{-0.2}$	$0.1^{+0.1}_{-0.1}$	$0.1^{+0.1}_{-0.1}$	0	0
$\Xi_c(3389)$	$\frac{5}{2}^+$	$ 1, 1, 0, 0\rangle$	$4P_{\rho,5/2}$	0	0	$0.4^{+0.2}_{-0.2}$	11^{+3}_{-3}	54^{+17}_{-17}	$0.9^{+0.6}_{-0.6}$	$3.9^{+2.6}_{-1.9}$	$3.9^{+2.8}_{-2.1}$	204^{+41}_{-37}	135^{+7}_{-9}	$0.1^{+0.1}_{-0.1}$	$0.5^{+0.3}_{-0.3}$	10^{+4}_{-4}	6^{+2}_{-2}	$0.1^{+0.1}_{-0.1}$	$0.1^{+0.1}_{-0.1}$	$0.4^{+0.4}_{-0.2}$	0
$\Xi_c(3362)$	$\frac{3}{2}^+$	$ 1, 1, 0, 0\rangle$	$4S_{\rho,3/2}$	0	0	0	8^{+1}_{-1}	16^{+2}_{-2}	$0.8^{+0.4}_{-0.4}$	137^{+32}_{-30}	$1.4^{+0.8}_{-0.7}$	122^{+39}_{-20}	21^{+1}_{-1}	$0.1^{+0.1}_{-0.1}$	$0.2^{+0.1}_{-0.1}$	6^{+2}_{-2}	$1.0^{+0.3}_{-0.3}$	$0.1^{+0.1}_{-0.1}$	$0.1^{+0.1}_{-0.1}$	$0.2^{+0.2}_{-0.2}$	0
$\Xi_c(3293)$	$\frac{1}{2}^+$	$ 1, 1, 0, 0\rangle$	$2S_{\lambda,1/2}$	0	0	0	7^{+1}_{-1}	13^{+2}_{-2}	219^{+34}_{-34}	$0.2^{+0.1}_{-0.1}$	44^{+2}_{-2}	0	$0.1^{+0.1}_{-0.1}$	12^{+3}_{-3}	$0.1^{+0.1}_{-0.1}$	$1.8^{+0.5}_{-0.5}$	0	0	0	$0.1^{+0.1}_{-0.1}$	0
$\Xi_c(3413)$	$\frac{3}{2}^+$	$ 0, 2, 0, 0\rangle$	$2D_{\rho,3/2}$	87^{+4}_{-4}	$1.4^{+0.7}_{-0.6}$	$0.5^{+0.3}_{-0.3}$	23^{+8}_{-8}	15^{+6}_{-6}	15^{+5}_{-5}	36^{+21}_{-16}	15^{+7}_{-7}	9^{+6}_{-6}	$0.7^{+0.4}_{-0.4}$	0	0	0	0	0	29^{+9}_{-9}	$4.5^{+1.6}_{-1.6}$	0
$\Xi_c(3458)$	$\frac{5}{2}^+$	$ 0, 2, 0, 0\rangle$	$2D_{\rho,5/2}$	84^{+5}_{-5}	$1.6^{+0.8}_{-0.7}$	$0.6^{+0.3}_{-0.3}$	10^{+3}_{-3}	34^{+12}_{-11}	36^{+14}_{-12}	$4.6^{+2.1}_{-2.1}$	28^{+9}_{-9}	19^{+10}_{-8}	12^{+6}_{-6}	0	$0.1^{+0.1}_{-0.1}$	0	0	0	$0.1^{+0.1}_{-0.1}$	$3.3^{+1.6}_{-1.6}$	0

especially challenging. Fortunately, recent experimental measurements by the LHCb collaboration [3] have established the quantum numbers of the charmed $\Xi_c(3055)^{+,0}$ states. Motivated by these results, we revisit their assignment and interpret them instead as members of the flavor antitriplet. In the same spirit, we also discuss the $\Xi_c(3080)^{+,0}$ states, whose quantum numbers have not yet been experimentally determined, and likewise consider them as antitriplet states. These states are displayed in the mass spectra shown in Fig. 2. In the following discussion, we provide information that may help establish their quantum number assignments based on the electromagnetic decay widths calculated in this work.

