

Production of excited Λ_c^+ baryons through Λ_b hadronic weak decays

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In this work, to establish a more abundant Λ_c baryon spectrum, we discuss the production potentials of the excited Λ_c baryons through Λ_b hadronic weak decays within a constituent quark model. Based on our successful explanations of the existing experimental data for the $\Lambda_b \rightarrow \Lambda_c(\pi^-, K^-, D^-, D_s^-, D_s^{*-})$ processes, we further calculate the decay rates of the Λ_b baryon into the $1P$ -, $1D$ -, $2S$ -, $3S$ -, $2P$ -, $1F$ -, and $2D$ -wave Λ_c excited states. It is found that these Λ_c excitations have large production rates in the Λ_b hadronic weak decay process associated with π^- meson emitting, i.e., $\Lambda_b \rightarrow \Lambda_c^* \pi^-$, their branching fractions can reach up to $\mathcal{O}(10^{-3})$. To search for the higher $3S$ -, $2P$ -, $1F$ -, and $2D$ -wave Λ_c states, the $\Lambda_b \rightarrow \Lambda_c(3S)\pi^- \rightarrow D^{*0}p\pi^-$, and $\Lambda_b \rightarrow \Lambda_c(2P, 2D, 1F)\pi^- \rightarrow D^{(*)0}p\pi^-$ decays are worth observing in future experiments.

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I. INTRODUCTION

Searching for more new hadron states and exploring the hadron structures are key topics in hadron physics. For the Λ_c^+ spectrum, since the ground state $\Lambda_c(2286)^+$ was first observed in 1976 at Fermilab [1], lots of studies have been carried out in both theory and experiments (for a review, see [2–9]). Seven candidates of Λ_c^+ excitations, $\Lambda_c(2595)^+$, $\Lambda_c(2625)^+$, $\Lambda_c(2765)^+$, $\Lambda_c(2860)^+$, $\Lambda_c(2880)^+$, $\Lambda_c(2910)^+$, and $\Lambda_c(2940)^+$ were observed in the past three decades [10]. It is widely accepted that the $\Lambda_c(2595)^+$ and $\Lambda_c(2625)^+$ should correspond to the two λ -mode $1P$ -wave Λ_c^+ baryons with $J^P = 1/2^-$ and $3/2^-$ predicted in the quark model [11–34]. The $\Lambda_c(2860)^+$ and $\Lambda_c(2880)^+$ resonances favor the two λ -mode $1D$ -wave Λ_c^+ baryons with $J^P = 3/2^+$ and $5/2^+$ [12–19, 21–24, 27, 29, 35–44]. While the $\Lambda_c(2910)^+$ and $\Lambda_c(2940)^+$ resonances may be assigned as the higher $2P$ λ -mode excitations with $J^P = 1/2^-$ and $3/2^-$ [12, 18, 21, 27, 29, 40, 41, 44–55], although there are other explanations, such as D^*N molecular states, in the literature [56–80]. The quark model classification of $\Lambda_c(2765)^+$ is still undetermined, it may be a radial

excitation of Λ_c^+ as suggested in the literature [12, 49, 53, 81]. Currently, except for better understanding the nature of the observed Λ_c^+ baryons, another important task that we face is searching for the missing higher orbital and radial excitations, such as the $3S$ -, $1F$ -, and $2D$ -wave states, in the Λ_c^+ baryon spectrum.

The LHCb experiments provide a good opportunity for systematically studying the excited Λ_c^+ baryons via Λ_b hadronic weak decays. For example, in 2017, the LHCb Collaboration performed an amplitude analysis of the decay $\Lambda_b \rightarrow D^0 p \pi^-$ [82]. A new resonance $\Lambda_c(2860)^+$ together with two early observed states $\Lambda_c(2880)^+$ and $\Lambda_c(2940)^+$ [83–85] were established in the $D^0 p$ invariant mass spectrum. With the accumulation of data sample of Λ_b baryon in Run 3, more and more higher Λ_c^+ excitations may have large potentials to be observed in the Λ_b weak decays. To provide a useful reference for forthcoming experiments and deeply understand the weak decay mechanism of bottom baryons, we carry out a systematical study of the hadronic weak decays $\Lambda_b \rightarrow \Lambda_c^{(*)} h^-$ [$\Lambda_c^{(*)} = \Lambda_c(1S, 2S, 3S, 1P, 2P, 1D, 2D, 1F)$, $h^- = \pi^-, \rho^-, K^-, K^{*-}, D^-, D^{*-}, D_s^-, D_s^{*-}$] within a constituent quark model, which has been developed recently, and successfully applied to study the hadronic weak decays of single charm baryons [86–90], Ω_b baryon [91], and charmed mesons [92]. This model is similar to the early model that was adopted to deal with the semileptonic decays of heavy Λ_Q and Ω_Q baryons [93, 94].

The hadronic weak decays of Λ_b into the ground Λ_c^+ baryon have been widely discussed in the literature with various methods, such as light-front quark model [95–98],

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heavy quark effective theory [99,100], the factorization approach [101,102], relativistic three-quark model [103], covariant oscillator quark model [104], perturbative QCD approach [105], etc.. However, the studies of the Λ_b decaying into the excited Λ_c^+ baryons are quite scarce, only a few studies of the $\Lambda_b \rightarrow \Lambda_c(1P, 2P, 2S)h^-$ processes are found in the literature [95,106,107].

This paper is organized as follows. In Sec. II, a detailed review of two-body nonleptonic weak decays of $\Lambda_b \rightarrow \Lambda_c^{(*)}h^-$ in the constituent quark model. In Sec. III, the theoretical numerical results and discussions are presented. Finally, a short summary is given in Sec. IV.

II. FRAMEWORK

A. The model

The $\Lambda_b \rightarrow \Lambda_c^{(*)}h^-$ decay is particularly interesting because there is only a W -emission diagram contribution [3], which is displayed in Fig. 1. At the quark level, we consider the $b \rightarrow c\bar{q}_4q_5$ ($\bar{q}_4q_5 = \bar{u}d, \bar{u}s, \bar{c}d, \bar{c}s$) transitions. The effective Hamiltonian is given by [108]

$$H_W = \frac{G_F}{\sqrt{2}} V_{cb} V_{45}^* (C_1 \mathcal{O}_1 + C_2 \mathcal{O}_2), \quad (1)$$

where G_F is the Fermi constant [10], C_1 and C_2 are the Wilson coefficients. V_{cb} and V_{45} are the Cabibbo-Kobayashi-Maskawa matrix elements [10], and the current-current operators are

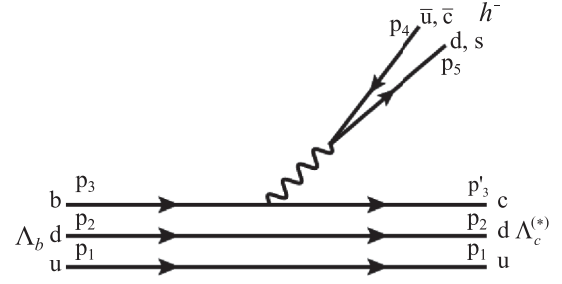


FIG. 1. Feynman diagram for the nonleptonic weak decay processes of $\Lambda_b \rightarrow \Lambda_c^{(*)}h^-$ ($h^- = \pi^-, \rho^-, K^-, K^{*-}, D^-, D^{*-}, D_s^-, D_s^{*-}$).

$$\mathcal{O}_1 = \bar{\psi}_{\bar{q}_\beta} \gamma_\mu (1 - \gamma_5) \psi_{q_\beta} \bar{\psi}_{\bar{c}_\alpha} \gamma^\mu (1 - \gamma_5) \psi_{b_\alpha}, \quad (2)$$

$$\mathcal{O}_2 = \bar{\psi}_{\bar{q}_\alpha} \gamma_\mu (1 - \gamma_5) \psi_{q_\beta} \bar{\psi}_{\bar{c}_\beta} \gamma^\mu (1 - \gamma_5) \psi_{b_\alpha}, \quad (3)$$

with ψ_{j_δ} ($j = u/d/s/c/b$, $\delta = \alpha/\beta$) representing the j th quark field with a color index δ in a meson or baryon.

Considering its parity behavior, H_W can be divided into two parts, the parity-conserving part H_W^{PC} and the parity-violating part H_W^{PV} [86,87],

$$H_W = H_W^{PC} + H_W^{PV}. \quad (4)$$

With a nonrelativistic expansion, the two operators can be approximately expressed as

$$\begin{aligned} H_W^{PC} &\simeq \left(C_1 + \frac{C_2}{3} \right) \frac{G_F}{\sqrt{2}} V_{cb} V_{45}^* \frac{\hat{\phi}_c \hat{\mathcal{O}}^f}{(2\pi)^3} \delta^3(\mathbf{p}_3 - \mathbf{p}_3' - \mathbf{p}_4 - \mathbf{p}_5) \left\{ \sigma_4 \cdot \left(\frac{\mathbf{p}_5}{2m_5} + \frac{\mathbf{p}_4}{2m_4} - \frac{\mathbf{p}_3'}{2m_3'} - \frac{\mathbf{p}_3}{2m_3} \right) \right. \\ &\quad \left. + \sigma_3 \cdot \left(\frac{\mathbf{p}_3'}{2m_3'} + \frac{\mathbf{p}_3}{2m_3} - \frac{\mathbf{p}_5}{2m_5} - \frac{\mathbf{p}_4}{2m_4} \right) + i\sigma_4 \cdot \left[\sigma_3 \times \left(\frac{\mathbf{p}_3}{2m_3} - \frac{\mathbf{p}_3'}{2m_3'} \right) \right] + i\sigma_3 \cdot \left[\sigma_4 \times \left(\frac{\mathbf{p}_4}{2m_4} - \frac{\mathbf{p}_5}{2m_5} \right) \right] \right\}, \\ H_W^{PV} &\simeq \frac{G_F}{\sqrt{2}} V_{cb} V_{45}^* \left(C_1 + \frac{C_2}{3} \right) \frac{\hat{\phi}_c \hat{\mathcal{O}}^f}{(2\pi)^3} (\sigma_3 \cdot \sigma_4 - 1) \delta^3(\mathbf{p}_3 - \mathbf{p}_3' - \mathbf{p}_4 - \mathbf{p}_5), \end{aligned} \quad (5)$$

where, $\mathbf{p}_j$, m_j , and σ_j stand for the momentum, mass, and spin operator of the j th quark, respectively, as shown in Fig. 1. While, $\hat{\phi}_c$ and $\hat{\mathcal{O}}^f$ stand for the color and flavor operators, respectively. They are explicitly given by

$$\hat{\mathcal{O}}^f = b_5^\dagger(q) b_4^\dagger(\bar{q}) b_3^\dagger(c) b_3(b), \quad \hat{\phi}_c = \delta_{c_4 c_5} \delta_{c_3' c_3}, \quad (6)$$

where $\hat{b}^\dagger$ and $\hat{b}$ are the quark creation and annihilation operators, and the $\delta_{c_i c_j}$ represents that the colors of two quarks, c_i and c_j , should be conserved.

