Strong decays of the higher excited Λ_Q and Σ_Q baryons

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In this work, we perform a systematic study of the strong decays for the higher singly heavy baryon resonances $\Lambda_Q(3S)$, $\Lambda_Q(2P)$, $\Lambda_Q(2D)$, $\Lambda_Q(1F)$, $\Sigma_Q(3S)$, $\Sigma_Q(2P)$, $\Sigma_Q(2D)$, and $\Sigma_Q(1F)$ within the 3P_0 model. Our results show that most of the λ -mode higher excited Λ_Q and Σ_Q states have a relatively narrow width, and mainly decay into two-body final states with one heavy meson plus one light baryon. Our calculations provide abundant theoretical information and demonstrate the general feature for these higher states, which may be valuable for future experimental searches and establishing the singly heavy baryon spectrum.

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I. INTRODUCTION

Recently, the observations of the singly heavy baryon spectrum have achieved significant progress in experiments. In 2017, a new charmed resonance $\Lambda_c(2860)$ was observed in the $D^0 p$ final state by the LHCb Collaboration [1]. Just in the same year, they also found five narrow Ω_c resonances in the $\Xi_c K$ invariant mass [2], and most of them were confirmed by the Belle Collaboration subsequently [3]. In 2018, two bottom resonances $\Sigma_b(6097)$ and $\Xi_b(6227)$ were found in the $\Lambda_b \pi$ and $\Lambda_b K$ final states at LHCb, respectively [4,5]. In 2019, the LHCb Collaboration reported the observation of two bottom baryon resonances $\Lambda_b(6146)$ and $\Lambda_b(6152)$ in the $\Lambda_b \pi^+ \pi^-$ channel, which are good candidates of the D -wave Λ_b doublet [6]. The experimental progress provides fruitful information for us to establish the low-lying singly heavy baryon spectrum.

Focusing on the nonstrange sectors Λ_Q and Σ_Q ($Q = c, b$), plenty of theoretical works have been made to investigate these low-lying singly heavy baryons [7–34]. In the traditional quark model, the Λ_Q and Σ_Q states belong to the antisymmetric flavor structure $\bar{3}_F$ and symmetric flavor structure 6_F , respectively. Take the low-lying Λ_c spectrum for example, the $\Lambda_c(2286)$ is the ground Λ_c state, and the $\Lambda_c(2595)$ and $\Lambda_c(2625)$ can be explained as the two

P -wave states [35–38]. The $\Lambda_c(2765)$ can be interpreted as the $\Lambda_c(2S)$ state, whose isospin has been confirmed to be zero by the Belle Collaboration [39]. The $\Lambda_c(2860)$ and $\Lambda_c(2880)$ resonances are consistent with the theoretical predictions of the $\Lambda_c(1D)$ doublet with $J^P = 3/2^+$ and $J^P = 5/2^+$, respectively [40–42]. Under this conventional interpretation, the low-lying λ -mode Λ_c spectrum with $N = 0, 1$ and 2 shells has been established, and is presented in Fig. 1. Other theoretical investigations of the low-lying Σ_c , Λ_b , and Σ_b spectra also achieve great successes. More interpretations and detailed discussions of these singly heavy baryons can be found in Refs. [43–47].

Above the DN threshold, three Λ_Q resonances $\Lambda_c(2860)$, $\Lambda_c(2880)$, and $\Lambda_c(2940)$ have been found in experiments. Although the $\Lambda_c(2860)$ and $\Lambda_c(2880)$ lie above the DN threshold, their partial widths decaying into the DN channel are small for the limited phase space. The $\Lambda_c(2940)$

FIG. 1. The mass spectrum of the λ -mode Λ_c family.

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resonance may favor the λ -mode $J^P = 3/2^- \Lambda_c(2P)$ state in the conventional quark model [1,9,10,48], which is the only higher excited Λ_c state in the $N = 3$ shell. Unlike $\Lambda_c(2860)$ and $\Lambda_c(2880)$, the $\Lambda_c(2940)$ has large partial decay width of DN decay mode [48].

It can be noticed that the dominant decay modes of low-lying singly heavy baryons are heavy baryon plus light meson channels. While for the high-lying states, the heavy meson plus light baryon channels, such as $D^{(*)}N$, $D^{(*)}\Delta$, $B^{(*)}N$, and $B^{(*)}\Delta$, are open, and these channels may be the dominant decay modes. Especially, the ρ -mode Λ_Q and Σ_Q states decaying into the heavy meson plus light baryon final states should be highly suppressed since the light quark system can be regarded as the spectator. If one observes a new resonance in $D^{(*)}N$, $D^{(*)}\Delta$, $B^{(*)}N$, or $B^{(*)}\Delta$ channel, this resonance strongly favors the λ -mode assignment.

Except for the $\Lambda_c(2940)$, the theoretical attentions are not enough for the higher Λ_Q and Σ_Q excitations with $N=3$ and 4 shells. There are few investigations of the strong decays for these higher Λ_Q and Σ_Q resonances, although some quark model studies of the mass spectra can be found in the literature [7–14]. In fact, the decay properties of the higher Λ_Q and Σ_Q excitations are crucial for our searching for them in experiments. If the higher resonances dominantly decay into the channels with one heavy meson plus one light baryon, they may be relatively easy to be observed in these special channels by future LHCb and BelleII experiments just as the $\Lambda_c(2940)$ resonance has been observed in the $D^0 p$ final state. In this work, we study the strong decays of the higher excited $\Lambda_Q(3S)$, $\Lambda_Q(2P)$, $\Lambda_Q(2D)$, $\Lambda_Q(1F)$, $\Sigma_Q(3S)$, $\Sigma_Q(2P)$, $\Sigma_Q(2D)$, and $\Sigma_Q(1F)$ states within the 3P_0 quark pair creation model. Our results indicate that most of the λ -mode higher excited Λ_Q and Σ_Q states have relatively narrow total widths, and mainly decay into the heavy meson plus light baryon final states. Our predictions show the general feature and provide helpful theoretical information for these higher states, which may be valuable for future experimental searches.

This paper is organized as follows. The formulas of the quark pair creation model and adopted notations are briefly introduced in Sec. II. The strong decay behaviors of the higher excited Λ_Q and Σ_Q baryons are estimated in Sec. III and Sec. IV, respectively. A short summary is presented in the last section.

II. 3P_0 MODEL

In present work, the 3P_0 model is adopted to estimate the Okubo-Zweig-Iizuka-allowed two-body strong decays of the higher excited Λ_Q and Σ_Q baryons. This model has been widely employed to investigate the strong decays of conventional hadrons and meet with considerable successes [49–59]. For a heavy baryon A , it can decay into two final states B and C via a $J^{PC} = 0^{++}$ quark-antiquark pair [49], and the transition operator can be taken as

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

where γ is a dimensionless constant of the $q_4 \bar{q}_5$ pair-production strength. $\mathbf{p}_4$ and $\mathbf{p}_5$ are the momenta of the created quark q_4 and antiquark $\bar{q}_5$, respectively. The P -wave momentum-space distribution of the $q_4 \bar{q}_5$ can be described by the solid harmonic polynomial $\mathcal{Y}_1^m(\mathbf{p}) \equiv |p| Y_1^m(\theta_p, \phi_p)$. $\chi_{1,-m}^{45}$, $\phi_0^{45} = (u\bar{u} + d\bar{d} + s\bar{s})/\sqrt{3}$, and $\omega_0^{45} = \delta_{ij}$ are the spin triplet, flavor singlet, and color singlet wave functions of the $q_4 \bar{q}_5$, respectively. The $b_{4i}^\dagger(\mathbf{p}_4) d_{4j}^\dagger(\mathbf{p}_5)$ stands for the creation operators, where the i and j are the color indices.

The definitions of the mock states are adopted. For instance, the total wave function of initial baryon A can be taken as [60]

$$\begin{aligned} & |A(n_A^{2S_A+1} L_A J_A M_{J_A})(\mathbf{p}_A)\rangle \\ & \equiv \sqrt{2E_A} \sum_{M_{L_A}, M_{S_A}} \langle L_A M_{L_A} S_A M_{S_A} | J_A M_{J_A} \rangle \\ & \times \int d^3\mathbf{p}_1 d^3\mathbf{p}_2 d^3\mathbf{p}_3 \delta^3(\mathbf{p}_1 + \mathbf{p}_2 + \mathbf{p}_3 - \mathbf{p}_A) \\ & \times \psi_{n_A L_A M_{L_A}}(\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3) \chi_{S_A M_{S_A}}^{123} \phi_A^{123} \omega_A^{123} \\ & \times |q_1(\mathbf{p}_1) q_2(\mathbf{p}_2) q_3(\mathbf{p}_3)\rangle, \end{aligned} \quad (2)$$

which satisfies the normalization condition

$$\langle A(\mathbf{p}_A) | A(\mathbf{p}'_A) \rangle = 2E_A \delta^3(\mathbf{p}_A - \mathbf{p}'_A). \quad (3)$$

The $\mathbf{p}_A$, $\mathbf{p}_1$, $\mathbf{p}_2$, and $\mathbf{p}_3$ are the momenta of the baryon A , quark q_1 , quark q_2 , and quark q_3 , respectively. E_A is the total energy of the baryon A . $\chi_{S_A M_{S_A}}^{123}$, ϕ_A^{123} , ω_A^{123} , $\psi_{n_A L_A M_{L_A}}(\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3)$ are the spin, flavor, color, and space wave functions, respectively. The definitions final states B and C are similar to that of initial state A , which can be found in Ref. [53].

