Canonical interpretations of the newly observed $\Xi_c(2923)^0$, $\Xi_c(2939)^0$, and $\Xi_c(2965)^0$ resonances

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Abstract Three neutral resonances $\Xi_c(2923)^0$, $\Xi_c(2939)^0$, and $\Xi_c(2965)^0$ have been observed in the $\Lambda_c^+ K^-$ mass spectrum by the LHCb Collaboration. Given the Ξ_c and Ξ'_c mass spectra predicted by the constituent quark models, these three resonances are tentatively treated as the λ -mode $\Xi_c(2S)$, $\Xi'_c(2S)$, $\Xi_c^*(2S)$, and $\Xi'_c(1P)$ states, and their strong decay behaviors are calculated within the 3P_0 model. Our results indicate that the $\Xi_c(2923)^0$ and $\Xi_c(2939)^0$ can be clarified into the $J^P = 3/2^-$ and $5/2^-$ $\Xi'_c(1P)$ states respectively, and the $\Xi_c(2965)^0$ can be regarded as the $J^P = 1/2^+$ $\Xi'_c(2S)$ state. Also, we suggest that the previous observed $\Xi_c(2930)$ may be the overlap of two structures $\Xi_c(2923)$ and $\Xi_c(2939)$, and the $\Xi_c(2970)$ should be the same state as $\Xi_c(2965)$. Other theoretical information on the missing $\Xi_c(2S)$, $\Xi_c^*(2S)$, and $\Xi'_c(1P)$ states may be helpful for future experimental searches.

1 Introduction

A charmed strange baryon Ξ_c is composed of a heavy charm quark, a light up or down quark, and a strange quark. Under the classification of constituent quark model, the Ξ_c baryons can be divided into two families, the antisymmetric flavor configuration $\bar{3}_F$ and symmetric flavor configuration 6_F . To distinguish these two families, the states with $\bar{3}_F$ flavor part are denoted as Ξ_c states, and the notation Ξ'_c stands for the states belonging to the 6_F flavor configuration. Unlike the Λ_c and Σ_c states with different isospins, both Ξ_c and Ξ'_c baryons have the same isospin $I = 1/2$. Since the observed resonances may belong to the flavor $\bar{3}_F$ or 6_F and can not be distinguished through the quantum numbers, it is more complicated and challenging to study these states both experimentally and theoretically.

Very recently, the LHCb Collaboration reported three new resonances $\Xi_c(2923)^0$, $\Xi_c(2939)^0$, and $\Xi_c(2965)^0$ in the $\Lambda_c^+ K^-$ mass spectrum [1]. The large significance indicates that these three baryons are unambiguously observed, and the measured masses and total widths are presented as follows,

$$m[\Xi_c(2923)^0] = 2923.04 \pm 0.25 \pm 0.20 \pm 0.14 \text{ MeV}, \quad (1)$$

$$\Gamma[\Xi_c(2923)^0] = 7.1 \pm 0.8 \pm 1.8 \text{ MeV}, \quad (2)$$

$$m[\Xi_c(2939)^0] = 2938.55 \pm 0.21 \pm 0.17 \pm 0.14 \text{ MeV}, \quad (3)$$

$$\Gamma[\Xi_c(2939)^0] = 10.2 \pm 0.8 \pm 1.1 \text{ MeV}, \quad (4)$$

$$m[\Xi_c(2965)^0] = 2964.88 \pm 0.26 \pm 0.14 \pm 0.14 \text{ MeV}, \quad (5)$$

$$\Gamma[\Xi_c(2965)^0] = 14.1 \pm 0.9 \pm 1.3 \text{ MeV}. \quad (6)$$

The LHCb Collaboration also pointed out several equalities of mass gaps,

$$m[\Omega_c(3050)^0] - m[\Xi_c(2923)^0] \simeq 125 \text{ MeV}, \quad (7)$$

$$m[\Omega_c(3065)^0] - m[\Xi_c(2939)^0] \simeq 125 \text{ MeV}, \quad (8)$$

$$m[\Omega_c(3090)^0] - m[\Xi_c(2965)^0] \simeq 125 \text{ MeV}, \quad (9)$$

$$m[\Xi_c(2923)^0] - m[\Sigma_c(2800)^0] \simeq 125 \text{ MeV}, \quad (10)$$

which strongly suggests that the $\Xi_c(2923)^0$, $\Xi_c(2939)^0$, and $\Xi_c(2965)^0$ should be the corresponding charmed strange partners of the $\Omega_c(3050)^0$, $\Omega_c(3065)^0$, and $\Omega_c(3090)^0$, respectively. Also, the $\Sigma_c(2800)^0$ may be the non-strange partner of the $\Xi_c(2923)^0$ and $\Omega_c(3050)^0$. A recent work with QCD sum rule suggests that these three newly observed states can be explained as P -wave Ξ'_c baryons [2].