In the quark model framework, the decay amplitude for the $\Lambda_b \rightarrow \Lambda_c^{(*)}h^-$ is given by

$$\begin{aligned} &\mathcal{M}_{M_{J_i}, M_{J_f}, M_{J_h}}^{J_i, J_f, J_h} (\Lambda_b \rightarrow \Lambda_c^{(*)} h^-) \\ &= \mathcal{M}_{M_{J_i}, M_{J_f}, M_{J_h}}^{J_i, J_f, J_h, PC} + \mathcal{M}_{M_{J_i}, M_{J_f}, M_{J_h}}^{J_i, J_f, J_h, PV}, \end{aligned} \quad (7)$$

with $\mathcal{M}_{M_{J_i}, M_{J_f}, M_{J_h}}^{J_i, J_f, J_h, PC} = \langle \Psi_{J_f M_{J_f}}^{\Lambda_c^{(*)}} \Psi_{J_h M_{J_h}}^h | H_W^{PC} | \Psi_{J_i M_{J_i}}^{\Lambda_b} \rangle$ and $\mathcal{M}_{M_{J_i}, M_{J_f}, M_{J_h}}^{J_i, J_f, J_h, PV} = \langle \Psi_{J_f M_{J_f}}^{\Lambda_c^{(*)}} \Psi_{J_h M_{J_h}}^h | H_W^{PV} | \Psi_{J_i M_{J_i}}^{\Lambda_b} \rangle$, where $\Psi_{J_i M_{J_i}}^{\Lambda_b}$, $\Psi_{J_f M_{J_f}}^{\Lambda_c^{(*)}}$, and $\Psi_{J_h M_{J_h}}^h$ stand for the wave functions of Λ_b , $\Lambda_c^{(*)}$, and the emitting meson h^- , respectively.

The total wave function of a hadron should include four parts: a color wave function ζ_c , a flavor wave function ϕ_f , a spin wave function χ , and a spatial wave function ψ . The color wave functions for the meson and baryon systems should be a color singlet, which are given by

$$\zeta_c = \begin{cases} \frac{1}{\sqrt{3}}(R\bar{R} + G\bar{G} + B\bar{B}), & \text{for meson,} \\ \frac{1}{\sqrt{6}}(RGB - RBG + GBR - GRB + BRG - BGR), & \text{for baryon,} \end{cases} \quad (8)$$

For the $\Lambda_Q^{(*)}$ ($Q = c, b$) baryons, the light quarks in which satisfy the SU(3) symmetry, their flavor wave function belong the $\bar{3}_F$ representation, i.e.,

$$\phi_f^{\Lambda_Q} = \frac{1}{\sqrt{2}}(ud - du)Q. \quad (9)$$

For the final meson states ($\pi^-, \rho^-, K^-, K^{*-}, D^-, D^{*-}, D_s^-, D_s^{*-}$), the flavor functions are given by

$$\phi_f^{h^-} = \begin{cases} \bar{u}d, & \text{for } \pi^-, \rho^- \\ \bar{u}s, & \text{for } K^-, K^{*-} \\ \bar{c}d, & \text{for } D^-, D^{*-} \\ \bar{c}s, & \text{for } D_s^-, D_s^{*-} \end{cases}. \quad (10)$$

For a single heavy baryon system $q_1 q_2 Q_3$, the relative momenta between quarks are defined by

$$\begin{aligned} \mathbf{p}_\rho &= \frac{\sqrt{2}}{2}(\mathbf{p}_1 - \mathbf{p}_2), \\ \mathbf{p}_\lambda &= \frac{\sqrt{6}}{2} \frac{m_3(\mathbf{p}_1 + \mathbf{p}_2) - (m_1 + m_2)\mathbf{p}_3}{m_1 + m_2 + m_3}. \end{aligned} \quad (11)$$

In this work, the spatial wave functions for the $\Lambda_Q^{(*)}$ states are used a simple harmonic oscillator (SHO) form. For a $\Lambda_Q^{(*)}$ baryon state with quantum numbers N, L , and M_L , the spatial wave function can be represented as a product of the ρ - and λ -oscillator parts [109–112]

$$\begin{aligned} \psi_{NLM_L}(\mathbf{p}_\rho, \mathbf{p}_\lambda) \\ = [R_{n_\rho l_\rho}(\mathbf{p}_\rho) \mathcal{Y}_{l_\rho m_\rho}(\mathbf{p}_\rho) \otimes R_{n_\lambda l_\lambda}(\mathbf{p}_\lambda) \mathcal{Y}_{l_\lambda m_\lambda}(\mathbf{p}_\lambda)]_{LM_L}^N, \end{aligned} \quad (12)$$

where $n_{\rho/\lambda}, l_{\rho/\lambda}, m_{\rho/\lambda}$ are the principal, orbital, and magnetic quantum numbers for the ρ/λ oscillators, respectively, while the quantum numbers N, L , and M_L satisfy $N = 2(n_\rho + n_\lambda) + l_\rho + l_\lambda$, $L = l_\rho + l_\lambda, \dots, |l_\rho - l_\lambda|$, and $M_L = m_\rho + m_\lambda$. In Eq. (12), the function $\mathcal{Y}_{lm}(\mathbf{p}) \equiv |\mathbf{p}|^l Y_{lm}(\hat{\mathbf{p}})$ is the l th solid harmonic polynomial, the SHO form of the radial part $R_{nl}(p)$ in momentum space is given by

$$\begin{aligned} R_{nl}(p) &= (i)^l (-1)^n \left[\frac{2n!}{(n+l+1/2)!} \right]^{1/2} \frac{1}{\alpha^{l+3/2}} \exp\left(-\frac{\mathbf{p}^2}{2\alpha^2}\right) \\ &\times L_n^{l+1/2}(\mathbf{p}^2/\alpha^2). \end{aligned} \quad (13)$$

There are two harmonic oscillator parameters α_ρ and α_λ in the spatial wave function. Finally, the total wave function of $\Lambda_Q^{(*)}$ baryons in the spin-orbital ($L-S$) coupling scheme for the states with quantum numbers of total angular momentum and its z -component, J and M_J , is given by [113]

$$\Psi_{JM_J}^{\Lambda_Q^{(*)}} = \mathcal{A} \left\{ [\psi_{NLM_L}(\mathbf{p}_\rho, \mathbf{p}_\lambda) \otimes \chi_{SM_S}^\sigma]_{JM_J} \phi_f^{\Lambda_Q} \zeta_c \right\}, \quad (14)$$

where $\mathcal{A}$ represents the operator that enforces antisymmetry on the total wave function when the two light quarks are exchanged, while S and M_S are the quantum numbers of the total spin angular momentum S and its z -component, respectively. The explicit forms of the spin wave function $\chi_{SM_S}^\sigma$ with different permutation symmetries $\sigma (= s, \rho, \lambda)$ can be found in Refs. [25, 114]. The detailed total wave functions of the $\Lambda_c^{(*)}$ baryons, up to the $2D$ states, are presented in Table I.

The wave functions for the ground pseudoscalar and vector mesons involved in the final states are given by

$$\Psi_{JM_{J_h}}^h = \zeta_c^h \phi_f^h \chi_{SM_S} \psi(\mathbf{p}_4, \mathbf{p}_5), \quad (15)$$

where the spatial wave function is adopted as the SHO form, i.e.,

$$\psi(\mathbf{p}_4, \mathbf{p}_5) = \frac{2^{3/4}}{\pi^{3/4} \beta_M^3} \exp\left[-\frac{(\mathbf{p}_4 - \mathbf{p}_5)^2}{4\beta^2}\right], \quad (16)$$

where β is the well-known HO parameter. For a pseudoscalar meson, the spin wave function is given by

$$\chi_{00} = \frac{1}{\sqrt{2}}(\uparrow\downarrow - \downarrow\uparrow), \quad (17)$$

while for a vector meson, the spin wave functions are given by

$$\chi_{11} = \uparrow\uparrow, \quad \chi_{10} = \frac{1}{\sqrt{2}}(\uparrow\downarrow + \downarrow\uparrow), \quad \chi_{1-1} = \downarrow\downarrow. \quad (18)$$

Then, with the decay amplitudes worked out in the constituent quark model, the partial decay width for the $\Lambda_b \rightarrow \Lambda_c^{(*)} h^-$ process is calculated by

TABLE I. The total wave functions of the Λ_c baryons up to the $2D$ states. The Clebsch-Gordan series for the spin and orbital angular-momentum addition $|JM_J\rangle = \sum_{M_L+M_S=M_J} \langle LM_L, SM_S | JM_J \rangle^N \psi_{LM_L} \chi_{SM_S}$ has been omitted.

State	n_ρ	L_ρ	n_λ	L_λ	N	L	S	J^P	Wave function
$ \Lambda_c 1^2 S J^P\rangle$	0	0	0	0	0	0	$\frac{1}{2}$	$\frac{1}{2}^+$	$^0\psi_{00}^S \chi_{S_z}^\rho \phi \zeta_B$
$ \Lambda_c 1^2 P_\lambda J^P\rangle$	0	0	0	1	1	1	$\frac{1}{2}$	$\frac{1}{2}^-, \frac{3}{2}^-$	$^1\psi_{1M_L}^\lambda \chi_{S_z}^\rho \phi \zeta_B$
$ \Lambda_c 2^2 S_\lambda J^P\rangle$	0	0	1	0	2	0	$\frac{1}{2}$	$\frac{1}{2}^+$	$^2\psi_{00}^\lambda \chi_{S_z}^\rho \phi \zeta_B$
$ \Lambda_c 1^2 D_\lambda J^P\rangle$	0	0	0	2	2	2	$\frac{1}{2}$	$\frac{3}{2}^+, \frac{5}{2}^+$	$^2\psi_{2M_L}^\lambda \chi_{S_z}^\rho \phi \zeta_B$
$ \Lambda_c 2^2 P_\lambda J^P\rangle$	0	0	1	1	3	1	$\frac{1}{2}$	$\frac{1}{2}^-, \frac{3}{2}^-$	$^3\psi_{1M_L}^\lambda \chi_{S_z}^\rho \phi \zeta_B$
$ \Lambda_c 1^2 F_\lambda J^P\rangle$	0	0	0	3	3	3	$\frac{1}{2}$	$\frac{5}{2}^-, \frac{7}{2}^-$	$^3\psi_{3M_L}^\lambda \chi_{S_z}^\rho \phi \zeta_B$
$ \Lambda_c 3^2 S_\lambda J^P\rangle$	0	0	2	0	4	0	$\frac{1}{2}$	$\frac{1}{2}^+$	$^4\psi_{00}^\lambda \chi_{S_z}^\rho \phi \zeta_B$
$ \Lambda_c 2^2 D_\lambda J^P\rangle$	0	0	1	2	4	2	$\frac{1}{2}$	$\frac{3}{2}^+, \frac{5}{2}^+$	$^4\psi_{2M_L}^\lambda \chi_{S_z}^\rho \phi \zeta_B$

$$\Gamma = 8\pi^2 \frac{|\mathbf{q}| E_h E_{\Lambda_c^{(*)}}}{M_{\Lambda_b}} \frac{1}{2J_{\Lambda_b} + 1} \sum_{M_{J_i}=M_{J_f}+M_{J_h}} \left| \mathcal{M}_{M_{J_i}, M_{J_f}, M_{J_h}}^{J_i, J_f, J_h} \right|^2, \quad (19)$$

where $\mathbf{q}$ and E_h are the three-momentum and energy of the meson h , respectively, $E_{\Lambda_c^{(*)}}$ is the energy of the $\Lambda_c^{(*)}$ baryon, and M_{Λ_b} is the mass of the Λ_b baryon.