For the decay of the singly heavy baryons Λ_Q and Σ_Q , three possible rearrangements exist

$$A(q_1, q_2, Q_3) + P(q_4, \bar{q}_5) \rightarrow B(q_2, q_4, Q_3) + C(q_1, \bar{q}_5), \quad (4)$$

FIG. 2. The baryon decay process $A \rightarrow B + C$ in the 3P_0 model.

$$A(q_1, q_2, Q_3) + P(q_4, \bar{q}_5) \rightarrow B(q_1, q_4, Q_3) + C(q_2, \bar{q}_5), \quad (5)$$

$$A(q_1, q_2, Q_3) + P(q_4, \bar{q}_5) \rightarrow B(q_1, q_2, q_4) + C(Q_3, \bar{q}_5), \quad (6)$$

which are also performed in Fig. 2. It can be noticed that the first and second cases correspond to the heavy baryon plus the light meson channels, while the third one denotes the light baryon plus the heavy meson decay mode.

The helicity amplitude $\mathcal{M}^{M_{J_A} M_{J_B} M_{J_C}}$ of the decay process $A \rightarrow B + C$ can be related to the S matrix

$$\langle f|S|i\rangle = I - i2\pi\delta(E_f - E_i)\mathcal{M}^{M_{J_A} M_{J_B} M_{J_C}}. \quad (7)$$

Take the $A(q_1, q_2, b_3) + P(q_4, \bar{q}_5) \rightarrow B(q_1, q_4, b_3) + C(q_2, \bar{q}_5)$ shown in Fig. 1(b) as an example, the helicity amplitude $\mathcal{M}^{M_{J_A} M_{J_B} M_{J_C}}$ can be expressed as,

$$\begin{aligned} & \delta^3(\mathbf{p}_B + \mathbf{p}_C - \mathbf{p}_A)\mathcal{M}^{M_{J_A} M_{J_B} M_{J_C}} \\ &= -\gamma\sqrt{8E_A E_B E_C} \sum_{M_{\rho_A}} \sum_{M_{L_A}} \sum_{M_{\rho_B}} \sum_{M_{L_B}} \sum_{M_{S_1}, M_{S_3}, M_{S_4}, m} \langle j_A M_{j_A} S_3 M_{S_3} | J_A M_{J_A} \rangle \langle L_{\rho_A} M_{L_{\rho_A}} L_{\lambda_A} M_{L_{\lambda_A}} | L_A M_{L_A} \rangle \\ & \times \langle L_A M_{L_A} S_{12} M_{S_{12}} | j_A M_{j_A} \rangle \langle S_1 M_{S_1} S_2 M_{S_2} | S_{12} M_{S_{12}} \rangle \langle j_B M_{j_B} S_3 M_{S_3} | J_B M_{J_B} \rangle \langle L_{\rho_B} M_{L_{\rho_B}} L_{\lambda_B} M_{L_{\lambda_B}} | L_B M_{L_B} \rangle \\ & \times \langle L_B M_{L_B} S_{14} M_{S_{14}} | j_B M_{j_B} \rangle \langle S_1 M_{S_1} S_4 M_{S_4} | S_{14} M_{S_{14}} \rangle \langle 1m1 - m | 00 \rangle \langle S_4 M_{S_4} S_5 M_{S_5} | 1 - m \rangle \\ & \times \langle L_C M_{L_C} S_C M_{S_C} | J_C M_{J_C} \rangle \langle S_2 M_{S_2} S_5 M_{S_5} | S_C M_{S_C} \rangle \langle \phi_B^{143} \phi_C^{25} | \phi_A^{123} \phi_0^{45} \rangle I_{M_{L_B} M_{L_C}}^{M_{L_A} m}(\mathbf{p}), \end{aligned} \quad (8)$$

where $\langle \phi_B^{143} \phi_C^{25} | \phi_A^{123} \phi_0^{45} \rangle$ and $I_{M_{L_B} M_{L_C}}^{M_{L_A} m}(\mathbf{p})$ are the overlaps of the flavor part and space part, respectively. Here, the overlap of space part $I_{M_{L_B} M_{L_C}}^{M_{L_A} m}(\mathbf{p})$ can be expressed as

$$\begin{aligned} I_{M_{L_B} M_{L_C}}^{M_{L_A} m}(\mathbf{p}) &= \int d^3\mathbf{p}_1 d^3\mathbf{p}_2 d^3\mathbf{p}_3 d^3\mathbf{p}_4 d^3\mathbf{p}_5 \delta^3(\mathbf{p}_1 + \mathbf{p}_2 + \mathbf{p}_3 - \mathbf{p}_A) \delta^3(\mathbf{p}_4 + \mathbf{p}_5) \delta^3(\mathbf{p}_1 + \mathbf{p}_4 + \mathbf{p}_3 - \mathbf{p}_B) \delta^3(\mathbf{p}_2 + \mathbf{p}_5 - \mathbf{p}_C) \\ & \times \psi_B^*(\mathbf{p}_1, \mathbf{p}_4, \mathbf{p}_3) \psi_C^*(\mathbf{p}_2, \mathbf{p}_5) \psi_A(\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3) \mathcal{Y}_1^m\left(\frac{\mathbf{p}_4 - \mathbf{p}_5}{2}\right). \end{aligned} \quad (9)$$

It should be mentioned that the overlap of space part not only relies on the magnetic quantum numbers, but also depends on the radial and orbital quantum numbers which are usually omitted for simplicity.

Then, the decay width $\Gamma(A \rightarrow BC)$ can be calculated straightforwardly

$$\Gamma = \pi^2 \frac{p}{M_A^2} \frac{s}{2J_A + 1} \sum_{M_{J_A}, M_{J_B}, M_{J_C}} |\mathcal{M}^{M_{J_A} M_{J_B} M_{J_C}}|^2, \quad (10)$$

where $p = |\mathbf{p}| = \frac{\sqrt{[M_A^2 - (M_B + M_C)^2][M_A^2 - (M_B - M_C)^2]}}{2M_A}$ is the momentum of the final states. The statistical factor $s = 1/(1 + \delta_{BC})$ always equals to one for B and C cannot be identical particles in present calculations.

The explicit notations of initial excited singly heavy baryons together with their predicted masses [9] are presented in Table I. For the initial higher excited states, the predicted masses are adopted to calculate their strong decay behaviors. For the final ground states, their masses are taken from the Review of Particle Physics [61]. The harmonic oscillator wave functions are employed to estimate the overlap of space part. For the harmonic oscillator parameters of different mesons, the effective values are

used as in Ref. [57]. For the baryon parameters, we use $\alpha_p = 400$ MeV and

$$\alpha_\lambda = \left(\frac{3m_Q}{2m_q + m_Q} \right)^{1/4} \alpha_p, \quad (11)$$

where the m_Q and m_q are the heavy and light quark masses, respectively [30,48,59]. The $m_{u/d} = 220$ MeV, $m_s = 419$ MeV, $m_c = 1628$ MeV, and $m_b = 4977$ MeV are introduced to take into account the mass differences of heavy and light quarks [7,57,62]. The overall parameter γ , can be determined by the well established $\Sigma_c(2520)^{++} \rightarrow \Lambda_c \pi^+$ process. The $\gamma = 9.83$ can reproduce the width $\Gamma[\Sigma_c(2520)^{++} \rightarrow \Lambda_c \pi^+] = 14.78$ MeV [48,61], and also describe the decay widths of ground states Σ_b and Σ_b^* to $\Lambda_b \pi$ well [59].

III. STRONG DECAYS OF THE HIGHER Λ_Q STATES

A. $\Lambda_Q(3S)$

In the constituent quark model, there is only one λ -mode $\Lambda_c(3S)$ state with $J^P = 1/2^+$. Its mass is estimated to be

TABLE I. Notations, quantum numbers, and the predicted masses of the relevant excited singly heavy baryons. The n_ρ and L_ρ denote the radial and orbital angular momenta between the two light quarks, respectively, while n_λ and L_λ correspond to the radial and angular momenta between the light quark system and heavy quark, respectively. L is the total orbital angular momentum, S_ρ is the total spin of the light quarks, j is total angular momentum of light quark system, J is the total angular momentum, and P stands for the parity. The predicted masses of these higher excited singly heavy baryons are taken from the relativistic quark model [9]. The units are in MeV.