From the Review of Particle Physics [3], there exist ten observed Ξ_c or Ξ'_c baryons. Plenty of theoretical works have been done to investigate their inner structures [4–35]. Three lowest structures correspond to the ground states Ξ_c , Ξ'_c , and Ξ_c^* undoubtedly. The $\Xi_c(2790)$ and $\Xi_c(2815)$ should belong to the $\Xi_c(1P)$ doublet, while the interpretations of other resonances are in dispute. For the resonances lying in the range of 2900 ~ 3000 MeV, there exist two resonances $\Xi_c(2930)$

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and $\Xi_c(2970)$, which were reported by the BaBar and Belle Collaborations, respectively [36, 37]. Theoretical interpretations on $\Xi_c(2930)$ and $\Xi_c(2970)$ resonances include conventional charmed strange baryons [6–22] and molecular states [23–26] with various quantum numbers. The observations of LHCb Collaboration indicate that the $\Xi_c(2930)^0$ should be the overlap of the two narrow states $\Xi_c(2923)^0$ and $\Xi_c(2939)^0$, and whether the $\Xi_c(2970)^0$ and $\Xi_c(2965)^0$ structures are different or not needs further investigations [1]. Above 3000 MeV, the situation becomes more complicated, and the detailed explanations and discussions can be found in the reviews [38–40]. It can be seen that the low-lying Ξ_c and Ξ'_c spectra are far from being established.

The observations of $\Xi_c(2923)^0$, $\Xi_c(2939)^0$, and $\Xi_c(2965)^0$ resonances provide a good opportunity to study the low-lying Ξ_c and Ξ'_c spectra. Compared with the predictions of constituent quark models [4–8], these three resonances lie in the mass region of λ -mode $\Xi_c(2S)$, $\Xi'_c(2S)$, $\Xi_c^*(2S)$, and $\Xi'_c(1P)$ states. Although the strong decay behaviors of these low-lying Ξ_c and Ξ'_c states have been studied by several works within the quark models [7–14], it is essential to clarify the newly observed $\Xi_c(2923)^0$, $\Xi_c(2939)^0$, and $\Xi_c(2965)^0$ resonances into the Ξ_c or Ξ'_c family. Due to the lack of the accurate experimental information, the previous works did not agree with each other and can hardly establish the low-lying Ξ_c and Ξ'_c spectra. In fact, the $\Xi_c(2930)^0$ which is absent in present experimental observation, may have caused lots of troubles in previous studies.

In this issue, we calculate the strong decay behaviors of the newly observed $\Xi_c(2923)^0$, $\Xi_c(2939)^0$, and $\Xi_c(2965)^0$ resonances under various assignments within the 3P_0 model. Our results suggest that the $\Xi_c(2923)^0$ and $\Xi_c(2939)^0$ can be clarified into the λ -mode $J^P = 3/2^-$ and $5/2^-$ $\Xi'_c(1P)$ states respectively, and the $\Xi_c(2965)^0$ can be assigned as the λ -mode $J^P = 1/2^+$ $\Xi'_c(2S)$ state. Meanwhile, the strong decays of some missing partners are also presented, which may provide valuable information for future experimental searches.

This paper is organized as follows. The 3P_0 model and notations are introduced in Sect. 2. The strong decay behaviors of the $\Xi_c(2923)^0$, $\Xi_c(2939)^0$, and $\Xi_c(2965)^0$ resonances are estimated and discussed in Sect. 3. A summary is given in the last section.