1. Assignment of the $\Xi_c(3055)^{+,0}$ baryon

Following the recent determination of the spin-parity of the $\Xi_c(3055)^{+,0}$ baryons by the LHCb Collaboration [3], we discuss the interpretation of this state based on the theoretical results of Ref. [102]. The $\Xi_c(3055)^{+,0}$ is identified as a D_λ -wave excitation with quantum numbers $\mathbf{J}^P = 3/2^+$ and spin $S = 1/2$, belonging to the flavor antitriplet, in agreement with the measurement of Ref. [3].

In Tables IV and V the electromagnetic widths are calculated with theory masses of Ref. [102]. Although the theoretical mass for this state is slightly overestimated, we show that the framework employed in this paper still gives useful results by using the experimental mass to calculate the electromagnetic decay widths. That is, the experimental mass reported by the PDG is 3055.9 MeV, while the theory mass in Ref. [102] 3118.9 MeV. We make a comparison of the electromagnetic decay widths calculated for both masses for the states $\Xi_c(3055)^{+,0}$

- (1) $\Xi_c(3055)^+$
- (a) $\Gamma_{em}[\Xi_c(3118)^+ \rightarrow \Xi_c^+\gamma] = 49_{-8}^{+9}$ keV,
 $\Gamma_{em}[\Xi_c(3055)^+ \rightarrow \Xi_c^+\gamma] = 43_{-8}^{+8}$ keV,
 - (b) $\Gamma_{em}[\Xi_c(3118)^+ \rightarrow \Xi_c^{'+}\gamma] = 10_{-4}^{+5}$ keV,
 $\Gamma_{em}[\Xi_c(3055)^+ \rightarrow \Xi_c^{'+}\gamma] = 5_{-2}^{+2}$ keV,
 - (c) $\Gamma_{em}[\Xi_c(3118)^+ \rightarrow \Xi_c^{*+}\gamma] = 2.5_{-1.0}^{+1.4}$ keV,
 $\Gamma_{em}[\Xi_c(3055)^+ \rightarrow \Xi_c^{*+}\gamma] = 1.1_{-0.4}^{+0.4}$ keV,
 - (d) $\Gamma_{em}[\Xi_c(3118)^+ \rightarrow \Xi_c^{+2}P_{\lambda,1/2}\gamma] = 34_{-21}^{+22}$ keV,
 $\Gamma_{em}[\Xi_c(3055)^+ \rightarrow \Xi_c^{+2}P_{\lambda,1/2}\gamma] = 34_{-21}^{+21}$ keV,
 - (e) $\Gamma_{em}[\Xi_c(3118)^+ \rightarrow \Xi_c^{+4}P_{\lambda,3/2}\gamma] = 7_{-4}^{+4}$ keV,
 $\Gamma_{em}[\Xi_c(3055)^+ \rightarrow \Xi_c^{+4}P_{\lambda,3/2}\gamma] = 6_{-3}^{+3}$ keV,
 - (f) $\Gamma_{em}[\Xi_c(3118)^+ \rightarrow \Xi_c^{'+2}P_{\lambda,1/2}\gamma] = 2.0_{-0.9}^{+1.4}$ keV,
 $\Gamma_{em}[\Xi_c(3055)^+ \rightarrow \Xi_c^{'+2}P_{\lambda,1/2}\gamma] = 0.4_{-0.1}^{+0.1}$ keV,
 - (g) $\Gamma_{em}[\Xi_c(3118)^+ \rightarrow \Xi_c^{'+4}P_{\lambda,1/2}\gamma] = 2.5_{-1.7}^{+3.1}$ keV,
 $\Gamma_{em}[\Xi_c(3055)^+ \rightarrow \Xi_c^{'+4}P_{\lambda,1/2}\gamma] = 0.5_{-0.2}^{+0.2}$ keV,
 - (h) $\Gamma_{em}[\Xi_c(3118)^+ \rightarrow \Xi_c^{'+2}P_{\lambda,3/2}\gamma] = 1.5_{-0.8}^{+1.2}$ keV,
 $\Gamma_{em}[\Xi_c(3055)^+ \rightarrow \Xi_c^{'+2}P_{\lambda,3/2}\gamma] = 0.12_{-0.03}^{+0.03}$ keV,
 - (i) $\Gamma_{em}[\Xi_c(3118)^+ \rightarrow \Xi_c^{'+4}P_{\lambda,3/2}\gamma] = 0.3_{-0.2}^{+0.4}$ keV,
 $\Gamma_{em}[\Xi_c(3055)^+ \rightarrow \Xi_c^{'+4}P_{\lambda,3/2}\gamma] = 0.02_{-0.01}^{+0.01}$ keV.