State	n_ρ	L_ρ	n_λ	L_λ	L	S_ρ	j	J^P	Charmed	Bottom
$\Lambda_Q(3S)$	0	0	2	0	0	0	0	$\frac{1}{2}^+$	3130	6455
$\Sigma_Q(3S)$	0	0	2	0	0	1	1	$\frac{1}{2}^+$	3271	6575
$\Sigma_Q^*(3S)$	0	0	2	0	0	1	1	$\frac{3}{2}^+$	3293	6583
$\Lambda_{Q1}(\frac{1}{2}^-, 2P)$	0	0	1	1	1	0	1	$\frac{1}{2}^-$	2983	6326
$\Lambda_{Q1}(\frac{3}{2}^-, 2P)$	0	0	1	1	1	0	1	$\frac{3}{2}^-$	3005	6333
$\Sigma_{Q0}(\frac{1}{2}^-, 2P)$	0	0	1	1	1	1	0	$\frac{1}{2}^-$	3172	6440
$\Sigma_{Q1}(\frac{1}{2}^-, 2P)$	0	0	1	1	1	1	1	$\frac{1}{2}^-$	3125	6430
$\Sigma_{Q1}(\frac{3}{2}^-, 2P)$	0	0	1	1	1	1	1	$\frac{3}{2}^-$	3172	6430
$\Sigma_{Q2}(\frac{3}{2}^-, 2P)$	0	0	1	1	1	1	2	$\frac{5}{2}^-$	3151	6423
$\Sigma_{Q2}(\frac{5}{2}^-, 2P)$	0	0	1	1	1	1	2	$\frac{5}{2}^-$	3161	6421
$\Lambda_{Q2}(\frac{3}{2}^+, 2D)$	0	0	1	2	2	0	2	$\frac{3}{2}^+$	3189	6526
$\Lambda_{Q2}(\frac{5}{2}^+, 2D)$	0	0	1	2	2	0	2	$\frac{5}{2}^+$	3209	6531
$\Sigma_{Q1}(\frac{1}{2}^+, 2D)$	0	0	1	2	2	1	1	$\frac{1}{2}^+$	3370	6636
$\Sigma_{Q1}(\frac{3}{2}^+, 2D)$	0	0	1	2	2	1	1	$\frac{3}{2}^+$	3366	6647
$\Sigma_{Q2}(\frac{3}{2}^+, 2D)$	0	0	1	2	2	1	2	$\frac{3}{2}^+$	3364	6612
$\Sigma_{Q2}(\frac{5}{2}^+, 2D)$	0	0	1	2	2	1	2	$\frac{5}{2}^+$	3365	6612
$\Sigma_{Q3}(\frac{3}{2}^+, 2D)$	0	0	1	2	2	1	3	$\frac{5}{2}^+$	3349	6598
$\Sigma_{Q3}(\frac{7}{2}^+, 2D)$	0	0	1	2	2	1	3	$\frac{7}{2}^+$	3342	6590
$\Lambda_{Q3}(\frac{5}{2}^-, 1F)$	0	0	0	3	3	0	3	$\frac{5}{2}^-$	3097	6408
$\Lambda_{Q3}(\frac{7}{2}^-, 1F)$	0	0	0	3	3	0	3	$\frac{7}{2}^-$	3078	6411
$\Sigma_{Q2}(\frac{3}{2}^-, 1F)$	0	0	0	3	3	1	2	$\frac{3}{2}^-$	3288	6550
$\Sigma_{Q2}(\frac{5}{2}^-, 1F)$	0	0	0	3	3	1	2	$\frac{5}{2}^-$	3283	6564
$\Sigma_{Q3}(\frac{5}{2}^-, 1F)$	0	0	0	3	3	1	3	$\frac{5}{2}^-$	3254	6501
$\Sigma_{Q3}(\frac{7}{2}^-, 1F)$	0	0	0	3	3	1	3	$\frac{7}{2}^-$	3253	6500
$\Sigma_{Q4}(\frac{7}{2}^-, 1F)$	0	0	0	3	3	1	4	$\frac{7}{2}^-$	3227	6472
$\Sigma_{Q4}(\frac{9}{2}^-, 1F)$	0	0	0	3	3	1	4	$\frac{9}{2}^-$	3209	6459

~ 3130 MeV within the relativistic quark model, which lies above the $D^{(*)}N$ thresholds. The strong decay behaviors are performed in Table. II. The $\Lambda_c(3S)$ state may be a relatively narrow state with a width of ~ 69 MeV. Its decays may be governed by the D^*N channel. The branching ratio of the D^*N channel is predicted to be

$$\text{Br}(\Lambda_c(3S) \rightarrow D^*N) = 95\%, \quad (12)$$

which is independent with the overall parameter γ .

From the heavy flavor symmetry, the mass and decay behaviors of the $\Lambda_b(3S)$ state should be similar to that of the $\Lambda_c(3S)$. From Table I, the predicted mass gaps are

$$m[\Lambda_c(3S)] - m[\Lambda_c] = 844 \text{ MeV} \quad (13)$$

and

TABLE II. Decay widths of the $\Lambda_c(3S)$ state in MeV.

Mode	$\Lambda_c(3S)$
$\Sigma_c^{++}\pi^-$	0.11
$\Sigma_c^+\pi^0$	0.11
$\Sigma_c^0\pi^+$	0.11
$\Sigma_c^{*++}\pi^-$	0.27
$\Sigma_c^{*+}\pi^0$	0.27
$\Sigma_c^{*0}\pi^+$	0.27
$\Lambda_c\omega$	0.32
$\Xi_c^{'+}K^0$	0.08
$\Xi_c^{*0}K^+$	0.08
D^0p	0.04
D^+n	0.10
$D^{*0}p$	32.00
$D^{*+}n$	33.43
$D_s\Lambda$	1.83
Total width	69.03

TABLE III. Decay widths of the $\Lambda_b(3S)$ state in MeV.

Mode	$\Lambda_b(3S)$
$\Sigma_b^+ \pi^-$	0.19
$\Sigma_b^0 \pi^0$	0.19
$\Sigma_b^- \pi^+$	0.19
$\Sigma_b^{*+} \pi^-$	0.40
$\Sigma_b^{*0} \pi^0$	0.40
$\Sigma_b^{*-} \pi^+$	0.41
$\Lambda_b \omega$	0.47
$\Xi_b^{*0} K^0$	0.02
$\Xi_b^{*-} K^+$	0.03
$\Xi_b^{*0} K^0$	0.01
$\Xi_b^{*-} K^+$	0.01
$B^- p$	1.51
$B^0 n$	1.61
$B^{*-} p$	22.81
$B^{*0} n$	23.39
Total width	51.65

$$m[\Lambda_b(3S)] - m[\Lambda_b] = 835 \text{ MeV}, \quad (14)$$

which preserve the heavy flavor symmetry well. From Table III, it can be seen that total decay width of $\Lambda_b(3S)$ is about 52 MeV, and the main decay mode is B^*N channel. The branching ratio of B^*N channel is predicted to be

$$\text{Br}(\Lambda_b(3S) \rightarrow B^*N) = 89\%. \quad (15)$$

It should be mentioned that the λ -mode $\Lambda_c(3S)$ and $\Lambda_b(3S)$ states mainly decay into the D^*N and B^*N channels, respectively, which indicate that these heavy meson plus light baryon final states should be ideal channels to search for these $\Lambda_Q(3S)$ states in future experiments.

B. $\Lambda_Q(2P)$

In the conventional quark model, there are two λ -type $\Lambda_c(2P)$ states with $J^P = 1/2^-$ and $J^P = 3/2^-$. The predicted masses in the relativistic quark model are around 2983 and 3005 MeV, respectively, and their strong decay widths are listed in Table IV. It can be seen that the dominated decay channels of these two states are D^*N and DN , while other decay modes can be neglected.

As mentioned in the Introduction, the $\Lambda_c(2940)$ is a good candidate of the $\Lambda_c(2P)$ states in the consideration of the mass uncertainties of quark model. The mass of $\Lambda_c(2940)$ lies below the D^*N threshold, which leads to a narrow total decay width. In previous work [48], the analysis of the strong decays indicates that $\Lambda_c(2940)$ can be well explained as the $J^P = 3/2^-$ $\Lambda_c(2P)$ state in the $N = 3$ shell within the same model and parameters adopted in present work. The detailed discussions of these two λ -type $\Lambda_c(2P)$ states can be found in Ref. [48].