B. Model parameters

In this work, the CKM matrix elements and the lifetime of the Λ_b^0 baryon are taken from the PDG [10], which are listed as follows:

$$\begin{aligned} (V_{ud}, V_{us}) &= (0.9737, 0.2245), \\ (V_{cd}, V_{cs}, V_{cb}) &= (0.221, 0.987, 0.041), \\ \tau_{\Lambda_b^0} &= 1.468 \times 10^{-12} \text{ s}. \end{aligned} \quad (20)$$

The Wilson coefficients $(C_1, C_2) = (1.1, -0.25)$ are taken from Refs. [98,108,115].

In the calculation, the standard quark model parameters are adopted. The constituent masses for the u/d , s , c , and b are taken as $m_{u/d} = 450$ MeV, $m_s = 550$ MeV, $m_c = 1450$ MeV, and $m_b = 4800$ MeV, which are consistent with those adopted for the recent heavy-light meson spectrum calculations within the potential model [116]. For the Λ_b and $\Lambda_c^{(*)}$ baryons, the ρ -mode HO parameter is set to the commonly used value in the literature, i.e.

$\alpha_\rho = 400$ MeV, while the λ -mode HO parameter α_λ is related to that of ρ mode with the following relation [25,42]

$$\alpha_\lambda = \sqrt[4]{\frac{3m_{b(c)}}{m_u + m_d + m_{b(c)}}} \alpha_\rho. \quad (21)$$

For the mesons, the HO parameter β is determined by [117]

$$\beta = \sqrt{\frac{2m_q m_{\bar{q}}}{(m_q + m_{\bar{q}})m_u}} \alpha, \quad (22)$$

where the parameter α corresponds to the HO parameter of the π^- and ρ^- mesons. To maintain consistency with baryons, α is also taken as $\alpha = \alpha_\rho = 400$ MeV.

The masses for the baryons [Λ_b^0 and $\Lambda_c^{(*)+}$] and mesons (π^- , ρ^- , K^- , K^{*-} , D^- , D^{*-} , D_s^- , D_s^{*-}) observed by experiments are taken from the PDG [10]. For the unestablished Λ_c^* resonances, the masses are taken from the quark model predictions [19]. The corresponding numerical values are listed in Tables II and IV.

It should be pointed out that there are some uncertainties in our predictions due to the uncertainties of the model parameters. Our analysis shows that the uncertainties of our predictions mainly come from the HO parameters α_ρ and β adopted in the calculations. Usually, these HO parameters have an uncertainty of $\sim 10\%$. Taking a 10% variation for the HO parameters α_ρ and β , we further evaluate the uncertainties of our predictions, which are given in Tables III and IV. It is found that uncertainties of the

TABLE II. The masses (MeV) for the observed baryons and mesons taken from the PDG [10].

State	Λ_b^0	π^-	K^-	D^-	D_s^-	ρ^-	K^{*-}	D^{*-}	D_s^{*-}
Mass	5620	140	494	1870	1968	775	896	2007	2112
State	Λ_c^+	$\Lambda_c(2595)^+$	$\Lambda_c(2625)^+$	$\Lambda_c(2765)^+$	$\Lambda_c(2860)^+$	$\Lambda_c(2880)^+$	$\Lambda_c(2910)^+$	$\Lambda_c(2940)^+$	
Mass	2286	2592	2628	2767	2856	2882	2914	2940	

TABLE III. Branching fractions (with a unit of 10^{-3}) of the $\Lambda_b \rightarrow \Lambda_c h^-$ processes ($h^- = \pi^-, \rho^-, K^-, K^{*-}, D^-, D^{*-}, D_s^-, D_s^{*-}$). The first error of our predictions comes from the baryon HO parameter α_ρ with uncertainties of $\pm 10\%$. The second error of our predictions comes from the meson HO parameter β with uncertainties of $\pm 10\%$. For a comparison, the other model results and experimental data are included.

Decays	This work	[95]	[99]	[101]	[103]	[100]	[102]	[104]	[97]	[98]	[96]	Exp [10].
$\Lambda_b \rightarrow \Lambda_c \pi^-$	$5.67^{+3.17+1.88}_{-2.55-1.55}$	$4.16^{+2.43}_{-1.73}$	$4.6^{+2.0}_{-3.1}$	4.6	5.62	3.91		1.75	4.96		5.67	4.9 ± 0.4
$\Lambda_b \rightarrow \Lambda_c K^-$	$0.31^{+0.17+0.10}_{-0.14-0.08}$	$0.31^{+0.18}_{-0.13}$						0.13	0.393		0.46	0.356 ± 0.028
$\Lambda_b \rightarrow \Lambda_c D^-$	$0.43^{+0.14+0.14}_{-0.14-0.12}$	$0.47^{+0.30}_{-0.21}$						0.30	0.522		0.76	0.46 ± 0.06
$\Lambda_b \rightarrow \Lambda_c D_s^-$	$10.3^{+3.10+3.39}_{-3.08-2.78}$	$11.92^{+7.69}_{-5.28}$	23^{+3}_{-4}	13.7		12.91	22.3	7.70	12.4	14.78	19.94	11.0 ± 1.0
$\Lambda_b \rightarrow \Lambda_c D_s^{*-}$	$17.5^{+4.91+5.80}_{-4.97-4.74}$	$17.49^{+10.60}_{-7.48}$	$17.3^{+2.0}_{-3.0}$	21.8		19.83	32.6	14.14	10.5	25.16	30.86	18.3 ± 1.8
$\Lambda_b \rightarrow \Lambda_c \rho^-$	$6.91^{+3.08+1.62}_{-3.39-2.24}$	$12.28^{+7.19}_{-5.11}$	$6.6^{+2.4}_{-4.0}$	12.9		10.82		4.91	8.65		16.71	
$\Lambda_b \rightarrow \Lambda_c K^{*-}$	$0.37^{+0.18+0.12}_{-0.16-0.10}$	$0.63^{+0.37}_{-0.26}$						0.27	0.441		0.87	
$\Lambda_b \rightarrow \Lambda_c D^{*-}$	$0.82^{+0.25+0.27}_{-0.24-0.22}$	$0.84^{+0.51}_{-0.36}$						0.49	0.520		1.38	

TABLE IV. Predicted decay properties of the $\Lambda_b \rightarrow \Lambda_c^{(*)} h^-$ processes. The first error of our predictions comes from the baryon HO parameter α_ρ with uncertainties of $\pm 10\%$. The second error of our predictions comes from the meson HO parameter β with uncertainties of $\pm 10\%$. $\mathcal{B}$ stands for the branching fraction, and M_f stands for the mass of the final state $\Lambda_c^{(*)}$. For the branching fractions ratios, the uncertainties come from β are tiny, which are omitted.

State	Mass	$\mathcal{B}_{\pi^-}(10^{-3})$	$\frac{\mathcal{B}[\Lambda_b^0 \rightarrow \Lambda_c^{(*)+} \pi^-]}{\mathcal{B}[\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-]}$	$\mathcal{B}(10^{-3})$ [95]	$\mathcal{B}_{\rho^-}(10^{-3})$	$\frac{\mathcal{B}[\Lambda_b^0 \rightarrow \Lambda_c^{(*)+} \rho^-]}{\mathcal{B}[\Lambda_b^0 \rightarrow \Lambda_c^+ \rho^-]}$	$\mathcal{B}(10^{-3})$ [95]
$ \Lambda_c \ 1^2 P_{\lambda_2}^{1-}\rangle$	2592	$5.12^{+1.36+1.70}_{-1.52-1.39}$	$0.90^{+0.17}_{-0.25}$	$1.09^{+0.76}_{-0.51}$	$5.74^{+1.32+1.90}_{-1.54-1.56}$	$0.90^{+0.19}_{-0.30}$	$2.99^{+2.20}_{-1.44}$
$ \Lambda_c \ 1^2 P_{\lambda_2}^{3-}\rangle$	2628	$8.73^{+1.92+2.88}_{-2.37-2.37}$	$1.54^{+0.33}_{-0.51}$	$2.40^{+4.09}_{-1.82}$	$8.88^{+1.71+2.94}_{-2.18-2.41}$	$1.39^{+0.33}_{-0.52}$	$4.38^{+6.78}_{-3.17}$
$ \Lambda_c \ 2^2 S_{\lambda_2}^{1+}\rangle$	2767	$5.73^{+0.28+1.90}_{-0.70-1.55}$	$1.01^{+0.33}_{-0.60}$	$1.70^{+0.69}_{-0.52}$	$5.30^{+0.12+1.75}_{-0.49-1.44}$	$0.83^{+0.28}_{-0.54}$	$4.84^{+2.01}_{-1.50}$
$ \Lambda_c \ 1^2 D_{\lambda_2}^{3+}\rangle$	2856	$4.09^{+0.10+1.36}_{-0.40-1.11}$	$0.72^{+0.25}_{-0.47}$		$4.15^{+0.01+1.38}_{-0.25-1.12}$	$0.65^{+0.23}_{-0.46}$	
$ \Lambda_c \ 1^2 D_{\lambda_2}^{5+}\rangle$	2882	$4.56^{+0.16+1.51}_{-0.21-1.24}$	$0.80^{+0.31}_{-0.59}$		$4.82^{+0.26+1.59}_{-0.07-1.31}$	$0.75^{+0.30}_{-0.60}$	
$ \Lambda_c \ 2^2 P_{\lambda_2}^{1-}\rangle$	2983 [19]	$2.39^{+0.07+1.06}_{-0.35-0.50}$	$0.42^{+0.18}_{-0.40}$	$0.68^{+0.21}_{-0.21}$	$2.28^{+0.30+0.75}_{-0.24-0.62}$	$0.35^{+0.16}_{-0.36}$	$1.85^{+0.63}_{-0.60}$
$ \Lambda_c \ 2^2 P_{\lambda_2}^{3-}\rangle$	3005 [19]	$3.91^{+0.26+1.72}_{-0.73-0.83}$	$0.69^{+0.31}_{-0.71}$	$1.00^{+2.00}_{-0.83}$	$3.79^{+0.60+1.26}_{-0.55-1.02}$	$0.59^{+0.27}_{-0.64}$	$1.93^{+3.19}_{-1.43}$
$ \Lambda_c \ 1^2 F_{\lambda_2}^{5-}\rangle$	3097 [19]	$1.06^{+0.21+0.35}_{-0.21-0.29}$	$0.19^{+0.09}_{-0.22}$		$0.96^{+0.21+0.32}_{-0.23-0.26}$	$0.15^{+0.075}_{-0.19}$	
$ \Lambda_c \ 1^2 F_{\lambda_2}^{7-}\rangle$	3078 [19]	$1.46^{+0.29+0.48}_{-0.28-0.40}$	$0.26^{+0.12}_{-0.30}$		$1.33^{+0.29+0.45}_{-0.32-0.36}$	$0.21^{+0.10}_{-0.26}$	
$ \Lambda_c \ 3^2 S_{\lambda_2}^{1+}\rangle$	3130 [19]	$1.11^{+0.27+0.37}_{-0.33-0.30}$	$0.20^{+0.10}_{-0.27}$		$0.83^{+0.21+0.28}_{-0.28-0.22}$	$0.13^{+0.068}_{-0.19}$	
$ \Lambda_c \ 2^2 D_{\lambda_2}^{3+}\rangle$	3189 [19]	$1.07^{+0.27+0.36}_{-0.35-0.29}$	$0.19^{+0.10}_{-0.27}$		$0.89^{+0.23+0.30}_{-0.32-0.24}$	$0.14^{+0.074}_{-0.21}$	
$ \Lambda_c \ 2^2 D_{\lambda_2}^{5+}\rangle$	3209 [19]	$1.13^{+0.33+0.38}_{-0.45-0.31}$	$0.20^{+0.11}_{-0.31}$		$0.97^{+0.29+0.33}_{-0.42-0.26}$	$0.15^{+0.084}_{-0.24}$	