- (2) $\Xi_c(3055)^0$
- (a) $\Gamma_{em}[\Xi_c(3118)^0 \rightarrow \Xi_c^0\gamma] = 22_{-8}^{+8}$ keV,
 $\Gamma_{em}[\Xi_c(3055)^0 \rightarrow \Xi_c^0\gamma] = 20_{-8}^{+8}$ keV,
 - (b) $\Gamma_{em}[\Xi_c(3118)^0 \rightarrow \Xi_c^{*0}\gamma] = 0.2_{-0.1}^{+0.2}$ keV,
 $\Gamma_{em}[\Xi_c(3055)^0 \rightarrow \Xi_c^{*0}\gamma] = 0.1_{-0.1}^{+0.1}$ keV,
 - (c) $\Gamma_{em}[\Xi_c(3118)^0 \rightarrow \Xi_c^{*0}\gamma] = 0.1_{-0.0}^{+0.0}$ keV,
 $\Gamma_{em}[\Xi_c(3055)^0 \rightarrow \Xi_c^{*0}\gamma] = 0.02_{-0.0}^{+0.0}$ keV,
 - (d) $\Gamma_{em}[\Xi_c(3118)^0 \rightarrow \Xi_c^{02}P_{\lambda,1/2}\gamma] = 543_{-32}^{+31}$ keV,
 $\Gamma_{em}[\Xi_c(3055)^0 \rightarrow \Xi_c^{02}P_{\lambda,1/2}\gamma] = 495_{-30}^{+30}$ keV,
 - (e) $\Gamma_{em}[\Xi_c(3118)^0 \rightarrow \Xi_c^{02}P_{\lambda,3/2}\gamma] = 74_{-5}^{+5}$ keV,
 $\Gamma_{em}[\Xi_c(3055)^0 \rightarrow \Xi_c^{02}P_{\lambda,3/2}\gamma] = 65_{-5}^{+5}$ keV,
 - (f) $\Gamma_{em}[\Xi_c(3118)^0 \rightarrow \Xi_c^{04}P_{\lambda,1/2}\gamma] = 0.1_{-0.0}^{+0.1}$ keV,
 $\Gamma_{em}[\Xi_c(3055)^0 \rightarrow \Xi_c^{04}P_{\lambda,1/2}\gamma] = 0.01_{-0.0}^{+0.0}$ keV.

With these decay widths we can get several branching ratios. If we analyze, for example the following cases

$$\frac{\Gamma_{em}[\Xi_c(3055)^+ \rightarrow \Xi_c^+\gamma]}{\Gamma_{em}[\Xi_c(3055)^+ \rightarrow \Xi_c^{'+}\gamma]} = 8.6_{-1.2}^{+1.2}, \quad (8)$$

$$\frac{\Gamma_{em}[\Xi_c(3055)^+ \rightarrow \Xi_c^+\gamma]}{\Gamma_{em}[\Xi_c(3055)^+ \rightarrow \Xi_c^{*+}\gamma]} = 39_{-5}^{+5}, \quad (9)$$

$$\frac{\Gamma_{em}[\Xi_c(3055)^+ \rightarrow \Xi_c^{'+}\gamma]}{\Gamma_{em}[\Xi_c(3055)^+ \rightarrow \Xi_c^{*+}\gamma]} = 4.5_{-1}^{+1}, \quad (10)$$