2 3P_0 model and notations

In present work, the 3P_0 model is adopted to estimate the strong decays of the $\Xi_c(2923)^0$, $\Xi_c(2939)^0$, and $\Xi_c(2965)^0$ resonances. This model has been extensively used for the strong decay behaviors of conventional hadrons and made great successes. There exist plenty of literatures on the 3P_0

model and some details can be found in Refs. [8, 9, 12, 41–45]. Here, we only present the main ingredients of the 3P_0 model. For a Ξ_c baryon, the transition operator T of the decay $A \rightarrow BC$ is given by

$$T = -3\gamma \sum_m \langle 1m1 - m | 00 \rangle \int d^3p_4 d^3p_5 \delta^3(\mathbf{p}_4 + \mathbf{p}_5) \times \mathcal{Y}_1^m \left(\frac{\mathbf{p}_4 - \mathbf{p}_5}{2} \right) \chi_{1,-m}^{45} \phi_0^{45} \omega_0^{45} b_{4i}^\dagger(\mathbf{p}_4) d_{4j}^\dagger(\mathbf{p}_5), \quad (11)$$

where γ is a dimensionless $q_4\bar{q}_5$ pair creation strength, and $\mathbf{p}_4$ and $\mathbf{p}_5$ are the momenta of the created quark q_4 and antiquark $\bar{q}_5$, respectively. The solid harmonic polynomial $\mathcal{Y}_1^m(\mathbf{p}) \equiv |p| Y_1^m(\theta_p, \phi_p)$ reflects the P -wave distribution of the $q_4\bar{q}_5$ in the momentum space. $\phi_0^{45} = (u\bar{u} + d\bar{d} + s\bar{s})/\sqrt{3}$, $\omega_0^{45} = \delta_{ij}$, and $\chi_{1,-m}^{45}$ are the flavor, color, and spin wave functions of the $q_4\bar{q}_5$, respectively.

With the transition operator, the helicity amplitude $\mathcal{M}^{M_{JA} M_{JB} M_{JC}}$ is defined as

$$\langle BC | T | A \rangle = \delta^3(\mathbf{P}_A - \mathbf{P}_B - \mathbf{P}_C) \mathcal{M}^{M_{JA} M_{JB} M_{JC}}. \quad (12)$$

The explicit formula of the helicity amplitude can be found in Refs. [8, 9, 12, 44, 45]. Then, the decay width of $A \rightarrow BC$ process can be obtained straightforward

$$\Gamma = \pi^2 \frac{p}{M_A^2} \frac{1}{2J_A + 1} \sum_{M_{JA}, M_{JB}, M_{JC}} |\mathcal{M}^{M_{JA} M_{JB} M_{JC}}|^2, \quad (13)$$

where $p = |\mathbf{p}|$ is the momentum of the final hadrons in the center of mass system.

The notations of relevant initial states and the predicted masses from quark models are listed in Table 1. Here, the ρ -mode quantum numbers $n_\rho = l_\rho = 0$ are omitted, since only the λ -mode $\Xi_c(2S)$, $\Xi'_c(2S)$, $\Xi_c^*(2S)$, and $\Xi'_c(1P)$ states are considered. For the masses of these initial states, we first adopt the experimental values of $\Xi_c(2923)^0$, $\Xi_c(2939)^0$, and $\Xi_c(2965)^0$ resonances by assuming that they are possible candidates. If a assignment is finally disfavored, the predicted mass of this state is applied to recalculate its strong decays. The masses of final states are taken from the Review of Particle Physics [3].

All the parameters in the 3P_0 model used here are the same as our previous works [44–47], which have been employed to describe the strong decay behaviors of various singly heavy baryons successfully. More specifically, the effective value $R = 2.5 \text{ GeV}^{-1}$ is adopted for the pseudoscalar mesons [48], while the $\alpha_\rho = 400 \text{ MeV}$, 420 MeV , and 440 MeV are applied for the $\Lambda_{c(b)}$ and $\Sigma_{c(b)}$, $\Xi_{c(b)}$ and $\Xi'_{c(b)}$, and $\Omega_{c(b)}$, respectively [44, 49]. The α_λ can be obtained

$$\alpha_\lambda = \left(\frac{3m_Q}{m_{q_1} + m_{q_2} + m_Q} \right)^{1/4} \alpha_\rho, \quad (14)$$