State	Mass	$\mathcal{B}_{K^-}(10^{-4})$	$\frac{\mathcal{B}[\Lambda_b^0 \rightarrow \Lambda_c^{(*)+} K^-]}{\mathcal{B}[\Lambda_b^0 \rightarrow \Lambda_c^+ K^-]}$	$\mathcal{B}(10^{-4})$ [95]	$\mathcal{B}_{K^{*-}}(10^{-4})$	$\frac{\mathcal{B}[\Lambda_b^0 \rightarrow \Lambda_c^{(*)+} K^{*-}]}{\mathcal{B}[\Lambda_b^0 \rightarrow \Lambda_c^+ K^{*-}]}$	$\mathcal{B}(10^{-4})$ [95]
$ \Lambda_c \ 1^2 P_{\lambda_2}^{1-}\rangle$	2592	$2.77^{+0.70+0.91}_{-0.80-0.75}$	$0.89^{+0.17}_{-0.25}$	$0.8^{+0.6}_{-0.4}$	$2.97^{+0.66+0.99}_{-0.77-0.80}$	$0.81^{+0.15}_{-0.23}$	$1.5^{+1.1}_{-0.7}$
$ \Lambda_c \ 1^2 P_{\lambda_2}^{3-}\rangle$	2628	$4.65^{+0.96+1.53}_{-1.21-1.26}$	$1.49^{+0.33}_{-0.49}$	$1.7^{+3.0}_{-1.3}$	$4.72^{+0.86+1.57}_{-1.11-1.28}$	$1.29^{+0.28}_{-0.42}$	$2.2^{+3.3}_{-1.6}$
$ \Lambda_c \ 2^2 S_{\lambda_2}^{1+}\rangle$	2767	$3.00^{+0.11+0.99}_{-0.34-0.82}$	$0.96^{+0.31}_{-0.57}$	$1.3^{+0.05}_{-0.04}$	$2.76^{+0.05+0.92}_{-0.22-0.75}$	$0.76^{+0.25}_{-0.45}$	$2.5^{+0.10}_{-0.08}$
$ \Lambda_c \ 1^2 D_{\lambda_2}^{3+}\rangle$	2856	$2.15^{+0.03+0.71}_{-0.19-0.58}$	$0.69^{+0.24}_{-0.44}$		$2.09^{+0.02+0.69}_{-0.11-0.57}$	$0.57^{+0.20}_{-0.37}$	
$ \Lambda_c \ 1^2 D_{\lambda_2}^{5+}\rangle$	2882	$2.33^{+0.10+0.77}_{-0.07-0.63}$	$0.75^{+0.29}_{-0.56}$		$2.41^{+0.15+0.80}_{-0.01-0.65}$	$0.66^{+0.25}_{-0.48}$	
$ \Lambda_c \ 2^2 P_{\lambda_2}^{1-}\rangle$	2983 [19]	$1.22^{+0.14+0.40}_{-0.10-0.33}$	$0.39^{+0.17}_{-0.37}$	$0.5^{+0.2}_{-0.2}$	$1.12^{+0.15+0.37}_{-0.13-0.31}$	$0.31^{+0.13}_{-0.29}$	$0.9^{+0.3}_{-0.3}$
$ \Lambda_c \ 2^2 P_{\lambda_2}^{3-}\rangle$	3005 [19]	$1.96^{+0.29+0.65}_{-0.25-0.53}$	$0.63^{+0.28}_{-0.64}$	$0.7^{+1.4}_{-0.6}$	$1.85^{+0.30+0.61}_{-0.29-0.50}$	$0.51^{+0.22}_{-0.51}$	$1.0^{+1.5}_{-0.7}$
$ \Lambda_c \ 1^2 F_{\lambda_2}^{5-}\rangle$	3097 [19]	$0.53^{+0.11+0.17}_{-0.11-0.15}$	$0.17^{+0.08}_{-0.20}$		$0.46^{+0.10+0.16}_{-0.12-0.12}$	$0.13^{+0.061}_{-0.15}$	

(Table continued)

TABLE IV. (Continued)