$$\frac{\Gamma_{em}[\Xi_c(3055)^0 \rightarrow \Xi_c^0\gamma]}{\Gamma_{em}[\Xi_c(3055)^0 \rightarrow \Xi_c^{*0}\gamma]} = 200_{-25}^{+25}, \quad (11)$$

$$\frac{\Gamma_{em}[\Xi_c(3055)^0 \rightarrow \Xi_c^0\gamma]}{\Gamma_{em}[\Xi_c(3055)^0 \rightarrow \Xi_c^{*0}\gamma]} = 1000_{-50}^{+50}, \quad (12)$$

$$\frac{\Gamma_{em}[\Xi_c(3055)^0 \rightarrow \Xi_c^{*0}\gamma]}{\Gamma_{em}[\Xi_c(3055)^0 \rightarrow \Xi_c^{*0}\gamma]} = 5_{-0.5}^{+0.5}. \quad (13)$$

In particular, the electromagnetic decay branching ratios are highly sensitive to the underlying quantum numbers, making them valuable observables for discriminating between competing assignments. Since the phase-space dependence cancels out in the ratios, the resulting observables are governed by the underlying spectroscopic amplitudes. Consequently, the branching ratios given in Eqs. (8)–(13) can provide an independent probe of the internal structure and quantum-number assignments of the $\Xi_c(3055)^{+,0}$ states, complementary to the angular-distribution analyses performed by the LHCb collaboration in Ref. [3].

2. Assignment of the $\Xi_c(3080)^{+,0}$ baryon

The identification of the $\Xi_c(3055)^{+,0}$ baryons by the LHCb Collaboration as $1D$ states with $\mathbf{J}^P = 3/2^+$ [3] provides valuable insight into the interpretation of the nearby $\Xi_c(3080)^{+,0}$ states. In particular, the theoretical

study of Ref. [102] predicts a mass splitting of approximately 30 MeV between the $1D \mathbf{J}^P = 3/2^+$ and $\mathbf{J}^P = 5/2^+$ states, which naturally supports assigning the $\Xi_c(3080)^{+,0}$ baryons to the corresponding $1D \mathbf{J}^P = 5/2^+$ doublet. According to the PDG [103], the measured mass is 3077.2 MeV for the positively charged state, and 3079.9 MeV for the neutral state. Nevertheless, their quantum numbers have not yet been experimentally established. The theoretical mass predicted in Ref. [102] differs from the experimental value by about 2.5%. Motivated by these considerations, in the following we compare the numerical predictions for the electromagnetic decay widths obtained using both the theoretical and experimental masses, assuming that the $\Xi_c(3080)^{+,0}$ states belong to the $1D \mathbf{J}^P = 5/2^+$ configuration.