The strong decay behaviors of $\Lambda_b(2P)$ states with predicted masses are shown in Table V. The total decay

TABLE IV. Decay widths of the $\Lambda_c(2P)$ states in MeV.

Mode	$\Lambda_{c1}(\frac{1}{2}^-, 2P)$	$\Lambda_{c1}(\frac{3}{2}^-, 2P)$
$\Sigma_c^{++} \pi^-$	0.49	0.52
$\Sigma_c^+ \pi^0$	0.48	0.53
$\Sigma_c^0 \pi^+$	0.49	0.52
$\Sigma_c^{*++} \pi^-$	0.50	0.97
$\Sigma_c^{*+} \pi^0$	0.51	0.97
$\Sigma_c^{*0} \pi^+$	0.50	0.97
$D^0 p$	1.19	19.54
$D^+ n$	1.68	18.80
$D^{*0} p$	17.31	55.25
$D^{*+} n$	16.67	56.59
Total width	39.84	154.67

widths are 91 and 162 MeV for $J^P = 1/2^-$ and $J^P = 3/2^-$ states, respectively. The main decay channels are BN and B^*N . The variations of strong decays versus the harmonic oscillator parameter α_ρ are presented in Fig. 3, which shows relatively stable predictions. It should be mentioned that if the $\Lambda_c(2940)$ corresponds to the $J^P = 3/2^-$ $\Lambda_c(2P)$ state indeed, the masses of the $\Lambda_b(2P)$ may lie below the B^*N threshold as well considering the heavy flavor symmetry. The variations of strong decays versus the initial $\Lambda_b(2P)$ masses are shown in Fig. 4. When the initial masses decrease below the B^*N threshold, the total decay width of $J^P = 1/2^-$ states approximately remain because of the large BN channel. However, for the $J^P = 3/2^-$ state, the total decay width drops into several MeV if its mass is lower than the B^*N threshold. This specific feature of $\Lambda_b(2P)$ states may provide helpful information for future experimental searches.

C. $\Lambda_Q(2D)$

The predicted masses of the two $\Lambda_c(2D)$ states with $J^P = 3/2^+$ and $J^P = 5/2^+$ are around 3189 and 3209 MeV, respectively. Until now, there is no

TABLE V. Decay widths of the $\Lambda_b(2P)$ states in MeV.

Mode	$\Lambda_{b1}(\frac{1}{2}^-, 2P)$	$\Lambda_{b1}(\frac{3}{2}^-, 2P)$
$\Sigma_b^+ \pi^-$	0.76	0.60
$\Sigma_b^0 \pi^0$	0.75	0.61
$\Sigma_b^- \pi^+$	0.78	0.58
$\Sigma_b^{*+} \pi^-$	0.94	1.34
$\Sigma_b^{*0} \pi^0$	0.95	1.34
$\Sigma_b^{*-} \pi^+$	0.92	1.35
$B^- p$	12.47	17.42
$B^0 n$	13.07	17.04
$B^{*-} p$	30.33	60.76
$B^{*0} n$	29.91	61.37
Total width	90.90	162.42

FIG. 3. The decay widths of the $\Lambda_{b1}(\frac{1}{2}^-, 2P)$ and $\Lambda_{b1}(\frac{3}{2}^-, 2P)$ states as functions of the harmonic oscillator parameter α_ρ .

experimental evidence of the Λ_c states above 3000 MeV. We employ the predicted masses to calculate their strong decay widths, and the results are performed in Table VI. The total decay widths of these two states are about 57 and 73 MeV, respectively. It is shown that the dominated decay channel is D^*N for the $J^P = 3/2^+$ state, while the main decay modes are both DN and D^*N final states for the $J^P = 5/2^+$ states. The partial decay width ratios are predicted to be

$$\Gamma\left[\Lambda_{c2}\left(\frac{3}{2}^+, 2D\right) \rightarrow DN\right] : \Gamma\left[\Lambda_{c2}\left(\frac{3}{2}^+, 2D\right) \rightarrow D^*N\right] = 9 \times 10^{-3} \quad (16)$$

and

$$\Gamma\left[\Lambda_{c2}\left(\frac{5}{2}^+, 2D\right) \rightarrow DN\right] : \Gamma\left[\Lambda_{c2}\left(\frac{5}{2}^+, 2D\right) \rightarrow D^*N\right] = 0.63. \quad (17)$$

FIG. 4. The decay widths of the $\Lambda_{b1}(\frac{1}{2}^-, 2P)$ and $\Lambda_{b1}(\frac{3}{2}^-, 2P)$ states as functions of their masses.

TABLE VI. Decay widths of the $\Lambda_c(2D)$ states in MeV.

Mode	$\Lambda_{c2}(\frac{3}{2}^+, 2D)$	$\Lambda_{c2}(\frac{5}{2}^+, 2D)$
$\Sigma_c^{++}\pi^-$	0.07	0.08
$\Sigma_c^+\pi^0$	0.07	0.08
$\Sigma_c^0\pi^+$	0.07	0.08
$\Sigma_c^{*++}\pi^-$	0.10	0.14
$\Sigma_c^{*+}\pi^0$	0.10	0.14
$\Sigma_c^{*0}\pi^+$	0.10	0.14
$\Lambda_c\omega$	0.17	0.19
$\Xi_c^{\prime+}K^0$	0.09	2×10^{-3}
$\Xi_c^{\prime0}K^+$	0.10	2×10^{-3}
$\Xi_c^{\prime*+}K^0$	0.01	0.06
$\Xi_c^{\prime*0}K^+$	0.01	0.06
D^0p	0.27	13.85
D^+n	0.18	13.69
$D^{*0}p$	26.69	22.00
$D^{*+}n$	26.02	22.03
$D_s\Lambda$	3.29	0.46
Total width	57.32	73.00

TABLE VII. Decay widths of the $\Lambda_b(2D)$ states in MeV.

Mode	$\Lambda_{b2}(\frac{3}{2}^+, 2D)$	$\Lambda_{b2}(\frac{5}{2}^+, 2D)$
$\Sigma_b^+ \pi^-$	0.10	0.10
$\Sigma_b^0 \pi^0$	0.10	0.10
$\Sigma_b^- \pi^+$	0.10	0.10
$\Sigma_b^{*+} \pi^-$	0.18	0.20
$\Sigma_b^{*0} \pi^0$	0.18	0.20
$\Sigma_b^{*-} \pi^+$	0.18	0.20
$\Lambda_b \omega$	0.29	0.30
$\Xi_b^{*0} K^0$	0.09	8×10^{-4}
$\Xi_b^{*-} K^+$	0.09	9×10^{-4}
$\Xi_b^{*0} K^0$	0.01	0.09
$\Xi_b^{*-} K^+$	0.01	0.09
$B^- p$	0.21	21.77
$B^0 n$	0.18	21.69
$B^{*-} p$	50.61	30.91
$B^{*0} n$	50.35	30.82
$B_s \Lambda$	4.40	0.09
Total width	107.06	106.67

These different partial decay ratios can help us to distinguish the two $\Lambda_c(2D)$ states.

In the bottom sector, the similar situation happens. The masses and total decay widths of the two $\Lambda_b(2D)$ states are almost same. The dominant decay channel is B^*N for the $J^P = 3/2^+$ state, while the main decay modes are BN and B^*N final states for the $J^P = 5/2^+$ states. To distinguish these two states, the partial decay ratios are needed. From Table VII, it is shown that

$$\Gamma\left[\Lambda_{b2}\left(\frac{3}{2}^+, 2D\right) \rightarrow BN\right] : \Gamma\left[\Lambda_{b2}\left(\frac{3}{2}^+, 2D\right) \rightarrow B^*N\right] = 4 \times 10^{-3} \quad (18)$$

TABLE VIII. Decay widths of the $\Lambda_c(1F)$ states in MeV.

Mode	$\Lambda_{c3}(\frac{5}{2}^-, 1F)$	$\Lambda_{c3}(\frac{7}{2}^-, 1F)$
$\Sigma_c^{++} \pi^-$	0.38	0.02
$\Sigma_c^+ \pi^0$	0.39	0.02
$\Sigma_c^0 \pi^+$	0.38	0.02
$\Sigma_c^{*++} \pi^-$	0.09	0.30
$\Sigma_c^{*+} \pi^0$	0.09	0.30
$\Sigma_c^{*0} \pi^+$	0.09	0.30
$\Lambda_c \omega$	0.01	3×10^{-4}
$\Xi_c^{*+} K^0$	4×10^{-4}	6×10^{-12}
$\Xi_c^{*0} K^+$	6×10^{-4}	9×10^{-11}
$D^0 p$	25.86	2.36
$D^+ n$	25.34	2.18
$D^{*0} p$	10.25	17.88
$D^{*+} n$	9.65	16.71
$D_s \Lambda$	0.02	...
Total width	72.54	40.08

TABLE IX. Decay widths of the $\Lambda_b(1F)$ states in MeV.