State	Mass	$\mathcal{B}_{K^-} (10^{-4})$	$\frac{\mathcal{B}[\Lambda_b^0 \rightarrow \Lambda_c^{(*)+} K^-]}{\mathcal{B}[\Lambda_b^0 \rightarrow \Lambda_c^+ K^-]}$	$\mathcal{B}(10^{-4})$ [95]	$\mathcal{B}_{K^{*-}} (10^{-4})$	$\frac{\mathcal{B}[\Lambda_b^0 \rightarrow \Lambda_c^{(*)+} K^{*-}]}{\mathcal{B}[\Lambda_b^0 \rightarrow \Lambda_c^+ K^{*-}]}$	$\mathcal{B}(10^{-4})$ [95]
$ \Lambda_c 1^2 F_{\lambda_2}^{7-}\rangle$	3078 [19]	$0.72_{-0.15-0.19}^{+0.15+0.24}$	$0.23_{-0.11}^{+0.15}$		$0.64_{-0.16-0.17}^{+0.14+0.21}$	$0.18_{-0.20}^{+0.085}$	
$ \Lambda_c 3^2 S_{\lambda_2}^{1+}\rangle$	3130 [19]	$0.54_{-0.17-0.15}^{+0.13+0.18}$	$0.17_{-0.23}^{+0.09}$		$0.41_{-0.14-0.11}^{+0.11+0.13}$	$0.11_{-0.15}^{+0.056}$	
$ \Lambda_c 2^2 D_{\lambda_2}^{3+}\rangle$	3189 [19]	$0.53_{-0.17-0.15}^{+0.14+0.17}$	$0.17_{-0.23}^{+0.09}$		$0.42_{-0.15-0.11}^{+0.11+0.14}$	$0.12_{-0.16}^{+0.059}$	
$ \Lambda_c 2^2 D_{\lambda_2}^{5+}\rangle$	3209 [19]	$0.54_{-0.22-0.15}^{+0.17+0.17}$	$0.17_{-0.27}^{+0.09}$		$0.45_{-0.20-0.12}^{+0.14+0.15}$	$0.12_{-0.19}^{+0.067}$	
State	Mass	$\mathcal{B}_{D^-} (10^{-4})$	$\frac{\mathcal{B}[\Lambda_b^0 \rightarrow \Lambda_c^{(*)+} D^-]}{\mathcal{B}[\Lambda_b^0 \rightarrow \Lambda_c^+ D^-]}$	$\mathcal{B}$ [95]	$\mathcal{B}_{D^{*-}} (10^{-4})$	$\frac{\mathcal{B}[\Lambda_b^0 \rightarrow \Lambda_c^{(*)+} D^{*-}]}{\mathcal{B}[\Lambda_b^0 \rightarrow \Lambda_c^+ D^{*-}]}$	$\mathcal{B}(10^{-4})$ [95]
$ \Lambda_c 1^2 P_{\lambda_2}^{1-}\rangle$	2592	$2.47_{-0.36-0.67}^{+0.26+0.82}$	$0.57_{-0.15}^{+0.098}$	$0.7_{-0.4}^{+0.7}$	$4.07_{-0.47-1.10}^{+0.32+1.35}$	$0.50_{-0.13}^{+0.087}$	$1.2_{-0.7}^{+1.1}$
$ \Lambda_c 1^2 P_{\lambda_2}^{3-}\rangle$	2625	$3.59_{-0.32-0.97}^{+0.13+1.19}$	$0.83_{-0.29}^{+0.19}$	$1.3_{-1.0}^{+2.2}$	$3.42_{-0.24-0.93}^{+0.083+1.13}$	$0.42_{-0.14}^{+0.090}$	$1.3_{-0.8}^{+1.7}$
$ \Lambda_c 2^2 S_{\lambda_2}^{1+}\rangle$	2767	$1.49_{-0.081-0.40}^{+0.11+0.49}$	$0.35_{-0.19}^{+0.11}$	$1.5_{-0.5}^{+0.7}$	$1.21_{-0.097-0.33}^{+0.108+0.40}$	$0.15_{-0.081}^{+0.045}$	$2.6_{-0.9}^{+1.2}$
$ \Lambda_c 1^2 D_{\lambda_2}^{3+}\rangle$	2856	$0.94_{-0.078-0.26}^{+0.087+0.31}$	$0.22_{-0.13}^{+0.070}$		$1.25_{-0.15-0.34}^{+0.141+0.42}$	$0.15_{-0.092}^{+0.049}$	
$ \Lambda_c 1^2 D_{\lambda_2}^{5+}\rangle$	2882	$0.77_{-0.15-0.21}^{+0.14+0.25}$	$0.18_{-0.14}^{+0.069}$		$1.03_{-0.24-0.28}^{+0.20+0.34}$	$0.13_{-0.096}^{+0.049}$	
$ \Lambda_c 2^2 P_{\lambda_2}^{1-}\rangle$	2983 [19]	$0.30_{-0.069-0.082}^{+0.053+0.10}$	$0.07_{-0.057}^{+0.027}$	$0.4_{-0.2}^{+0.2}$	$0.35_{-0.087-0.094}^{+0.064+0.11}$	$0.042_{-0.034}^{+0.016}$	$0.6_{-0.3}^{+0.3}$
$ \Lambda_c 2^2 P_{\lambda_2}^{3-}\rangle$	3005 [19]	$0.39_{-0.12-0.11}^{+0.090+0.13}$	$0.09_{-0.085}^{+0.038}$	$0.7_{-0.5}^{+1.0}$	$0.44_{-0.15-0.12}^{+0.10+0.15}$	$0.054_{-0.049}^{+0.022}$	$0.6_{-0.3}^{+0.6}$
$ \Lambda_c 1^2 F_{\lambda_2}^{5-}\rangle$	3097 [19]	$0.062_{-0.028-0.017}^{+0.018+0.020}$	$0.014_{-0.016}^{+0.007}$		$0.056_{-0.028-0.015}^{+0.017+0.019}$	$0.0069_{-0.0079}^{+0.0033}$	
$ \Lambda_c 1^2 F_{\lambda_2}^{7-}\rangle$	3078 [19]	$0.090_{-0.040-0.024}^{+0.027+0.030}$	$0.021_{-0.024}^{+0.010}$		$0.084_{-0.041-0.023}^{+0.026+0.028}$	$0.010_{-0.012}^{+0.0049}$	
$ \Lambda_c 3^2 S_{\lambda_2}^{1+}\rangle$	3130 [19]	$0.056_{-0.024-0.015}^{+0.015+0.019}$	$0.013_{-0.014}^{+0.006}$		$0.029_{-0.012-0.008}^{+0.008+0.010}$	$0.0035_{-0.0037}^{+0.0015}$	
$ \Lambda_c 2^2 D_{\lambda_2}^{3+}\rangle$	3189 [19]	$0.043_{-0.019-0.012}^{+0.012+0.014}$	$0.010_{-0.011}^{+0.005}$		$0.033_{-0.014-0.009}^{+0.009+0.011}$	$0.0040_{-0.0043}^{+0.0018}$	
$ \Lambda_c 2^2 D_{\lambda_2}^{5+}\rangle$	3209 [19]	$0.028_{-0.017-0.008}^{+0.010+0.009}$	$0.006_{-0.009}^{+0.003}$		$0.020_{-0.012-0.005}^{+0.007+0.007}$	$0.0025_{-0.0032}^{+0.0012}$	
State	Mass	$\mathcal{B}_{D_s^-} (10^{-3})$	$\frac{\mathcal{B}[\Lambda_b^0 \rightarrow \Lambda_c^{(*)+} D_s^-]}{\mathcal{B}[\Lambda_b^0 \rightarrow \Lambda_c^+ D_s^-]}$	$\mathcal{B}(10^{-3})$ [95]	$\mathcal{B}_{D_s^{*-}} (10^{-3})$	$\frac{\mathcal{B}[\Lambda_b^0 \rightarrow \Lambda_c^{(*)+} D_s^{*-}]}{\mathcal{B}[\Lambda_b^0 \rightarrow \Lambda_c^+ D_s^{*-}]}$	$\mathcal{B}(10^{-3})$ [95]
$ \Lambda_c 1^2 P_{\lambda_2}^{1-}\rangle$	2592	$5.37_{-0.70-1.45}^{+0.50+1.78}$	$0.55_{-0.14}^{+0.092}$	$1.72_{-1.01}^{+1.71}$	$8.23_{-0.82-2.23}^{+0.54+2.73}$	$0.47_{-0.12}^{+0.078}$	$2.28_{-1.29}^{+2.21}$
$ \Lambda_c 1^2 P_{\lambda_2}^{3-}\rangle$	2625	$7.52_{-0.52-2.04}^{+0.14+2.49}$	$0.77_{-0.27}^{+0.17}$	$2.88_{-2.16}^{+4.92}$	$7.02_{-0.34-1.90}^{+0.046+2.32}$	$0.40_{-0.13}^{+0.085}$	$2.41_{-1.52}^{+2.98}$
$ \Lambda_c 2^2 S_{\lambda_2}^{1+}\rangle$	2767	$2.95_{-0.21-0.80}^{+0.25+0.98}$	$0.30_{-0.17}^{+0.091}$	$3.54_{-1.24}^{+1.73}$	$2.29_{-0.22-0.62}^{+0.22+0.76}$	$0.13_{-0.069}^{+0.038}$	$5.29_{-1.84}^{+2.54}$
$ \Lambda_c 1^2 D_{\lambda_2}^{3+}\rangle$	2856	$1.85_{-0.18-0.50}^{+0.18+0.61}$	$0.19_{-0.11}^{+0.059}$		$2.19_{-0.28-0.59}^{+0.25+0.73}$	$0.12_{-0.072}^{+0.039}$	
$ \Lambda_c 1^2 D_{\lambda_2}^{5+}\rangle$	2882	$1.40_{-0.32-0.38}^{+0.28+0.46}$	$0.14_{-0.11}^{+0.056}$		$1.65_{-0.43-0.45}^{+0.35+0.55}$	$0.094_{-0.072}^{+0.036}$	
$ \Lambda_c 2^2 P_{\lambda_2}^{1-}\rangle$	2983 [19]	$0.53_{-0.13-0.14}^{+0.09+0.18}$	$0.055_{-0.043}^{+0.020}$	$0.87_{-0.38}^{+0.46}$	$0.53_{-0.13-0.14}^{+0.095+0.18}$	$0.030_{-0.023}^{+0.011}$	$1.16_{-0.48}^{+0.62}$
$ \Lambda_c 2^2 P_{\lambda_2}^{3-}\rangle$	3005 [19]	$0.65_{-0.22-0.18}^{+0.15+0.22}$	$0.067_{-0.062}^{+0.028}$	$1.69_{-1.23}^{+2.30}$	$0.63_{-0.22-0.17}^{+0.15+0.21}$	$0.036_{-0.031}^{+0.014}$	$1.11_{-0.62}^{+1.07}$
$ \Lambda_c 1^2 F_{\lambda_2}^{5-}\rangle$	3097 [19]	$0.093_{-0.044-0.025}^{+0.028+0.031}$	$0.010_{-0.011}^{+0.004}$		$0.066_{-0.034-0.018}^{+0.021+0.022}$	$0.0037_{-0.0042}^{+0.0017}$	
$ \Lambda_c 1^2 F_{\lambda_2}^{7-}\rangle$	3078 [19]	$0.14_{-0.065-0.037}^{+0.042+0.046}$	$0.014_{-0.016}^{+0.007}$		$0.10_{-0.051-0.027}^{+0.032+0.034}$	$0.0058_{-0.0064}^{+0.0027}$	
$ \Lambda_c 3^2 S_{\lambda_2}^{1+}\rangle$	3130 [19]	$0.083_{-0.035-0.022}^{+0.022+0.027}$	$0.008_{-0.009}^{+0.004}$		$0.036_{-0.015-0.0099}^{+0.0091+0.012}$	$0.0021_{-0.0020}^{+0.0009}$	
$ \Lambda_c 2^2 D_{\lambda_2}^{3+}\rangle$	3189 [19]	$0.061_{-0.026-0.017}^{+0.016+0.020}$	$0.006_{-0.007}^{+0.003}$		$0.035_{-0.014-0.0096}^{+0.0087+0.012}$	$0.0020_{-0.0019}^{+0.0008}$	
$ \Lambda_c 2^2 D_{\lambda_2}^{5+}\rangle$	3209 [19]	$0.035_{-0.022-0.009}^{+0.012+0.011}$	$0.004_{-0.005}^{+0.002}$		$0.018_{-0.011-0.0049}^{+0.0062+0.0059}$	$0.0010_{-0.0013}^{+0.0005}$	

branching fractions can reach up to $\sim 50\%$ due to the uncertainties of the HO parameters. However, the relative branching ratio $\frac{\mathcal{B}[\Lambda_b^0 \rightarrow \Lambda_c^{(*)+} M]}{\mathcal{B}[\Lambda_b^0 \rightarrow \Lambda_c^+ M]}$, as shown in Table IV, bears a small uncertainty of $\sim 10\%$ due to the variation of the baryon HO parameter α_ρ , however, is insensitive to the meson HO parameter β .

III. NUMERICAL RESULTS AND DISCUSSION

A. $\Lambda_b \rightarrow \Lambda_c h^-$

First, we study the weak decay process $\Lambda_b \rightarrow \Lambda_c h^-$ as a test of our model. Our predicted branching fractions for each decay channel are given in Table III. For a comparison, the experimental data and some results from other

theoretical models are listed in the same table as well. From Table III, it is seen that our predicted central values of branching fractions for $\Lambda_b \rightarrow \Lambda_c(\pi^-, K^-, D^-, D_s^-, D_s^{*-})$, $(5.67, 0.31, 0.43, 10.3, 17.5) \times 10^{-3}$, are in good agreement with the experimental data [10]. Furthermore, the predicted branching fraction ratios

$$R_{K/\pi} = \frac{\mathcal{B}[\Lambda_b \rightarrow \Lambda_c K^-]}{\mathcal{B}[\Lambda_b \rightarrow \Lambda_c \pi^-]} \simeq 0.0548_{-0.0007}^{+0.0006} \pm 0.0, \quad (23)$$

$$R_{D/D_s} = \frac{\mathcal{B}[\Lambda_b \rightarrow \Lambda_c D^-]}{\mathcal{B}[\Lambda_b \rightarrow \Lambda_c D_s^-]} \simeq 0.0440_{-0.0009+0.017}^{+0.0007-0.011}, \quad (24)$$

$$R_{D_s^*/D_s} = \frac{\mathcal{B}[\Lambda_b \rightarrow \Lambda_c D_s^{*-}]}{\mathcal{B}[\Lambda_b \rightarrow \Lambda_c D_s^-]} \simeq 1.80_{+0.06}^{-0.04} \pm 0.0, \quad (25)$$

are also consistent with the measured central values, $R_{K/\pi}^{\text{exp}} = 0.0731 \pm 0.0022$, $R_{D/D_s}^{\text{exp}} = 0.042 \pm 0.006$, $R_{D_s^*/D_s}^{\text{exp}} = 1.668 \pm 0.022_{-0.055}^{+0.061}$, respectively.

For the processes $\Lambda_b \rightarrow \Lambda_c(\rho^-, K^{*-}, D^{*-})$, which have not been measured in experiments, the branching fractions are predicted to be $(6.91_{-3.39-2.24}^{+3.08+1.62}, 0.37_{-0.16-0.10}^{+0.18+0.12}, 0.82_{-0.24-0.22}^{+0.25+0.27}) \times 10^{-3}$. From Table III, it is found that there are obviously model dependencies in the various model predictions. For example, for the $\Lambda_b \rightarrow \Lambda_c \rho^-$ process our predicted branching fractions are roughly consistent with those of heavy quark effective theory [99], covariant oscillator quark model [104], covariant light-front quark model [97], however, about a factor of ~ 2 smaller than those predicted in Refs. [95,96,100].