- (1) $\Xi_c(3080)^+$ as $\mathbf{J}^P = 5/2^+$
 - (a) $\Gamma_{em}[\Xi_c(3163)^+ \rightarrow \Xi_c^+ \gamma] = 61_{-7}^{+8}$ keV,
 $\Gamma_{em}[\Xi_c(3080)^+ \rightarrow \Xi_c^+ \gamma] = 51_{-8}^{+8}$ keV,
 - (b) $\Gamma_{em}[\Xi_c(3163)^+ \rightarrow \Xi_c'^+ \gamma] = 14_{-6}^{+7}$ keV,
 $\Gamma_{em}[\Xi_c(3080)^+ \rightarrow \Xi_c'^+ \gamma] = 6_{-2}^{+2}$ keV,
 - (c) $\Gamma_{em}[\Xi_c(3163)^+ \rightarrow \Xi_c^{*+} \gamma] = 4.0_{-1.7}^{+2.0}$ keV,
 $\Gamma_{em}[\Xi_c(3080)^+ \rightarrow \Xi_c^{*+} \gamma] = 1.4_{-1.0}^{+0.8}$ keV,
 - (d) $\Gamma_{em}[\Xi_c(3163)^+ \rightarrow \Xi_c^{+2} P_{\lambda,1/2} \gamma] = 0.2_{-0.1}^{+0.1}$ keV,
 $\Gamma_{em}[\Xi_c(3080)^+ \rightarrow \Xi_c^{+2} P_{\lambda,1/2} \gamma] = 0.05_{-0.02}^{+0.02}$ keV,
 - (e) $\Gamma_{em}[\Xi_c(3163)^+ \rightarrow \Xi_c^{+2} P_{\lambda,3/2} \gamma] = 31_{-22}^{+24}$ keV,
 $\Gamma_{em}[\Xi_c(3080)^+ \rightarrow \Xi_c^{+2} P_{\lambda,3/2} \gamma] = 36_{-8}^{+8}$ keV,
 - (f) $\Gamma_{em}[\Xi_c(3163)^+ \rightarrow \Xi_c'^{+2} P_{\lambda,1/2} \gamma] = 8_{-3}^{+4}$ keV,
 $\Gamma_{em}[\Xi_c(3080)^+ \rightarrow \Xi_c'^{+2} P_{\lambda,1/2} \gamma] = 1.5_{-0.9}^{+1.0}$ keV,
 - (g) $\Gamma_{em}[\Xi_c(3163)^+ \rightarrow \Xi_c'^{+4} P_{\lambda,1/2} \gamma] = 0.5_{-0.3}^{+0.5}$ keV,
 $\Gamma_{em}[\Xi_c(3080)^+ \rightarrow \Xi_c'^{+4} P_{\lambda,1/2} \gamma] = 0.1_{-0.1}^{+0.1}$ keV,
 - (h) $\Gamma_{em}[\Xi_c(3163)^+ \rightarrow \Xi_c'^{+2} P_{\lambda,3/2} \gamma] = 4.7_{-2.1}^{+2.9}$ keV,
 $\Gamma_{em}[\Xi_c(3080)^+ \rightarrow \Xi_c'^{+2} P_{\lambda,3/2} \gamma] = 0.3_{-0.1}^{+0.1}$ keV,
 - (i) $\Gamma_{em}[\Xi_c(3163)^+ \rightarrow \Xi_c'^{+4} P_{\lambda,3/2} \gamma] = 1.7_{-0.8}^{+1.2}$ keV,
 $\Gamma_{em}[\Xi_c(3080)^+ \rightarrow \Xi_c'^{+4} P_{\lambda,3/2} \gamma] = 0.3_{-0.1}^{+0.1}$ keV,
 - (j) $\Gamma_{em}[\Xi_c(3163)^+ \rightarrow \Xi_c'^{+4} P_{\lambda,5/2} \gamma] = 0.6_{-0.4}^{+0.6}$ keV,
 $\Gamma_{em}[\Xi_c(3080)^+ \rightarrow \Xi_c'^{+4} P_{\lambda,5/2} \gamma] = 0.1_{-0.1}^{+0.1}$ keV.
- (2) $\Xi_c(3080)^0$ as $\mathbf{J}^P = 5/2^+$
 - (a) $\Gamma_{em}[\Xi_c(3163)^0 \rightarrow \Xi_c^0 \gamma] = 18_{-8}^{+7}$ keV,
 $\Gamma_{em}[\Xi_c(3080)^0 \rightarrow \Xi_c^0 \gamma] = 17_{-8}^{+8}$ keV,
 - (b) $\Gamma_{em}[\Xi_c(3163)^0 \rightarrow \Xi_c'^0 \gamma] = 0.3_{-0.2}^{+0.2}$ keV,
 $\Gamma_{em}[\Xi_c(3080)^0 \rightarrow \Xi_c'^0 \gamma] = 0.13_{-0.1}^{+0.1}$ keV,
 - (c) $\Gamma_{em}[\Xi_c(3163)^0 \rightarrow \Xi_c^{*0} \gamma] = 0.1_{-0.7}^{+0.7}$ keV,
 $\Gamma_{em}[\Xi_c(3080)^0 \rightarrow \Xi_c^{*0} \gamma] = 0.05_{-0.0}^{+0.0}$ keV,
 - (d) $\Gamma_{em}[\Xi_c(3163)^0 \rightarrow \Xi_c^{02} P_{\lambda,1/2} \gamma] = 2.3_{-0.7}^{+0.7}$ keV,
 $\Gamma_{em}[\Xi_c(3080)^0 \rightarrow \Xi_c^{02} P_{\lambda,1/2} \gamma] = 0.7_{-0.2}^{+0.2}$ keV,
 - (e) $\Gamma_{em}[\Xi_c(3163)^0 \rightarrow \Xi_c^{02} P_{\lambda,3/2} \gamma] = 673_{-42}^{+41}$ keV,
 $\Gamma_{em}[\Xi_c(3080)^0 \rightarrow \Xi_c^{02} P_{\lambda,3/2} \gamma] = 586_{-35}^{+35}$ keV,
 - (f) $\Gamma_{em}[\Xi_c(3163)^0 \rightarrow \Xi_c^{02} P_{\lambda,1/2} \gamma] = 0.2_{-0.1}^{+0.1}$ keV,
 $\Gamma_{em}[\Xi_c(3080)^0 \rightarrow \Xi_c^{02} P_{\lambda,1/2} \gamma] = 0.03_{-0.01}^{+0.01}$ keV.