Mode	$\Lambda_{b3}(\frac{5}{2}^-, 1F)$	$\Lambda_{b3}(\frac{7}{2}^-, 1F)$
$\Sigma_b^+ \pi^-$	0.39	0.02
$\Sigma_b^0 \pi^0$	0.39	0.02
$\Sigma_b^- \pi^+$	0.38	0.02
$\Sigma_b^{*+} \pi^-$	0.12	0.45
$\Sigma_b^{*0} \pi^0$	0.12	0.45
$\Sigma_b^{*-} \pi^+$	0.12	0.44
$\Lambda_b \omega$	2×10^{-4}	5×10^{-4}
$B^- p$	27.07	2.01
$B^0 n$	26.81	1.95
$B^{*-} p$	16.28	37.26
$B^{*0} n$	16.04	36.79
Total width	87.71	79.42

FIG. 5. The decay widths of the $\Lambda_{c3}(\frac{5}{2}^-, 1F)$ and $\Lambda_{c3}(\frac{7}{2}^-, 1F)$ states as functions of their masses. The partial decay widths of $\Lambda_c \omega$, $\Xi_c^{*+} K^0$, $\Xi_c^{*0} K^+$, and $D_s \Lambda$ channels are relatively small, which are not presented here.

FIG. 6. The decay widths of the $\Lambda_{b3}(\frac{5}{2}^-, 1F)$ and $\Lambda_{b3}(\frac{7}{2}^-, 1F)$ states as functions of their masses. The partial decay width of $\Lambda_b \omega$ channel is relatively small, which is not presented here.

and

$$\Gamma\left[\Lambda_{b2}\left(\frac{5}{2}^+, 2D\right) \rightarrow BN\right] : \Gamma\left[\Lambda_{b2}\left(\frac{5}{2}^+, 2D\right) \rightarrow B^*N\right] = 0.70, \quad (19)$$

which is independent with the quark pair creation strength. To sum up, the λ -mode $\Lambda_Q(2D)$ states mainly decay into heavy meson plus light baryon final states, which can be tested by future experiments.

D. $\Lambda_Q(1F)$

For the $\Lambda_c(1F)$ states, the predicted masses are around 3097 and 3078 MeV for the $J^P = 5/2^-$ and $J^P = 7/2^-$ states, respectively. The calculated strong decay widths are listed in Table VIII. It is shown that the DN and D^*N are the dominated decay modes for these F -wave states, while the contribution of heavy baryon plus light meson final states can be neglected. Since the heavy flavor symmetry,

FIG. 7. The decay widths of the $\Lambda_{c3}(\frac{5}{2}^-, 1F)$ and $\Lambda_{c3}(\frac{7}{2}^-, 1F)$ states as functions of the harmonic oscillator parameter α_ρ . The partial decay widths of $\Lambda_c \omega$, $\Xi_c'^+ K^0$, $\Xi_c'^0 K^+$, and $D_s \Lambda$ channels are relatively small, which are not presented here.

the $\Lambda_b(1F)$ states have the similar properties to the charm sector. We perform their strong decay behaviors in Table IX for reference.

From Table I, it can be found that the predicted masses of $\Lambda_Q(1F)$ states lie about 70–100 MeV above the $\Lambda_Q(2P)$ states. The total decay widths are about 40–90 MeV, and for the $\Lambda_c(1F)$ states the main decay channels are $D^{(*)}N$, while for the $\Lambda_b(1F)$ states, the main decay modes are $B^{(*)}N$. The variations of strong decays versus the initial $\Lambda_Q(1F)$ masses are also presented in Figs. 5 and 6. It is shown that the total decay widths increase smoothly with the initial masses. With the 50 MeV mass uncertainties, the total decay widths vary in certain ranges. For instance, with the 50 MeV variations of initial masses, the total decay widths of two $\Lambda_b(1F)$ states lie in the range 64–105 MeV and 51–99 MeV, respectively. Compared with the predicted central values 88 MeV and 79 MeV from Table IX, the uncertainties of total decay widths are up to 27% and 35% for the $\Lambda_{b3}(\frac{5}{2}^-, 1F)$ and $\Lambda_{b3}(\frac{7}{2}^-, 1F)$ states, respectively.

FIG. 8. The decay widths of the $\Lambda_{b3}(\frac{5}{2}^-, 1F)$ and $\Lambda_{b3}(\frac{7}{2}^-, 1F)$ states as functions of the harmonic oscillator parameter α_ρ . The partial decay width of $\Lambda_b\omega$ channel is relatively small, which is not presented here.

Moreover, the uncertainties raising from the harmonic oscillator parameter α_ρ are calculated. From Figs. 7 and 8, it can be seen that our results are rather stable when the parameter α_ρ varies in a reasonable range. Considering the $\Lambda_c(2940)$ observed in the $D^0 p$ invariant mass by the LHCb Collaboration, we hope further experiments can be carried out to search for these $\Lambda_Q(1F)$ states in the $D^{(*)}N$ and $B^{(*)}N$ final states.

IV. STRONG DECAYS OF THE HIGHER Σ_Q STATES

A. $\Sigma_Q(3S)$

In the constituent quark model, there are two λ -mode $3S$ Σ_c states, $\Sigma_c(3S)$ and $\Sigma_c^*(3S)$. From Table I, the predicted masses of $\Sigma_c(3S)$ and $\Sigma_c^*(3S)$ are around 3271 and 3293 MeV, respectively. With this predicted masses, their strong decays are presented in Table X. Our results show that the total decay widths of $\Sigma_c(3S)$ and $\Sigma_c^*(3S)$ states are

TABLE X. Decay widths of the $\Sigma_c(3S)$ states in MeV.

Mode	$\Sigma_c^*(3S)$	$\Sigma_c(3S)$
$\Lambda_c\pi^+$	1×10^{-4}	2×10^{-3}
$\Lambda_c\rho^+$	0.42	0.40
$\Sigma_c^{++}\pi^0$	0.06	0.01
$\Sigma_c^+\pi^+$	0.06	0.01
$\Sigma_c^{*++}\pi^0$	0.05	0.10
$\Sigma_c^{*+}\pi^+$	0.05	0.11
$\Sigma_c^{++}\rho^0$	0.39	0.08
$\Sigma_c^+\rho^+$	0.41	0.08
$\Sigma_c^{*+}\rho^+$	...	5×10^{-4}
$\Sigma_c^{++}\eta$	0.12	0.03
$\Sigma_c^{*++}\eta$	0.06	0.16
$\Sigma_c^{++}\omega$	0.31	0.07
$\Xi_c^+K^+$	0.42	0.42
$\Xi_c'^+K^+$	0.47	0.13
$\Xi_c^{*+}K^+$	0.16	0.47
D^+p	0.39	2.07
$D^{*+}p$	0.02	0.10
$D^0\Delta^{++}$	11.68	5.20
$D^+\Delta^+$	4.12	1.87
$D^{*0}\Delta^{++}$	29.64	57.85
$D^{*+}\Delta^+$	8.73	18.33
$D_s\Sigma^+$	0.33	1.20
Total	57.90	88.66

58 and 89 MeV, respectively. The main decay channels of these two $3S$ Σ_c states are $D\Delta$ and $D^*\Delta$ other than DN and D^*N . For the $\Sigma_c(3S)$ state, the branching ratios of DN , D^*N , $D\Delta$, and $D^*\Delta$ modes are predicted to be

TABLE XI. Decay widths of the $\Sigma_b(3S)$ states in MeV.

Mode	$\Sigma_b^*(3S)$	$\Sigma_b(3S)$
$\Lambda_b\pi^+$	4×10^{-4}	1×10^{-3}
$\Lambda_b\rho^+$	0.70	0.69
$\Sigma_b^+\pi^0$	0.13	0.03
$\Sigma_b^0\pi^+$	0.13	0.03
$\Sigma_b^{*+}\pi^0$	0.08	0.18
$\Sigma_b^{*0}\pi^+$	0.08	0.18
$\Sigma_b^+\eta$	0.20	0.05
$\Sigma_b^{*+}\eta$	0.10	0.24
$\Xi_b^0K^+$	0.45	0.45
$\Xi_b'^0K^+$	0.39	0.10
$\Xi_b^{*0}K^+$	0.17	0.46
B^0p	0.42	1.97
$B^{*0}p$	1.34	1.41
$B^-\Delta^{++}$	34.21	22.04
$B^0\Delta^+$	11.39	7.34
$B^{*-}\Delta^{++}$	28.10	50.67
$B^{*0}\Delta^+$	9.37	16.89
$B_s\Sigma^+$	0.22	1.33
Total	87.46	104.06

TABLE XII. Decay widths of the $\Sigma_c(2P)$ states in MeV.