To further understand the branching fractions of the vector meson emission processes, $\mathcal{B}(\Lambda_b \rightarrow \Lambda_c V)$ ($V = \rho^-, K^{*-}, D^*, D_s^*$), we analyze their transition amplitudes. The extracted transition amplitudes for the $\Lambda_b \rightarrow \Lambda_c V$ process are given by

$$\mathcal{M}_{-1/2,-1/2,0}^{1/2,1/2,1,PV} = 32\sqrt{3}\pi^{3/4}C_W\beta^{9/2}T_\alpha F(q^2), \quad (26)$$

$$\mathcal{M}_{-1/2,1/2,-1}^{1/2,1/2,1,PV} = -16\sqrt{6}\pi^{3/4}C_W\beta^{9/2}T_\alpha F(q^2), \quad (27)$$

$$\begin{aligned} \mathcal{M}_{-1/2,-1/2,0}^{1/2,1/2,1,PC} = & -C_W T_\alpha |\mathbf{q}| F(q^2) \left[\alpha_{\lambda_i}^2 \left(2 - \frac{4m_2}{m_3} + \frac{2m_2}{m_4} + \frac{2m_2}{m_5} + \frac{m_{3'}}{m_4} + \frac{m_{3'}}{m_5} \right) \right. \\ & \left. + \alpha_{\lambda_f}^2 \left(2 + \frac{2m_2}{m_4} + \frac{2m_2}{m_5} + \frac{4m_2}{m_{3'}} + \frac{m_{3'}}{m_4} + \frac{m_{3'}}{m_5} \right) \right], \end{aligned} \quad (28)$$

$$\begin{aligned} \mathcal{M}_{-1/2,1/2,-1}^{1/2,1/2,1,PC} = & -\sqrt{2}C_W T_\alpha |\mathbf{q}| F(q^2) \left[\alpha_{\lambda_i}^2 \left(2 + \frac{4m_2}{m_3} - \frac{2m_2}{m_4} + \frac{2m_2}{m_5} - \frac{m_{3'}}{m_4} + \frac{m_{3'}}{m_5} \right) \right. \\ & \left. + \alpha_{\lambda_f}^2 \left(2 - \frac{2m_2}{m_4} + \frac{2m_2}{m_5} + \frac{4m_2}{m_{3'}} - \frac{m_{3'}}{m_4} + \frac{m_{3'}}{m_5} \right) \right], \end{aligned} \quad (29)$$

with

$$C_W = \frac{G_F}{\sqrt{2}} \frac{1}{8\pi^3} V_{cb} V_{45}^* \left(C_1 + \frac{C_2}{3} \right), \quad (30)$$

$$F(q^2) = \exp \left(-\frac{3m_2^2 q^2}{(\alpha_{\lambda_f}^2 + \alpha_{\lambda_i}^2)(2m_2 + m_{3'})^2} \right), \quad (31)$$

$$T_\alpha = \frac{8\sqrt{3}\pi^{3/4}\alpha_{\lambda_f}^3\alpha_{\lambda_i}^3\alpha_{\rho_f}^{3/2}\alpha_{\rho_i}^{3/2}\beta^{3/2}}{(2m_2 + m_{3'})^2(\alpha_{\lambda_f}^2 + \alpha_{\lambda_i}^2)^{5/2}(\alpha_{\rho_f}^2 + \alpha_{\rho_i}^2)^{3/2}}, \quad (32)$$

where $(\alpha_{\rho_i}, \alpha_{\lambda_i})$ and $(\alpha_{\rho_f}, \alpha_{\lambda_f})$ are (ρ, λ) -mode HO parameters of Λ_b and Λ_c , respectively, while β stands for the HO parameters of the emitting mesons. From the amplitudes given in Eqs. (26)–(29), one can see that the contributions

of the parity-violating amplitudes $\mathcal{M}_{-1/2,-1/2,0}^{1/2,1/2,1,PV}$ and $\mathcal{M}_{-1/2,1/2,-1}^{1/2,1/2,1,PV}$ are relatively small due to the suppression of the heavy charmed quark mass, $m_{3'}$. For the $\Lambda_b \rightarrow \Lambda_c D^{*-}, \Lambda_c D_s^{*-}$ processes, the dominant contributions arise from the parity-conserving amplitudes $\mathcal{M}_{-1/2,-1/2,0}^{1/2,1/2,1,PC}$ and $\mathcal{M}_{-1/2,1/2,-1}^{1/2,1/2,1,PC}$ given in Eqs. (28) and (29), where the $\frac{m_{3'}}{m_5} \simeq 3.2$ term plays a crucial role (note that $m_{3'} = m_c, m_5 = m_u$). For the $\Lambda_b \rightarrow \Lambda_c(\rho^-, K^{*-})$ processes, the dominant contribution arise from the parity-conserving amplitude $\mathcal{M}_{-1/2,-1/2,0}^{1/2,1/2,1,PC}$, however, the $\mathcal{M}_{-1/2,1/2,-1}^{1/2,1/2,1,PC}$ contribution is strongly suppressed due to a large cancellations between the main terms $\frac{m_{2(3')}}{m_5}$ and $\frac{m_{2(3')}}{m_4}$. This cancellation mechanism is the main reason why large ratios $\frac{\mathcal{B}(\Lambda_b \rightarrow \Lambda_c D_s^{*-})}{\mathcal{B}(\Lambda_b \rightarrow \Lambda_c \rho^-)} \simeq 2.5_{+0.6}^{-0.4}$ and $\frac{\mathcal{B}(\Lambda_b \rightarrow \Lambda_c D^{*-})}{\mathcal{B}(\Lambda_b \rightarrow \Lambda_c K^{*-})} \simeq 2.2_{+0.5}^{-0.3}$ are predicted in this work.

Finally, it should be mentioned that for the $\Lambda_b \rightarrow \Lambda_c(\pi^-, K^-)$ processes, except for a sign difference, the transition amplitudes $\mathcal{M}_{-1/2, -1/2, 0}^{1/2, 1/2, 0, PV}$ and $\mathcal{M}_{-1/2, -1/2, 0}^{1/2, 1/2, 0, PC}$ have the same forms of those for the $\Lambda_b \rightarrow \Lambda_c V$ process given in Eqs. (26) and (28), respectively. Since the $\mathcal{M}_{-1/2, 1/2, 1}^{1/2, 1/2, 1, PV}$ and $\mathcal{M}_{-1/2, 1/2, -1}^{1/2, 1/2, 1, PC}$ are negligibly small for the $\Lambda_b \rightarrow \Lambda_c(\rho^-, K^{*-})$ processes, we obtain $\mathcal{B}[\Lambda_b \rightarrow \Lambda_c \pi^-] \simeq \mathcal{B}[\Lambda_b \rightarrow \Lambda_c \rho^-]$ and $\mathcal{B}[\Lambda_b \rightarrow \Lambda_c K^-] \simeq \mathcal{B}[\Lambda_b \rightarrow \Lambda_c K^{*-}]$ as those given in Table III.

B. $\Lambda_b \rightarrow \Lambda_c(1P)h^-$

There are two λ -mode $1P$ -wave Λ_c states $|\Lambda_c 1^2 P_{\lambda_2}^{1-}\rangle$ and $|\Lambda_c 1^2 P_{\lambda_2}^{3-}\rangle$ predicted within the quark model, which should correspond to the two well-established resonances $\Lambda_c(2595)^+$ and $\Lambda_c(2625)^+$ listed by PDG. In this work, we study the $\Lambda_b \rightarrow \Lambda_c(2595, 2625)^+ h^-$ ($h^- = \pi^-, \rho^-, K^-, K^{*-}, D^-, D^{*-}, D_s^-, D_s^{*-}$) processes, and our results are given in Table IV.

It is seen that the nonleptonic weak decays associated with the emission of π^- mesons, $\Lambda_b \rightarrow \Lambda_c(2595, 2625)^+ \pi^-$, have large decay rates. The branching fractions are predicted to be

$$\mathcal{B}[\Lambda_b \rightarrow \Lambda_c(2595, 2625)^+ \pi^-] \simeq (5.12_{-1.52-1.39}^{+1.36+1.70}, 8.73_{-2.37-2.37}^{+1.92+2.88}) \times 10^{-3}, \quad (33)$$

the order of magnitude, $\mathcal{O}(10^{-3})$, is consistent with that predicted within the light-front quark model [95] and constituent quark model [106]. The branching fraction ratio between the $\Lambda_c(2595)^+ \pi^-$ and $\Lambda_c(2625)^+ \pi^-$ is estimated to be

$$\frac{\mathcal{B}[\Lambda_b \rightarrow \Lambda_c(2595)^+ \pi^-]}{\mathcal{B}[\Lambda_b \rightarrow \Lambda_c(2625)^+ \pi^-]} \simeq 0.59_{-0.02}^{+0.02}, \quad (34)$$

which is in agreement with the prediction, ~ 0.45 , in Ref. [95].

In experiments, the decay chains $\Lambda_b \rightarrow \Lambda_c(2595, 2625)^+ \pi^-$, with $\Lambda_c(2595, 2625)^+ \rightarrow \Lambda_c^+ \pi^+ \pi^-$, have been observed by the CDF and LHCb collaborations [118, 119]. The branching fractions relative to the $\Lambda_b \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-$ measured by the CDF are $\mathcal{B}[\Lambda_b \rightarrow \Lambda_c(2595)^+ \pi^-] \cdot \mathcal{B}[\Lambda_c(2595)^+ \rightarrow \Lambda_c^+ \pi^+ \pi^-] = (2.3 \pm 0.5 \pm 0.4)\%$ and $\mathcal{B}[\Lambda_b \rightarrow \Lambda_c(2625)^+ \pi^-] \cdot \mathcal{B}[\Lambda_c(2625)^+ \rightarrow \Lambda_c^+ \pi^+ \pi^-] = (6.8 \pm 1.0 \pm 2.3)\%$ [118], which are comparable with the LHCb measured values $(4.4 \pm 1.7_{-0.4}^{+0.6})\%$ and $(4.3 \pm 1.5 \pm 0.3)\%$, respectively. Combining the measured central value $\mathcal{B}[\Lambda_c(2625)^+ \rightarrow \Lambda_c^+ \pi^+ \pi^-] = 50.2\%$ and the theoretical prediction $\mathcal{B}[\Lambda_c(2595)^+ \rightarrow \Lambda_c^+ \pi^+ \pi^-] = 39.9\%$ in Ref. [38], from the data measured at CDF one can extract a branching

fraction ratio $\frac{\mathcal{B}[\Lambda_b \rightarrow \Lambda_c(2595)^+ \pi^-]}{\mathcal{B}[\Lambda_b \rightarrow \Lambda_c(2625)^+ \pi^-]} \simeq 0.42$ (central value), which is close to our prediction in Eq. (34).