From our previous results, we observe that the theoretical predictions for the electromagnetic decay widths are essentially independent of the mass once the uncertainties in the calculation, estimated through the bootstrap Monte Carlo method, are taken into account. Considering the electromagnetic decays calculated with the experimental mass, we compute some relevant branching ratios assuming the assignment $\mathbf{J}^P = 5/2^+$ for the $\Xi_c(3080)^{+,0}$,

$$\frac{\Gamma_{em}[\Xi_c(3080)^+ \rightarrow \Xi_c^+ \gamma]}{\Gamma_{em}[\Xi_c(3080)^+ \rightarrow \Xi_c'^+ \gamma]} = 8.5_{-1.5}^{+1.5}, \quad (14)$$

$$\frac{\Gamma_{em}[\Xi_c(3080)^+ \rightarrow \Xi_c^+ \gamma]}{\Gamma_{em}[\Xi_c(3080)^+ \rightarrow \Xi_c^{*+} \gamma]} = 36_{-4}^{+4}, \quad (15)$$

$$\frac{\Gamma_{em}[\Xi_c(3080)^0 \rightarrow \Xi_c^0 \gamma]}{\Gamma_{em}[\Xi_c(3080)^0 \rightarrow \Xi_c'^0 \gamma]} = 130_{-15}^{+15}, \quad (16)$$

$$\frac{\Gamma_{em}[\Xi_c(3080)^0 \rightarrow \Xi_c^{*0} \gamma]}{\Gamma_{em}[\Xi_c(3080)^0 \rightarrow \Xi_c^{*0} \gamma]} = 340_{-40}^{+40}. \quad (17)$$

An alternative interpretation of the $\Xi_c(3080)^{+,0}$ state is the assignment $\mathbf{J}^P = 1/2^+$. In Ref. [109], Chen *et al.* argued that the $\mathbf{J}^P = 5/2^+$ assignment is not strongly supported by their analysis. Therefore, we also present the electromagnetic decay widths for the $\Xi_c(3080)^{+,0}$ states assuming a $\mathbf{J}^P = 1/2^+$ assignment,