Table 1 Notations, quantum numbers, and the predicted masses of the relevant states. The n_λ and l_λ are the nodal quantum number and orbital angular momentum between the light quark subsystem and the charm quark, respectively. L , S_ρ , and j stand for the total orbital angular momentum, total spin of the two light quarks, total angular momentum of L and S_ρ , respectively. J^P represent the spin-parity of the hadron. The units are in MeV

State	n_λ	l_λ	L	S_ρ	j	J^P	RM [6]	NR [8]
$\Xi_c(2S)$	1	0	0	0	0	$\frac{1}{2}^+$	2959	2940
$\Xi'_c(2S)$	1	0	0	1	1	$\frac{1}{2}^+$	2983	2977
$\Xi_c^{*}(2S)$	1	0	0	1	1	$\frac{3}{2}^+$	3026	3007
$\Xi'_{c0}(\frac{1}{2}^-)$	0	1	1	1	0	$\frac{1}{2}^-$	2936	2839
$\Xi'_{c1}(\frac{1}{2}^-)$	0	1	1	1	1	$\frac{1}{2}^-$	2854	2900
$\Xi'_{c1}(\frac{3}{2}^-)$	0	1	1	1	1	$\frac{3}{2}^-$	2935	2932
$\Xi'_{c2}(\frac{3}{2}^-)$	0	1	1	1	2	$\frac{3}{2}^-$	2912	2921
$\Xi'_{c2}(\frac{5}{2}^-)$	0	1	1	1	2	$\frac{5}{2}^-$	2929	2927

where the m_Q and $m_{q_1}(m_{q_2})$ are the heavy and light quark masses, respectively. The $m_{u/d} = 220$ MeV, $m_s = 419$ MeV, and $m_c = 1628$ MeV are introduced to explicitly take into account the quark mass differences [48,50,51]. The overall parameter γ equals to 9.83 is obtained by reproducing the well established process, and more discussions on this parameter can be found in Ref. [47]. The dependence of the harmonic parameter α_ρ for baryons will be discussed in the following section.

3 Strong decays

3.1 $\Xi_c(2S)$ state

In the constituent quark model, only one λ -mode $\Xi_c(2S)$ state exists. From Table 1, the predicted masses of the $\Xi_c(2S)$ state are 2959 and 2940 MeV within the relativistic and nonrelativistic quark models, respectively. The strong decay behaviors of the $\Xi_c(2923)^0$, $\Xi_c(2939)^0$, and $\Xi_c(2965)^0$ under $\Xi_c(2S)$ assignments are presented in Table 2. It is shown that the total decay widths for the $\Xi_c(2923)^0$, $\Xi_c(2939)^0$, and $\Xi_c(2965)^0$ are predicted to be 4.41, 5.31, and 7.66 MeV, respectively. The calculated total decay widths are smaller than the experimental data. Moreover, the $\Lambda_c \bar{K}$ decay mode is forbidden for the $\Xi_c(2S)$ state due to the quantum number conservation, which contradicts with the experimental observations. Thus, the $\Xi_c(2S)$ assignment can be totally excluded.

Given the flavor symmetry, the mass gap between $\Xi_c(2S)$ and Ξ_c should be similar with the non-strange Λ_c case, that

Table 2 Strong decays of the $\Xi_c(2923)^0$, $\Xi_c(2939)^0$, and $\Xi_c(2965)^0$ under $\Xi_c(2S)$ assignments in MeV

Mode	$\Xi_c(2S)$		
	$\Xi_c(2923)^0$	$\Xi_c(2939)^0$	$\Xi_c(2965)^0$
$\Xi'_c \pi$	2.36	2.74	3.44
$\Xi_c^{*} \pi$	2.05	2.57	3.58
$\Sigma_c \bar{K}$	...	...	0.64
Total width	4.41	5.31	7.66
Experiments	$7.1 \pm 0.8 \pm 1.8$	$10.2 \pm 0.8 \pm 1.1$	$14.1 \pm 0.9 \pm 1.3$

Table 3 Strong decays of the $\Xi_c(2S)$ state with a mass of 2959 MeV

Mode	$\Xi_c(2S)$
$\Xi'_c \pi$	3.28
$\Xi_c^{*} \pi$	3.34
$\Sigma_c \bar{K}$	0.31
Total width	6.93

is

$$m[\Xi_c(2S)] - m[\Xi_c] \simeq m[\Lambda_c(2S)] - m[\Lambda_c] = 480 \text{ MeV}. \quad (15)$$