Due to the large CKM matrix element $V_{cs} = 0.987$, the nonleptonic weak decays associated D_s and D_s^* emitting, $\Lambda_b \rightarrow \Lambda_c(2595, 2625)^+ D_s^-$, $\Lambda_c(2595, 2625)^+ D_s^{*-}$, have large decay rates as well as that of the π^- meson emitting processes. The order of magnitude of the branching fractions can reach up to $\mathcal{O}(10^{-3})$. The $\Lambda_b \rightarrow \Lambda_c(2595, 2625)^+ D_s^{(*)-}$ processes were also studied within the light-front quark model in Ref. [95], where the predicted branching fractions are systematically a factor of ~ 3 smaller than ours. According to our predictions, the branching fractions of $\Lambda_b \rightarrow \Lambda_c(2595, 2625)^+ D_s^{(*)-}$ are only a factor of ~ 2 smaller those of $\Lambda_b \rightarrow \Lambda_c D_s^{(*)-}$, thus, with the accumulation of the Λ_b sample, the $\Lambda_c(2595)^+ D_s^{(*)-}$ and $\Lambda_c(2625)^+ D_s^{(*)-}$ channels may have great potential to be observed in future experiments.

C. $\Lambda_b \rightarrow \Lambda_c(1D_\lambda)h^-$

There are two λ -mode $1D$ -wave Λ_c states $|\Lambda_c 1^2 D_{\lambda_2}^{3+}\rangle$ and $|\Lambda_c 1^2 D_{\lambda_2}^{5+}\rangle$ predicted within the quark model. The $\Lambda_c(2860)3/2^+$ and $\Lambda_c(2880)5/2^+$ resonances observed in experiments favor the λ -mode $1D$ -wave states [12–19, 21–24, 27, 29, 35–44]. With this assignment, we study the $\Lambda_b \rightarrow \Lambda_c(2860, 2880)^+ h^-$ ($h^- = \pi^-, \rho^-, K^-, K^{*-}, D^-, D^{*-}, D_s^-, D_s^{*-}$) processes, and our results are given in Table IV. It is found that the Λ_b has large decay rates into both the $\Lambda_c(2860)^+ \pi^-$ and $\Lambda_c(2880)^+ \pi^-$ final states. The branching fractions are predicted to be

$$\mathcal{B}[\Lambda_b \rightarrow \Lambda_c(2860, 2880)^+ \pi^-] \simeq (4.09_{-0.40-1.11}^{+0.10+1.36}, 4.56_{-0.21-1.24}^{+0.16+1.51}) \times 10^{-3}, \quad (35)$$

which are comparable to that of the $\Lambda_c^+ \pi^-$ channel.

The $\Lambda_b \rightarrow \Lambda_c(2860, 2880)^+ \pi^-$ processes have been observed by the LHCb collaboration [82]. From the data, they extract a branching fraction ratio

$$\frac{\mathcal{B}[\Lambda_b \rightarrow \Lambda_c(2860)^+ \pi^-] \cdot \mathcal{B}[\Lambda_c(2860)^+ \rightarrow D^0 p]}{\mathcal{B}[\Lambda_b \rightarrow \Lambda_c(2880)^+ \pi^-] \cdot \mathcal{B}[\Lambda_c(2880)^+ \rightarrow D^0 p]} \simeq 4.54_{-0.39}^{+0.51} \pm 0.12. \quad (36)$$

In a recent work [28], the partial widths of $\Lambda_c(2860, 2880)^+$ into the $D^0 p$ channel are predicted to be $\Gamma[\Lambda_c(2860)^+ \rightarrow D^0 p] \simeq 22$ MeV and $\Gamma[\Lambda_c(2880)^+ \rightarrow D^0 p] \simeq 0.35$ MeV. Combining these predicted partial widths with the measured widths of $\Gamma_{\Lambda_c(2860)} \simeq 67.6$ MeV and $\Gamma_{\Lambda_c(2880)} \simeq 5.6$ MeV from PDG, we estimate the branching fractions of $\Lambda_c(2860, 2880)$ into the $D^0 p$ as $\mathcal{B}[\Lambda_c(2860)^+ \rightarrow D^0 p] \simeq 32.5\%$ and $\mathcal{B}[\Lambda_c(2880)^+ \rightarrow D^0 p] \simeq 6.3\%$. Further combining the measured ratio given in Eq. (36), one can extract an

experimental ratio of $\frac{\mathcal{B}[\Lambda_b \rightarrow \Lambda_c(2860)^+\pi^-]}{\mathcal{B}[\Lambda_b \rightarrow \Lambda_c(2880)^+\pi^-]} \simeq 0.88$, which is in good agreement with the value,

$$\frac{\mathcal{B}[\Lambda_b \rightarrow \Lambda_c(2860)^+\pi^-]}{\mathcal{B}[\Lambda_b \rightarrow \Lambda_c(2880)^+\pi^-]} \simeq 0.90_{-0.05}^{+0.05}, \quad (37)$$

predicted in theory. Thus, the $\Lambda_c(2860)3/2^+$ and $\Lambda_c(2880)5/2^+$ production data via Λ_b weak decays from LHCb support their λ -mode $1D$ -wave assignment.

D. $\Lambda_b \rightarrow \Lambda_c(2P_\lambda)h^-$

There are two λ -mode $2P$ -wave states, $|\Lambda_c 2^2 P_{\lambda 2}^{1-}\rangle$ and $|\Lambda_c 2^2 P_{\lambda 2}^{3-}\rangle$, with masses of ~ 3.0 GeV according to various quark model predictions [11,19,20,22,23,30,45,47,48,51,53,120–123]. The weak decays of Λ_b may provide a good opportunity to establish the $2P$ -wave Λ_c states. In this work, we study the $\Lambda_b \rightarrow \Lambda_c(2P_\lambda)^+ h^-$ ($h^- = \pi^-, \rho^-, K^-, K^{*-}, D^-, D^{*-}, D_s^-, D_s^{*-}$) processes, and our results are given in Table IV. It is found that the Λ_b baryon has large decay rates into both $|\Lambda_c 2^2 P_{\lambda 2}^{1-}\rangle \pi^-$ and $|\Lambda_c 2^2 P_{\lambda 2}^{3-}\rangle \pi^-$ channels. The branching fraction ratios relative to $\Lambda_c \pi^-$ can reach up to

$$\frac{\mathcal{B}[\Lambda_b \rightarrow |\Lambda_c 2^2 P_{\lambda 2}^{1-}\rangle \pi^-]}{\mathcal{B}[\Lambda_b \rightarrow \Lambda_c^+ \pi^-]} \simeq 0.42_{+0.40}^{-0.18}, \quad (38)$$

$$\frac{\mathcal{B}[\Lambda_b \rightarrow |\Lambda_c 2^2 P_{\lambda 2}^{3-}\rangle \pi^-]}{\mathcal{B}[\Lambda_b \rightarrow \Lambda_c^+ \pi^-]} \simeq 0.69_{+0.71}^{-0.31}, \quad (39)$$

which are about 3–4 times larger than the central values predicted in Ref. [95]. There have been few studies of the Λ_b decaying into the higher $2P$ -wave Λ_c states before. More theoretical studies are expected to be carried out in the future to better understand the $\Lambda_b \rightarrow \Lambda_c(2P_\lambda)h^-$ processes.

The $\Lambda_b \rightarrow |\Lambda_c 2^2 P_{\lambda 2}^{3-}\rangle \pi^-$ process may have been observed in experiments if the $\Lambda_c(2940)^+$ resonance is assigned to the $|\Lambda_c 2^2 P_{\lambda 2}^{3-}\rangle$ as suggested in the literature [41,46–48]. In 2017, the $\Lambda_b \rightarrow \Lambda_c(2940)^+\pi^- \rightarrow D^0 p \pi^-$ was observed by the LHCb collaboration [82]. It is found that the spin-parity quantum numbers of $\Lambda_c(2940)^+$ tend to be $J^P = 3/2^-$. Furthermore, the collaboration extracted the following branching fraction ratio [82],

$$\frac{\mathcal{B}[\Lambda_b \rightarrow \Lambda_c(2940)^+\pi^-] \cdot \mathcal{B}[\Lambda_c(2940)^+ \rightarrow D^0 p]}{\mathcal{B}[\Lambda_b \rightarrow \Lambda_c(2880)^+\pi^-] \cdot \mathcal{B}[\Lambda_c(2880)^+ \rightarrow D^0 p]} \simeq 0.83_{-0.10}^{+0.31} \pm 0.06. \quad (40)$$

Considering $\Lambda_c(2940)$ as the $|\Lambda_c 2^2 P_{\lambda 2}^{3-}\rangle$ assignment, the branching fraction into the $D^0 p$ channel is estimated to be $\mathcal{B}[\Lambda_c(2940)^+ \rightarrow D^0 p] \simeq 40\%$ [28,46]. Together with $\mathcal{B}[\Lambda_c(2880)^+ \rightarrow D^0 p] \simeq 6.3\%$ extracted in Sec. III C, from

Eq. (40) one can extract the ratio $\frac{\mathcal{B}[\Lambda_b \rightarrow \Lambda_c(2940)^+\pi^-]}{\mathcal{B}[\Lambda_b \rightarrow \Lambda_c(2880)^+\pi^-]}$, the central value, ~ 0.13 , is about one order of magnitude smaller than our quark model prediction, $\sim 0.92_{-0.10}^{+0.14}$. Thus, we will face a challenge if the $\Lambda_c(2940)^+$ is assigned as a $2P$ -wave Λ_c state. It should be mentioned that the mass of the $\Lambda_c(2940)^+$ is about 60–100 MeV lower than the predictions of various quark models [11,19,22,50], which indicates it may not be a conventional baryon, but rather a molecular state as suggested in the literature [56–77].

The $\Lambda_c(2910)^+$ resonance recently observed in the $\Sigma_c(2455)^{0,++}\pi^\pm$ channels at Belle [124] may be assigned to $|\Lambda_c 2^2 P_{\lambda 2}^{1-}\rangle$ as suggested in the literature [47–49,125]. With this assignment, the $\Lambda_c(2910)^+$ resonance should have a large decay rate into $D^0 p$ with a branching fraction of $\mathcal{B}[\Lambda_c(2910)^+ \rightarrow D^0 p] \simeq 38\%$ [28,46]. Considering the $\Lambda_c(2910, 2940)^+$ as the $2P$ -wave doublet, we predict that

$$\frac{\mathcal{B}[\Lambda_b \rightarrow \Lambda_c(2910)^+\pi^-] \cdot \mathcal{B}[\Lambda_c(2910)^+ \rightarrow D^0 p]}{\mathcal{B}[\Lambda_b \rightarrow \Lambda_c(2940)^+\pi^-] \cdot \mathcal{B}[\Lambda_c(2940)^+ \rightarrow D^0 p]} \simeq 0.58_{-0.02}^{+0.02}. \quad (41)$$

This fairly large ratio indicates that with the accumulation of more Λ_b samples, the LHCb collaboration should establish the $\Lambda_c(2910)^+$ in the $\Lambda_b \rightarrow \Lambda_c(2910)^+\pi^- \rightarrow D^0 p \pi^-$ decay chain in forthcoming experiments as well.