- (1) $\Xi_c(3080)^+$ as $\mathbf{J}^P = 1/2^+$
 - (a) $\Gamma_{em}[\Xi_c(3080)^+ \rightarrow \Xi_c^+ \gamma] = 0.2_{-0.1}^{+0.1}$ keV,
 - (b) $\Gamma_{em}[\Xi_c(3080)^+ \rightarrow \Xi_c'^+ \gamma] = 15_{-5}^{+5}$ keV,
 - (c) $\Gamma_{em}[\Xi_c(3080)^+ \rightarrow \Xi_c^{*+} \gamma] = 3.5_{-1}^{+1}$ keV,
 - (d) $\Gamma_{em}[\Xi_c(3080)^+ \rightarrow \Xi_c^{+2} P_{\lambda,1/2} \gamma] = 10.7_{-3}^{+3}$ keV,
 - (e) $\Gamma_{em}[\Xi_c(3080)^+ \rightarrow \Xi_c^{+2} P_{\lambda,3/2} \gamma] = 36_{-4}^{+4}$ keV,
 - (f) $\Gamma_{em}[\Xi_c(3080)^+ \rightarrow \Xi_c'^{+2} P_{\lambda,1/2} \gamma] = 6.6_{-2}^{+2}$ keV,
 - (g) $\Gamma_{em}[\Xi_c(3080)^+ \rightarrow \Xi_c'^{+4} P_{\lambda,1/2} \gamma] = 0.02_{-0.01}^{+0.01}$ keV,
 - (h) $\Gamma_{em}[\Xi_c(3080)^+ \rightarrow \Xi_c'^{+2} P_{\lambda,3/2} \gamma] = 6_{-1}^{+1}$ keV,
 - (i) $\Gamma_{em}[\Xi_c(3080)^+ \rightarrow \Xi_c'^{+4} P_{\lambda,3/2} \gamma] = 0.02_{-0.01}^{+0.01}$ keV,
 - (j) $\Gamma_{em}[\Xi_c(3080)^+ \rightarrow \Xi_c'^{+4} P_{\lambda,5/2} \gamma] = 0.1_{-0.1}^{+0.1}$ keV.
- (2) $\Xi_c(3080)^0$ as $\mathbf{J}^P = 1/2^+$
 - (a) $\Gamma_{em}[\Xi_c(3080)^0 \rightarrow \Xi_c^0 \gamma] = 0.2_{-0.1}^{+0.1}$ keV,
 - (b) $\Gamma_{em}[\Xi_c(3080)^0 \rightarrow \Xi_c'^0 \gamma] = 0.3_{-0.1}^{+0.1}$ keV,
 - (c) $\Gamma_{em}[\Xi_c(3080)^0 \rightarrow \Xi_c^{*0} \gamma] = 0.07_{-0.02}^{+0.02}$ keV,
 - (d) $\Gamma_{em}[\Xi_c(3080)^0 \rightarrow \Xi_c^{02} P_{\lambda,1/2} \gamma] = 266_{-30}^{+30}$ keV,
 - (e) $\Gamma_{em}[\Xi_c(3080)^0 \rightarrow \Xi_c^{02} P_{\lambda,3/2} \gamma] = 91_{-28}^{+28}$ keV,
 - (f) $\Gamma_{em}[\Xi_c(3080)^0 \rightarrow \Xi_c^{02} P_{\lambda,1/2} \gamma] = 0.13_{-0.04}^{+0.04}$ keV.

To help discriminate between these possible configurations, it is useful to calculate the corresponding branching-ratio predictions for the $\Xi_c(3080)^{+,0}$ states under the $\mathbf{J}^P = 1/2^+$ assignment and compare them with those obtained for the

$\mathbf{J}^P = 5/2^+$ scenario. Such comparisons may provide valuable guidance for future experimental studies aimed at determining the quantum numbers of $\Xi_c(3080)^{+,0}$ states.

$$\frac{\Gamma_{em}[\Xi_c(3080)^+ \rightarrow \Xi_c^+\gamma]}{\Gamma_{em}[\Xi_c(3080)^+ \rightarrow \Xi_c'^+\gamma]} = 0.013^{+0.003}_{-0.003}, \quad (18)$$

$$\frac{\Gamma_{em}[\Xi_c(3080)^+ \rightarrow \Xi_c^+\gamma]}{\Gamma_{em}[\Xi_c(3080)^+ \rightarrow \Xi_c^{*+}\gamma]} = 0.06^{+0.01}_{-0.01}, \quad (19)$$

$$\frac{\Gamma_{em}[\Xi_c(3080)^0 \rightarrow \Xi_c^0\gamma]}{\Gamma_{em}[\Xi_c(3080)^0 \rightarrow \Xi_c'^0\gamma]} = 0.7^{+0.2}_{-0.2}, \quad (20)$$

$$\frac{\Gamma_{em}[\Xi_c(3080)^0 \rightarrow \Xi_c^0\gamma]}{\Gamma_{em}[\Xi_c(3080)^0 \rightarrow \Xi_c^{*0}\gamma]} = 3^{+0.5}_{-0.5}. \quad (21)$$