With this approximate equality, the mass of $\Xi_c(2S)$ state should be around 2951 MeV, which agrees well with the quark model predictions. We adopt the 2959 MeV predicted by relativistic quark model to calculate the strong decays for the $\Xi_c(2S)$. From Table 3, it can be seen that the $\Xi_c(2S)$ state should be a rather narrow state, and the branching ratios for this state are predicted to be

$$Br(\Xi'_c \pi, \Xi_c^{*} \pi, \Sigma_c \bar{K}) = 47.3\%, 48.2\%, 4.5\%, \quad (16)$$

which is independent with the overall strength γ . The predicted narrow width of $\Xi_c(2S)$ state here is consistent with that of the 3P_0 model [9,13] and chiral quark model [10], but quite different with the result of potential model [8]. The predicted branching ratios of ours are consistent with these works [8,10,13], which suggests that the future experiments can search for the $\Xi_c(2S)$ state in the $\Xi'_c \pi$ and $\Xi_c^{*} \pi$ final states.

3.2 $\Xi'_c(2S)$ and $\Xi_c^{*}(2S)$ states

The strong decays of the $\Xi_c(2923)^0$, $\Xi_c(2939)^0$, and $\Xi_c(2965)^0$ as $\Xi'_c(2S)$ and $\Xi_c^{*}(2S)$ states are calculated and listed in Table 4. It is shown that the predicted widths of these assignments are somewhat larger than the experimental data. Given the uncertainties of the 3P_0 model, these assignments seem to be acceptable. However, from Table 1, the predicted masses of the $\Xi'_c(2S)$ and $\Xi_c^{*}(2S)$ are around 2980 and 3010 MeV, which are significantly larger than the $\Xi_c(2923)^0$ and $\Xi_c(2939)^0$ resonances. When the masses and decay widths

Table 4 Strong decays of the $\Xi_c(2923)^0$, $\Xi_c(2939)^0$, and $\Xi_c(2965)^0$ as $\Xi'_c(2S)$ and $\Xi_c^{*}(2S)$ states in MeV

Mode	$\Xi'_c(2S)$			$\Xi_c^{*}(2S)$		
	$\Xi_c(2923)^0$	$\Xi_c(2939)^0$	$\Xi_c(2965)^0$	$\Xi_c(2923)^0$	$\Xi_c(2939)^0$	$\Xi_c(2965)^0$
$\Xi_c\pi$	5.36	5.84	6.64	5.36	5.84	6.64
$\Xi'_c\pi$	3.14	3.65	4.58	0.79	0.91	1.15
$\Xi_c^{*}\pi$	0.69	0.86	1.20	1.71	2.14	2.99
$\Lambda_c\bar{K}$	4.76	5.35	6.29	4.76	5.35	6.29
$\Sigma_c\bar{K}$	...	...	0.86	...	...	0.21
Total width	13.95	15.70	19.57	12.62	14.24	17.28
Experiments	$7.1 \pm 0.8 \pm 1.8$	$10.2 \pm 0.8 \pm 1.1$	$14.1 \pm 0.9 \pm 1.3$	$7.1 \pm 0.8 \pm 1.8$	$10.2 \pm 0.8 \pm 1.1$	$14.1 \pm 0.9 \pm 1.3$

are considered together, the $\Xi_c(2965)^0$ as $\Xi'_c(2S)$ state is favored and other assignments are disfavored.

Two factors, the harmonic oscillator parameter α_ρ and overall strength γ , may affect the final total decay width. We plot the decay widths of the $\Xi_c(2965)^0$ under $\Xi'_c(2S)$ assignment versus the α_ρ in Fig. 1. It can be seen that when the α_ρ varies, the partial and total decay widths are almost unchanged. Within the reasonable range of α_ρ , our conclusions remain. The uncertainties arising from the overall constant γ can be eliminated when the branching ratios are concentrated. The predicted branching ratios of dominating channels for the $\Xi_c(2965)^0$ are

$$Br(\Xi_c\pi, \Xi'_c\pi, \Lambda_c\bar{K}) = 34.0\%, 23.4\%, 32.2\%, \quad (17)$$

which is also consistent with experimental observation in the $\Lambda_c\bar{K}$ mass spectrum.