To finally establish the λ -mode $2P$ -wave states and clarify the nature of the $\Lambda_c(2910)^+$ and $\Lambda_c(2940)^+$ resonances, more accurate observations of the $\Lambda_b \rightarrow \Lambda_c(2910, 2940)^+\pi^- \rightarrow D^0 p \pi^-$ processes and the measurements of the relative fraction ratios $\frac{\mathcal{B}[\Lambda_b \rightarrow \Lambda_c(2910, 2940)^+\pi^-]}{\mathcal{B}[\Lambda_b \rightarrow \Lambda_c^+\pi^-]}$ are expected to be carried out in future experiments.

E. $\Lambda_b \rightarrow \Lambda_c(2S, 3S)h^-$

The λ -mode $2S$ and $3S$ states, denoted by $|\Lambda_c 2^2 S_{\lambda 2}^{1+}\rangle$ and $|\Lambda_c 3^2 S_{\lambda 2}^{1+}\rangle$, belong to the first and second radial excitations of Λ_c , respectively. The masses of the $2S$ and $3S$ states are predicted to be ~ 2.8 and 3.1 GeV, respectively, in quark models [11,19,20]. In this work, we calculate the branching fraction ratios of the $\Lambda_b \rightarrow |\Lambda_c 2^2 S_{\lambda 2}^{1+}\rangle h^-$, $|\Lambda_c 3^2 S_{\lambda 2}^{1+}\rangle h^-$, processes, and the results are given in Table IV.

The $\Lambda_c(2765)^+$ observed in the $\Lambda_c^+\pi^-\pi^+$ final state by the CLEO collaboration may be a good candidate of the $|\Lambda_c 2^2 S_{\lambda 2}^{1+}\rangle$ as suggested in the literature [12,49,53,81]. Considering the $\Lambda_c(2765)^+$ as the $|\Lambda_c 2^2 S_{\lambda 2}^{1+}\rangle$ state, the branching ratio between $\Lambda_c(2765)^+\pi^-$ and $\Lambda_c^+\pi^-$ channels is predicted to be a fairly large value,

$$\frac{\mathcal{B}[\Lambda_b \rightarrow \Lambda_c(2765)^+\pi^-]}{\mathcal{B}[\Lambda_b \rightarrow \Lambda_c^+\pi^-]} \simeq 1.01_{-0.60}^{+0.33}. \quad (42)$$

It should be mentioned that this branching ratio predicted in this work is about 3 times larger than that of the light-front

quark model approach [95]. According to our prediction, the $\Lambda_c(2765)^+$, as a radial excitation of Λ_c^+ , should have a large potential to be established by using the decay chain $\Lambda_b \rightarrow \Lambda_c(2765)^+\pi^- \rightarrow (\Sigma_c^{(*)++0}\pi^{-,+})\pi^- \rightarrow (\Lambda_c^+\pi^+\pi^-)\pi^-$.

The high-lying radial excitation $|\Lambda_c 3^2S_{\lambda_2}^{1+}\rangle$ is still missing. It is found that there is a sizeable production rate for this $3S$ state via the pionic weak decay of the Λ_b baryon. Taking the predicted mass $M = 3130$ MeV [19] for $|\Lambda_c 3^2S_{\lambda_2}^{1+}\rangle$, we have

$$\frac{\mathcal{B}[\Lambda_b \rightarrow |\Lambda_c 3^2S_{\lambda_2}^{1+}\rangle\pi^-]}{\mathcal{B}[\Lambda_b \rightarrow \Lambda_c^+\pi^-]} \simeq 0.19_{+0.09}^{-0.09}. \quad (43)$$

The production rate of the $3S$ state is about 5 times smaller than that of the $2S$ state. According to quark model predictions, the $|\Lambda_c 3^2S_{\lambda_2}^{1+}\rangle$ dominantly decays into the $D^{*0}p$ and $D^{*+}n$ channels with a comparable branching fraction, $\sim 45\%$. To search for the $|\Lambda_c 3^2S_{\lambda_2}^{1+}\rangle$ state, the $\Lambda_b \rightarrow \Lambda_c(3S)\pi^- \rightarrow D^{*0}p\pi^-$ decay chain is worth observing in future experiments.

F. $\Lambda_b \rightarrow \Lambda_c(2D, 1F)h^-$

There are two λ -mode $2D$ -wave states, $|\Lambda_c 2^2D_{\lambda_2}^{3+}\rangle$ and $|\Lambda_c 2^2D_{\lambda_2}^{5+}\rangle$, and two λ -mode $1F$ -wave states, $|\Lambda_c 1^2F_{\lambda_2}^{5-}\rangle$ and $|\Lambda_c 1^2F_{\lambda_2}^{7-}\rangle$ according to quark model classification. These states are still missing. In theory, the masses for the $1F$ and $2D$ -wave Λ_c states are predicted to be ~ 3.1 and ~ 3.2 GeV, respectively [11,19,20,45,47,48,51,53]. In this work, using the predicted masses from Ref. [19] we calculate the branching fraction ratios of the $\Lambda_b \rightarrow \Lambda_c(2D_\lambda, 1F_\lambda)h^-$ ($h^- = \pi^-, \rho^-, K^-, K^{*-}, D^-, D^{*-}, D_s^-, D_s^{*-}$) processes for the first time, and our results are given in Table IV.

It is found that both the $1F$ and $2D$ -wave Λ_c states have significant production rates via the pionic nonleptonic weak decays of Λ_b . The branching ratios relative to $\Lambda_c^+\pi$ are predicted to be

$$\frac{\mathcal{B}[\Lambda_b \rightarrow |\Lambda_c 2^2D_{\lambda_2}^{3+}\rangle\pi^-]}{\mathcal{B}[\Lambda_b \rightarrow \Lambda_c^+\pi^-]} \simeq 0.19_{+0.27}^{-0.10},$$

$$\frac{\mathcal{B}[\Lambda_b \rightarrow |\Lambda_c 2^2D_{\lambda_2}^{5+}\rangle\pi^-]}{\mathcal{B}[\Lambda_b \rightarrow \Lambda_c^+\pi^-]} \simeq 0.20_{+0.31}^{-0.11}, \quad (44)$$

$$\frac{\mathcal{B}[\Lambda_b \rightarrow |\Lambda_c 1^2F_{\lambda_2}^{5-}\rangle\pi^-]}{\mathcal{B}[\Lambda_b \rightarrow \Lambda_c^+\pi^-]} \simeq 0.19_{+0.22}^{-0.09},$$

$$\frac{\mathcal{B}[\Lambda_b \rightarrow |\Lambda_c 1^2F_{\lambda_2}^{7-}\rangle\pi^-]}{\mathcal{B}[\Lambda_b \rightarrow \Lambda_c^+\pi^-]} \simeq 0.26_{+0.30}^{-0.12}. \quad (45)$$

According to the predictions of the OZI-allowed strong decays of the excited Λ_c states in Ref. [45], the $|\Lambda_c 2^2D_{\lambda_2}^{5+}\rangle$ and $|\Lambda_c 1^2F_{\lambda_2}^{5-}\rangle$ states have significant decay rates into the D^0p channel with a branching fraction of $\sim 20\% - 30\%$. While the $|\Lambda_c 2^2D_{\lambda_2}^{3+}\rangle$ and $|\Lambda_c 1^2F_{\lambda_2}^{7-}\rangle$ states have significant decay rates into the $D^{*0}p$ channel with a branching

fraction of $\sim 40\% - 50\%$. Thus, the $1F$ and $2D$ -wave Λ_c states are likely to be established in the decays $\Lambda_b \rightarrow \Lambda_c(2D, 1F)\pi^- \rightarrow D^0p\pi^-, D^{*0}p\pi^-$.

IV. SUMMARY

In this work, we systematically study the production of the Λ_c baryon and its excitations via the nonleptonic weak decays of the Λ_b baryon within a constituent quark model. The existing branching fractions measured in experiments for the $\Lambda_b \rightarrow \Lambda_c(\pi^-, K^-, D^-, D_s^-, D_s^{*-})$ processes can be well described by theoretical calculations.

Furthermore, we present our predictions of the production rates of the $2S$ -, $3S$ -, $1P$ -, $2P$ -, $1D$ -, $2D$ -, and $1F$ -wave Λ_c^+ excitations in the $\Lambda_b \rightarrow \Lambda_c^*(\pi^-, \rho^-, K^-, K^{*-}, D^-, D^{*-}, D_s^-, D_s^{*-})$ processes. It is found that the excited Λ_c baryons have a large production rate in the Λ_b nonleptonic weak decay process associated with π^- meson emission. Considering the $\Lambda_c(2595, 2625)^+$ as the $1P$ -wave Λ_c^+ states, while $\Lambda_c(2860, 2880)^+$ as the $1D$ -wave states, the observations of the $\Lambda_b \rightarrow \Lambda_c(2595, 2625)^+\pi^- \rightarrow \Lambda_c^+\pi^-\pi^+\pi^-$ and $\Lambda_b \rightarrow \Lambda_c(2860, 2880)^+\pi^- \rightarrow D^0p\pi^-$ decays are consistent with our quark model predictions as well. However, if we assign the $\Lambda_c(2940)^+$ as a $2P$ -wave Λ_c state, we cannot explain the $\Lambda_b \rightarrow \Lambda_c(2940)^+\pi^- \rightarrow D^0p\pi^-$ decay rate observed at LHCb.

To establish the $2P$ -wave Λ_c states and clarify the nature of the $\Lambda_c(2910)^+$ and $\Lambda_c(2940)^+$ resonances, more accurate observations of the $\Lambda_b \rightarrow \Lambda_c(2910, 2940)^+\pi^- \rightarrow D^0p\pi^-$ processes are expected to be carried out in future experiments.

To establish the $2S$ -wave Λ_c state and clarify the nature of the $\Lambda_c(2765)^+$, the decay chain $\Lambda_b \rightarrow \Lambda_c(2765)^+\pi^- \rightarrow (\Sigma_c^{(*)++0}\pi^{-,+})\pi^- \rightarrow (\Lambda_c^+\pi^+\pi^-)\pi^-$ is expected to be observed in future experiments.

To search for the high-lying $3S$ -, $1F$ -, and $2D$ -wave Λ_c states, the $\Lambda_b \rightarrow \Lambda_c(3S)\pi^- \rightarrow D^{*0}p\pi^-$, and $\Lambda_b \rightarrow \Lambda_c(2D, 1F)\pi^- \rightarrow D^0p\pi^-, D^{*0}p\pi^-$ decays are worth observing in future experiments.

Finally, it should be pointed out that there is a notable model dependency in the predictions of the $\Lambda_b \rightarrow \Lambda_c(\rho^-, K^{*-})$ decays. These processes are also expected to be observed in future experiments to test different model predictions.

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DATA AVAILABILITY

The data that support the findings of this article are openly available [1,19,28,38,46,82,95–104,106,118,119].

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