Mode	$\Sigma_{c0}(\frac{1}{2}^-, 2P)$	$\Sigma_{c1}(\frac{1}{2}^-, 2P)$	$\Sigma_{c1}(\frac{3}{2}^-, 2P)$	$\Sigma_{c2}(\frac{3}{2}^-, 2P)$	$\Sigma_{c2}(\frac{5}{2}^-, 2P)$
$\Lambda_c \pi^+$	0.91	...	...	2.09	2.12
$\Lambda_c \rho^+$	...	4.42	3.60	0.31	0.39
$\Sigma_c^{++} \pi^0$	...	0.08	0.63	1.06	0.49
$\Sigma_c^+ \pi^+$	...	0.08	0.63	1.06	0.49
$\Sigma_c^{*++} \pi^0$	...	0.77	0.63	0.80	1.30
$\Sigma_c^{*+} \pi^+$	...	0.77	0.63	0.80	1.30
$\Sigma_c^{++} \eta$	...	1.50	0.09	0.12	0.06
$\Sigma_c^{*++} \eta$	...	0.02	1.67	0.03	0.07
$\Xi_c^+ K^+$	5.36	...	...	0.51	0.58
$\Xi_c'^+ K^+$	...	4.93	0.05	0.05	0.03
$\Xi_c^{*+} K^+$	...	...	4.25	4×10^{-4}	3×10^{-3}
$D^+ p$	3.74	4.31	3.31	0.67	10.66
$D^{*+} p$	0.39	7.69	6.71	26.45	17.28
$D^0 \Delta^{++}$	6.83	0.38	14.07	49.42	3.43
$D^+ \Delta^+$	2.00	0.08	4.60	17.26	0.98
$D_s \Sigma^+$	4.07	...	0.01	...	4×10^{-4}
Total	23.31	25.03	40.88	100.62	39.18

$$\text{Br}(DN, D^*N, D\Delta, D^*\Delta) = 0.67\%, 0.03\%, 27.29\%, 66.27\%. \quad (20)$$

For the $\Sigma_c^*(3S)$ state, the branching ratios of DN , D^*N , $D\Delta$, and $D^*\Delta$ modes are predicted to be

$$\text{Br}(DN, D^*N, D\Delta, D^*\Delta) = 2.33\%, 0.11\%, 7.97\%, 85.92\%. \quad (21)$$

These branching ratios are independent on the overall γ and can be employed to distinguish these two states.

The predicted masses of $\Sigma_b(3S)$ and $\Sigma_b^*(3S)$ are around 6575 and 6583 MeV, respectively. From Table XI, it is shown that the total decay widths of $\Sigma_b(3S)$ and $\Sigma_b^*(3S)$

states are 87 and 104 MeV, respectively. The dominated decay channels of these two bottom baryons are $B\Delta$ and $B^*\Delta$. For the $\Sigma_b(3S)$ state, the branching ratios of BN , B^*N , $B\Delta$, and $B^*\Delta$ modes are

$$\text{Br}(BN, B^*N, B\Delta, B^*\Delta) = 0.48\%, 1.53\%, 52.14\%, 42.84\%. \quad (22)$$

For the $\Sigma_b^*(3S)$ state, the branching ratios of BN , B^*N , $B\Delta$, and $B^*\Delta$ modes are predicted to be

$$\text{Br}(BN, B^*N, B\Delta, B^*\Delta) = 1.89\%, 1.35\%, 28.23\%, 64.92\%. \quad (23)$$

 TABLE XIII. Decay widths of the $\Sigma_b(2P)$ states in MeV.

Mode	$\Sigma_{b0}(\frac{1}{2}^-, 2P)$	$\Sigma_{b1}(\frac{1}{2}^-, 2P)$	$\Sigma_{b1}(\frac{3}{2}^-, 2P)$	$\Sigma_{b2}(\frac{3}{2}^-, 2P)$	$\Sigma_{b2}(\frac{5}{2}^-, 2P)$
$\Lambda_b \pi^+$	0.73	...	...	2.84	2.83
$\Lambda_b \rho^+$	...	6.44	6.44	0.04	0.03
$\Sigma_b^+ \pi^0$	...	0.39	0.60	1.04	0.46
$\Sigma_b^0 \pi^+$	...	0.40	0.60	1.04	0.46
$\Sigma_b^{*+} \pi^0$	...	1.06	1.10	0.91	1.40
$\Sigma_b^{*0} \pi^+$	...	1.06	1.11	0.91	1.40
$\Sigma_b^+ \eta$	...	2.51	0.02	0.03	0.01
$\Sigma_b^{*+} \eta$	...	0.02	2.47	0.01	0.01
$\Xi_b^0 K^+$	7.78	...	...	0.29	0.28
$\Xi_b^{*0} K^+$	...	1.07	1×10^{-6}	...	...
$B^0 p$	1.18	1.55	4.50	0.87	13.86
$B^{*0} p$	0.06	11.00	6.91	30.39	18.38
Total	9.75	25.50	23.75	38.35	39.11

TABLE XIV. Decay widths of the $\Sigma_c(2D)$ states in MeV.

Mode	$\Sigma_{c1}(\frac{1}{2}^+, 2D)$	$\Sigma_{c1}(\frac{3}{2}^+, 2D)$	$\Sigma_{c2}(\frac{3}{2}^+, 2D)$	$\Sigma_{c2}(\frac{5}{2}^+, 2D)$	$\Sigma_{c3}(\frac{5}{2}^+, 2D)$	$\Sigma_{c3}(\frac{7}{2}^+, 2D)$
$\Lambda_c \pi^+$	0.02	0.02	...	...	0.29	0.28
$\Lambda_c \rho^+$	0.10	0.10	0.28	0.28	0.13	0.12
$\Sigma_c^{++} \pi^0$	5×10^{-3}	1×10^{-3}	0.01	0.11	0.12	0.06
$\Sigma_c^+ \pi^+$	5×10^{-3}	1×10^{-3}	0.01	0.11	0.12	0.06
$\Sigma_c^{*++} \pi^0$	0.01	0.02	0.16	0.11	0.11	0.15
$\Sigma_c^{*+} \pi^+$	0.01	0.02	0.16	0.11	0.11	0.15
$\Sigma_c^{++} \rho^0$	0.05	0.07	0.15	0.02	0.52	3×10^{-3}
$\Sigma_c^+ \rho^+$	0.05	0.07	0.15	0.02	0.52	3×10^{-3}
$\Sigma_c^{*++} \rho^0$	0.05	0.06	0.03	0.10	0.07	0.28
$\Sigma_c^{*+} \rho^+$	0.06	0.06	0.03	0.11	0.07	0.28
$\Sigma_c^{++} \eta$	0.03	0.01	0.07	0.03	0.03	0.01
$\Sigma_c^{*++} \eta$	0.02	0.05	0.04	0.12	0.02	0.02
$\Sigma_c^{++} \omega$	0.05	0.06	0.14	0.02	0.51	2×10^{-3}
$\Sigma_c^{*++} \omega$	0.05	0.05	0.03	0.09	0.06	0.23
$\Xi_c^+ K^+$	0.32	0.32	...	...	0.10	0.09
$\Xi_c^{'+} K^+$	0.13	0.03	0.29	0.02	0.02	0.01
$\Xi_c^{*+} K^+$	0.06	0.15	0.07	0.33	0.01	0.01
$\Xi_c^+ K^{*+}$	0.01	5×10^{-3}	5×10^{-3}	0.01	...	...
$D^+ p$	6.38	0.39	3.43	2.01	0.15	5.46
$D^{*+} p$	0.81	2.10	8.50	5.97	19.35	11.03
$D^0 \Delta^{++}$	0.15	19.25	2.82	15.16	3.95	7.66
$D^+ \Delta^+$	0.06	6.24	0.97	4.92	1.46	2.46
$D^{*0} \Delta^{++}$	21.54	16.52	23.33	30.00	26.01	54.55
$D^{*+} \Delta^+$	6.83	5.31	7.57	9.93	8.58	18.11
$D_s \Sigma^+$	1.11	0.08	0.71	0.45	0.03	0.87
$D_s^* \Sigma^+$	2.32	6.41	1.54	4.01	0.07	0.02
$D_s \Sigma^{*+}$	0.77	0.03	0.26	1×10^{-4}	...	...
Total	40.98	57.40	50.75	74.07	62.41	101.95

These branching ratios suggest that the $B\Delta$ and $B^*\Delta$ final states are the ideal channels to hunt for the $\Sigma_b(3S)$ and $\Sigma_b^*(3S)$ states. Moreover, the heavy flavor symmetry is approximately preserved by comparing the decay behaviors between the charmed and bottom sectors.