We observe that the electromagnetic branching ratios for the decays into $\Xi_c^{+,0}\gamma$, $\Xi_c'^{+,0}\gamma$, and $\Xi_c^{*+,0}\gamma$ differ substantially between the assignment $\mathbf{J}^P = 5/2^+$ [see Eqs. (14)–(15)] and the assignment $\mathbf{J}^P = 1/2^+$ [see Eqs. (18)–(21)]. Hence, these branching ratios constitute particularly useful observables for discriminating between possible quantum-number assignments of the $\Xi_c(3080)^{+,0}$ states.

3. Mixing effects

Configuration mixing is not currently introduced in our framework through the mass Hamiltonian, in light of the predicted spectrum accurately reproducing the available experimental masses. However, it should be noted that electromagnetic decay transitions between states sharing the same total angular momentum J , but differing in their total light-quark spin content, can potentially be affected by mixing effects—via mixing angles—as their transitions are expected to vary significantly, making the associated observables mixing sensitive. Nonetheless, to reliably determine these mixing angles, precise experimental measurements are needed. Some experimental data are available for the Ξ_c states, e.g., those discussed in Ref. [87]. Nevertheless, the data and analyses of electromagnetic decay widths referred to in Ref. [87] solely correspond to the P -wave sector; up to now, there was no data available for the D -wave sector, which is the main focus of the present work for the Ξ_c states. In addition, the currently available experimental measurements are not sufficiently accurate to establish the presence of mixing effects, since predictions in Ref. [87] remain within the experimental bounds. Consequently, more accurate experimental data are required to establish the presence or absence of mixing effects and, correspondingly, it is not currently possible to reliably determine mixing angles. In this sense, electromagnetic decay widths hold promise as valuable probes of mixing in the near future, when more precise experimental data

become available, motivating the formalism herein to be naturally extended to account for such effects.

IV. CONCLUSIONS

We calculate the electromagnetic decay widths for the Λ_c and Ξ_c charmed baryons belonging to the flavor $\bar{\mathbf{3}}_F$ -plet. We consider transitions from ground and P -wave states to ground states for the Λ_c baryons, since transitions involving the Ξ_c baryons at this level were already addressed in our previous work [87]. We also analyze transitions from all second-shell Λ_c and Ξ_c states to both ground and P -wave final states. We calculate for the first time the electromagnetic decays of D_ρ -wave states, $\rho\lambda$ mixed states, and radially excited ρ -mode states for singly charmed baryons belonging to the flavor antitriplet. The EMDs of P -wave states have been investigated in Refs. [80–82,84–86,89,91–94]. The EMDs of second shell singly charmed baryons were studied in Refs. [90,91]; however, in both cases only a subset of second shell states was considered.

We discuss the importance of the electromagnetic decay widths of charmed baryons for determining their quantum configurations when different states exhibit similar masses and strong decay widths. We interpret the $\Xi_c(3055)^{+,-}$ baryons as D_λ -wave excitations with $\mathbf{J}^P = 3/2^+$ and $S = 1/2$, belonging to the flavor antitriplet, being consistent with the recent LHCb determination [3]. Our results indicate that the electromagnetic branching ratios of the $\Xi_c(3080)^{+,0}$ states are highly sensitive to their quantum-number assignments, making them powerful observables for distinguishing between the $\mathbf{J}^P = 5/2^+$ and $\mathbf{J}^P = 1/2^+$ scenarios. In this sense, they can provide additional information for future angular-distribution-based experimental analyses aimed at determining the quantum numbers of the $\Xi_c(3080)^{+,0}$ states.

Finally, for the present work, we have accounted for the propagation of parameter uncertainties using a Monte Carlo bootstrap method. The inclusion of uncertainties, often missed in similar and related research studies, is essential for a statistical significant comparison between theory and experiment to take place, driving future discussion.

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DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

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