B. $\Sigma_Q(2P)$

Five λ -mode $\Sigma_c(2P)$ states exist theoretically, and the estimated masses in the relativistic quark model are about 3125–3172 MeV. Until now, there is no experimental information for these states. With the predicted masses within the relativistic quark model [9], their strong decays are calculated and listed in Table XII. The total decay widths of these five states are about 23–100 MeV, which are relatively narrow. Roughly speaking, the dominant decay modes are light baryon plus heavy meson channels. These relatively narrow total widths and large $D^{(*)}N$ partial decay widths suggest that these states may be easily observed in future experiments.

In previous work [48], the strong decay behaviors have been investigated with the calculated masses in the relativized quark model proposed by Capstick and Isgur [7]. Due to the small differences of the initial baryon masses,

the total decay widths change a little, but the conclusions are similar to present ones.

In the same way, the strong decays of five $\Sigma_b(2P)$ states are investigated and presented in Table XIII. Since the predicted masses of $\Sigma(2P)$ states are lower than the $B\Delta$ threshold, the total widths and dominated decay channels are quite different with the charmed baryon sector. For the $\Sigma_{b0}(\frac{1}{2}^-, 2P)$ state, the main decay channel is $\Xi_b K$, while other modes are rather small. For the two $j = 1$ states, the dominating decay modes are $\Lambda_b \rho$, BN , and B^*N final states. From the heavy quark spin symmetry, the two $j = 1$ states should have similar properties, such as masses and total widths. Indeed, the predicted masses and total decay widths of these two states are almost the same. The partial decay width ratios of BN and B^*N are predicted to be

$$\Gamma\left[\Sigma_{b1}\left(\frac{1}{2}^-, 2P\right) \rightarrow BN\right] : \Gamma\left[\Sigma_{b1}\left(\frac{1}{2}^-, 2P\right) \rightarrow B^*N\right] = 0.14 \quad (24)$$

and

TABLE XV. Decay widths of the $\Sigma_b(2D)$ states in MeV.

Mode	$\Sigma_{b1}(\frac{1}{2}^+, 2D)$	$\Sigma_{b1}(\frac{3}{2}^+, 2D)$	$\Sigma_{b2}(\frac{3}{2}^+, 2D)$	$\Sigma_{b2}(\frac{5}{2}^+, 2D)$	$\Sigma_{b3}(\frac{5}{2}^+, 2D)$	$\Sigma_{b3}(\frac{7}{2}^+, 2D)$
$\Lambda_b \pi^+$	0.02	0.02	...	...	0.40	0.39
$\Lambda_b \rho^+$	0.19	0.18	0.47	0.47	0.10	0.09
$\Sigma_b^+ \pi^0$	0.02	0.01	0.07	0.11	0.12	0.06
$\Sigma_b^0 \pi^+$	0.02	0.01	0.08	0.11	0.12	0.06
$\Sigma_b^{*+} \pi^0$	0.02	0.03	0.20	0.19	0.13	0.17
$\Sigma_b^{*0} \pi^+$	0.02	0.04	0.20	0.19	0.13	0.17
$\Sigma_b^+ \rho^0$	0.03	0.03	0.04	3×10^{-3}	0.05	3×10^{-8}
$\Sigma_b^0 \rho^+$	0.03	0.03	0.04	3×10^{-3}	0.05	4×10^{-8}
$\Sigma_b^{*+} \rho^0$	0.02	0.04	1×10^{-3}	4×10^{-3}	...	...
$\Sigma_b^{*0} \rho^+$	0.02	0.04	1×10^{-3}	4×10^{-3}	...	...
$\Sigma_b^+ \eta$	0.06	0.01	0.14	0.02	0.01	7×10^{-3}
$\Sigma_b^{*+} \eta$	0.03	0.08	0.05	0.19	0.01	0.02
$\Sigma_b^+ \omega$	0.03	0.03	0.02	1×10^{-3}	0.01	...
$\Sigma_b^{*+} \omega$	0.02	0.03	...	...	...	...
$\Xi_b^0 K^+$	0.39	0.38	...	...	0.06	0.06
$\Xi_b^{*0} K^+$	0.13	0.03	0.26	0.01	4×10^{-3}	2×10^{-3}
$\Xi_b^{*0} K^+$	0.06	0.16	0.06	0.30	4×10^{-3}	4×10^{-3}
$B^0 p$	6.13	0.44	2.42	3.59	0.26	9.26
$B^{*0} p$	1.78	6.37	10.76	7.62	24.45	13.89
$B^- \Delta^{++}$	3.23	14.50	14.78	7.16	34.65	1.43
$B^0 \Delta^+$	1.08	4.81	4.93	2.37	11.55	0.47
$B^{*-} \Delta^{++}$	17.39	19.31	18.46	30.81	22.02	42.38
$B^{*0} \Delta^+$	5.80	6.44	6.15	10.27	7.34	14.13
$B_s \Sigma^+$	5.93	0.37	2.90	0.04	1×10^{-3}	0.02
$B_s^* \Sigma^+$	1.96	7.56	0.19	0.51	...	...
Total	44.41	60.96	62.24	63.97	101.49	82.62

 TABLE XVI. Decay widths of the $\Sigma_c(1F)$ states in MeV.

Mode	$\Sigma_{c2}(\frac{3}{2}^-, 1F)$	$\Sigma_{c2}(\frac{5}{2}^-, 1F)$	$\Sigma_{c3}(\frac{5}{2}^-, 1F)$	$\Sigma_{c3}(\frac{7}{2}^-, 1F)$	$\Sigma_{c4}(\frac{7}{2}^-, 1F)$	$\Sigma_{c4}(\frac{9}{2}^-, 1F)$
$\Lambda_c \pi^+$	1.60	1.60	...	...	0.41	0.36
$\Lambda_c \rho^+$	0.56	0.54	0.60	0.60	0.01	5×10^{-3}
$\Sigma_c^{++} \pi^0$	0.46	0.20	0.94	0.08	0.06	0.03
$\Sigma_c^+ \pi^+$	0.46	0.20	0.94	0.08	0.06	0.03
$\Sigma_c^{*++} \pi^0$	0.39	0.60	0.30	1.03	0.04	0.04
$\Sigma_c^{*+} \pi^+$	0.39	0.60	0.30	1.03	0.04	0.04
$\Sigma_c^{++} \rho^0$	0.01	0.01	4×10^{-3}	4×10^{-4}	...	...
$\Sigma_c^+ \rho^+$	0.01	0.01	4×10^{-3}	4×10^{-4}	...	...
$\Sigma_c^{++} \eta$	0.13	0.06	0.23	4×10^{-3}	2×10^{-3}	1×10^{-3}
$\Sigma_c^{*++} \eta$	0.08	0.12	0.04	0.16	7×10^{-4}	5×10^{-4}
$\Sigma_c^{++} \omega$	0.01	4×10^{-3}	2×10^{-3}	2×10^{-4}	...	...
$\Xi_c^+ K^+$	0.52	0.51	...	...	0.01	0.01
$\Xi_c'^+ K^+$	0.08	0.03	0.11	7×10^{-4}	3×10^{-4}	1×10^{-4}
$\Xi_c^{*+} K^+$	0.03	0.04	0.01	0.05	3×10^{-5}	1×10^{-5}
$D^+ p$	17.60	0.49	9.94	2.55	0.08	4.12
$D^{*+} p$	14.03	34.17	10.04	19.75	3.73	1.60
$D^0 \Delta^{++}$	8.09	2.92	15.04	1.75	20.33	0.10
$D^+ \Delta^+$	2.60	0.90	4.77	0.54	6.35	0.03
$D^{*0} \Delta^{++}$	0.78	1.17	0.12	0.20	...	...
$D^{*+} \Delta^+$	0.22	0.33	0.02	0.03	...	...
$D_s \Sigma^+$	4.54	0.12	1.35	0.01	5×10^{-5}	9×10^{-4}
Total	52.61	44.62	44.76	27.86	31.12	6.37

TABLE XVII. Decay widths of the $\Sigma_b(1F)$ states in MeV.

Mode	$\Sigma_{b2}(\frac{3}{2}^-, 1F)$	$\Sigma_{b2}(\frac{5}{2}^-, 1F)$	$\Sigma_{b3}(\frac{5}{2}^-, 1F)$	$\Sigma_{b3}(\frac{7}{2}^-, 1F)$	$\Sigma_{b4}(\frac{7}{2}^-, 1F)$	$\Sigma_{b4}(\frac{9}{2}^-, 1F)$
$\Lambda_b \pi^+$	1.95	1.95	...	...	0.37	0.33
$\Lambda_b \rho^+$	0.43	0.51	0.28	0.28	6×10^{-4}	2×10^{-4}
$\Sigma_b^+ \pi^0$	0.47	0.22	0.86	0.04	0.03	0.01
$\Sigma_b^0 \pi^+$	0.47	0.22	0.86	0.04	0.03	0.01
$\Sigma_b^{*+} \pi^0$	0.43	0.71	0.28	1.02	0.03	0.03
$\Sigma_b^{*0} \pi^+$	0.43	0.71	0.28	1.02	0.03	0.03
$\Sigma_b^+ \eta$	0.08	0.04	0.09	5×10^{-4}	1×10^{-4}	5×10^{-5}
$\Sigma_b^{*+} \eta$	0.06	0.12	0.02	0.08	8×10^{-5}	5×10^{-5}
$\Xi_b^0 K^+$	0.46	0.51	...	...	2×10^{-3}	1×10^{-3}
$\Xi_b^{*0} K^+$	0.02	0.01	0.01	1×10^{-5}	9×10^{-7}	1×10^{-7}
$\Xi_b^{*0} K^+$	0.02	0.04	2×10^{-3}	0.01	2×10^{-7}	1×10^{-8}
$B^0 p$	23.36	0.65	12.25	1.51	0.04	1.94
$B^{*0} p$	16.57	41.53	10.75	21.72	2.99	1.29
$B^- \Delta^{++}$	0.87	0.26	...	...	...	...
$B^0 \Delta^+$	0.29	0.09	...	...	...	...
$B^{*-} \Delta^{++}$	...	0.04	...	...	...	...
$B^{*0} \Delta^+$	...	0.01	...	...	...	...
$B_s \Sigma^+$	...	5×10^{-4}	...	...	...	...
Total	45.91	47.62	25.68	25.72	3.51	3.65

$$\Gamma\left[\Sigma_{b1}\left(\frac{3}{2}^-, 2P\right) \rightarrow BN\right] : \Gamma\left[\Sigma_{b1}\left(\frac{3}{2}^-, 2P\right) \rightarrow B^*N\right] = 0.65, \quad (25)$$

and

$$\Gamma\left[\Sigma_{b2}\left(\frac{5}{2}^-, 2P\right) \rightarrow BN\right] : \Gamma\left[\Sigma_{b1}\left(\frac{3}{2}^-, 2P\right) \rightarrow B^*N\right] = 0.75. \quad (27)$$

which are essential to distinguish them. The two $j = 2$ states mainly decay into the $\Lambda\pi$, BN , and B^*N final states, and also have similar masses and total decay widths. The partial decay width ratios of BN and B^*N are

$$\Gamma\left[\Sigma_{b2}\left(\frac{3}{2}^-, 2P\right) \rightarrow BN\right] : \Gamma\left[\Sigma_{b1}\left(\frac{1}{2}^-, 2P\right) \rightarrow B^*N\right] = 0.03 \quad (26)$$

FIG. 9. The spatial overlaps $|I_{00}^{00}(p)|^2$ versus the final momentum p for the initial $\Lambda_c(3S)$, $\Sigma_c(3S)$, and $\Sigma_c^*(3S)$ baryons.

These five narrow $\Sigma_b(2P)$ states can be searched in BN and B^*N final states, and the ratios of BN and B^*N can help us to distinguish the states with same light spin j .

C. $\Sigma_Q(2D)$

In the constituent quark model, six $\Sigma_c(2D)$ states are allowed to exist. The predicted masses are much higher than the DN , D^*N , $D\Delta$, and $D^*\Delta$ thresholds, and these channels provide dominating contributions to their total decay widths. From Table XIV, the total decay widths of these six states lie in 41–102 MeV, which can be searched in the heavy meson plus light baryon channels experimentally.

The six $\Sigma_b(2D)$ states have rather higher masses of around 6600 MeV. From Table XV, it can be seen that they mainly decay into the heavy meson plus light baryon final states, which are similar to the charmed partners. The total decay widths varies from 44 to 102 MeV, which can be tested in future experiments.

D. $\Sigma_Q(1F)$

For the six $\Sigma_c(1F)$ states, the predicted masses are about 3209–3288 MeV, which are near the $D^*\Delta$ threshold. With these masses, the calculated strong decay widths are shown in Table XVI. Roughly speaking, the DN , D^*N , and $D\Delta$

decay modes are the dominating, while other decay channels seem to be small. Their calculated total decay widths are about 6–53 MeV, which are relatively narrow. The DN , D^*N , and $D\Delta$ channels may be ideal channels to hunt for these F -wave states.

The predicted masses of six $\Sigma_b(1F)$ states are around 6500 MeV. Due to the limit of phase space, the $B\Delta$ and $B^*\Delta$ decay modes are forbidden or provide negligible contributions. In this situation, the BN and B^*N channels become the dominating decay modes, and the $\Lambda_b\pi$ channel is also important for the $j=2$ and $j=4$ states. From Table XVII, the calculated total decay widths range from 4 to 46 MeV, and the ideal channels to search for these states are BN , B^*N , and $\Lambda_b\pi$ final states.

E. Discussions on decay modes

From our present calculations, it can be found that most of the λ -mode higher excited Λ_Q and Σ_Q states mainly decay into the final states with one heavy meson plus one light baryon. Several factors, such as phase space, flavor overlap, Clebsch-Gordan coefficients, and spatial overlaps, may result in this special feature. After careful examinations, it is found that some significant partial decay widths of heavy meson plus light baryon modes in various places mainly come from the larger spatial overlaps, while the phase space, flavor overlap, and Clebsch-Gordan coefficients may cause secondary contribution.

For instance, we plot the spatial overlaps $|I_{M_L^B M_L^C}^{M_L^A m}(p)|^2$ versus the final momentum p for the initial $\Lambda_c(3S)$, $\Sigma_c(3S)$, and $\Sigma_c^*(3S)$ baryons in Fig. 9. In this case, only the $I_{00}^{00}(p)$ s are nonzero, and four types of spatial overlaps can be classified by the final states. It can be seen that for the heavy meson plus light baryon modes the spatial overlaps are significantly larger in most regions. For some cases, together with the effects of phase space, flavor overlap, and Clebsch-Gordan coefficients, the partial decay widths of heavy meson plus light baryon modes are larger than that of heavy baryon plus light meson channels due to the significant spatial overlaps.

One possible interpretation of the significant spatial overlaps of some heavy meson plus light baryon modes is given as follows. For the higher excited λ -mode states, the light quark subsystem has no excitation and the final states also lie in the ground states. When the heavy meson plus light baryon decay mode occurs, the whole light quark subsystem goes into the final baryon as a spectator. Without the extra separation, the overlap of ρ -mode wave functions between initial and final baryons equals to 100% for the

heavy meson plus light baryon mode, and then the total spatial overlap may be large enough.

V. SUMMARY

In this work, we preform a systematic study of the strong decays of the higher excited singly heavy baryons Λ_Q and Σ_Q states. With the predicted masses of the relativistic quark model, the two body Okubo-Zweig-Iizuka-allowed strong decay widths of $\Lambda_Q(3S)$, $\Lambda_Q(2P)$, $\Lambda_Q(2D)$, $\Lambda_Q(1F)$, $\Sigma_Q(3S)$, $\Sigma_Q(2P)$, $\Sigma_Q(2D)$, and $\Sigma_Q(1F)$ states are calculated by using the 3P_0 quark pair creation model. Our results may provide useful information to look for these higher Λ_Q and Σ_Q states.

It should be mention that most of the λ -mode higher excited Λ_Q and Σ_Q states have relatively narrow total widths, and mainly decay into the heavy meson plus light baryon final states rather than heavy baryon plus light meson decay modes. For the heavy meson plus light baryon case, the whole light quark subsystem goes into the final baryon as a spectator and the overlap of ρ -mode wave functions between initial and final states equals to 100%, which might make the strong decay easier. These specific decay modes can help us to establish the λ -mode higher singly baryon spectrum since the ρ -mode states decaying into the heavy meson plus light baryon channels are highly suppressed. To be more specific, most of the higher Λ_Q states mainly decay into the $D^{(*)}N$ or $B^{(*)}N$ channels, while most of the higher Σ_Q states mainly decay into the $D^{(*)}\Delta$ or $B^{(*)}\Delta$ final states. However, for some of the $2P$ and $1F$ states, the predicted masses may lie near or below the relevant $D^{(*)}N$, $B^{(*)}N$, $D^{(*)}\Delta$, or $B^{(*)}\Delta$ threshold, and other decay channels may be important due to the phase space constraints.

Considering the uncertainties of the adopted masses and the 3P_0 model, one does not expect the estimated decay widths are accurate. Our predictions should bear uncertainties about 30% and be regarded as a semiquantitative estimation. Still, our calculations demonstrate the general feature and provide abundant theoretical information for these higher excited singly heavy baryons, which may be helpful for future experimental searches.

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