As mentioned in the Introduction, the $\Xi_c(2965)^0$ may be the corresponding charmed strange partner of the $\Omega_c(3090)$. Although various interpretations of the $\Omega_c(3090)$ exist, the predicted mass of $\Omega_c(2S)$ state is 3088 MeV in the relativistic quark model [6], which indicates that the $\Omega_c(3090)$ as the $\Omega_c(2S)$ state is possible. Moreover, a structure $\Sigma_c(2850)^0$ with 2846 MeV have been reported by the BaBar Collaboration [52], and the mass gap between $\Xi_c(2965)^0$ and $\Sigma_c(2850)^0$ is

$$m[\Xi_c(2965)^0] - m[\Sigma_c(2850)^0] = 119 \text{ MeV}. \quad (18)$$

This mass gap is similar with $m[\Omega_c(3090)^0] - m[\Xi_c(2965)^0]$, which suggests that the $\Sigma_c(2850)^0$ structure may be the nonstrange partner of $\Xi_c(2965)^0$. Meanwhile, the mass and strong decay behaviors of $\Sigma_c(2850)^0$ suggests that it should correspond to the $\Sigma_c(2S)$ state [8, 19]. All these evidences support $\Xi_c(2965)^0$ as the $\Xi'_c(2S)$ state. Further studies on the low-lying Σ_c , Ξ'_c and Ω_c states may reveal more connections among these three families.

When we regard the $\Xi_c(2965)^0$ as $\Xi'_c(2S)$ state, the mass of $\Xi_c^{*}(2S)$ state can be estimated via the fine splitting. In the traditional quark model, the fine splitting of $2S$ states should

Fig. 1 The dependence on the harmonic oscillator parameter α_ρ of the $\Xi_c(2965)^0$ as $\Xi'_c(2S)$ state. When the α_ρ for the $\Xi_c(2965)^0$ varies from 380 to 460 MeV, the corresponding ones for the final non-strange states change in the range of 360 ~ 440 MeV

be smaller than the corresponding $1S$ ones, that is

$$m[\Xi_c^{*}(2S)] - m[\Xi'_c(2S)] < m[\Xi_c^{*}] - m[\Xi'_c] = 67 \text{ MeV}, \quad (19)$$

which is consistent with the predicted fine splitting by the quark models [6, 8]. Here, we adopt the 3007 MeV to calculate the strong decays of $\Xi_c^{*}(2S)$. From Table 5, the predicted total decay width is about 23 MeV, and the dominating decay modes are $\Xi_c\pi$, $\Xi_c^{*}\pi$, and $\Lambda_c\bar{K}$. The branching ratios are

$$Br(\Xi_c\pi, \Xi_c^{*}\pi, \Lambda_c\bar{K}) = 34.1\%, 20.0\%, 32.7\%, \quad (20)$$

which are independent with the quark pair creation strength γ and can be tested by future experiments.

3.3 $\Xi'_c(1P)$ states

Five λ -mode $\Xi'_c(1P)$ states, denoted as $\Xi'_{c0}(\frac{1}{2}^-)$, $\Xi'_{c1}(\frac{1}{2}^-)$, $\Xi'_{c1}(\frac{3}{2}^-)$, $\Xi'_{c2}(\frac{3}{2}^-)$, and $\Xi'_{c2}(\frac{5}{2}^-)$, are allowed in the conventional quark model. From Table 1, it is shown that the predicted masses are in the range of 2854 ~ 2936 MeV, which indicates that the $\Xi_c(2923)^0$ and $\Xi_c(2939)^0$ are good

Table 5 Strong decays of the $\Xi_c^{*}(2S)$ state with a mass of 3007 MeV

Mode	$\Xi_c^{*}(2S)$
$\Xi_c \pi$	7.89
$\Xi_c' \pi$	1.55
$\Xi_c^{*} \pi$	4.63
$\Lambda_c \bar{K}$	7.57
$\Sigma_c \bar{K}$	1.48
Total width	23.12

Table 6 Total decay widths of the $\Xi_c(2923)^0$, $\Xi_c(2939)^0$, and $\Xi_c(2965)^0$ under various $\Xi_c'(1P)$ assignments in MeV

State	$\Xi_c(2923)^0$	$\Xi_c(2939)^0$	$\Xi_c(2965)^0$
$\Xi_{c0}'(\frac{1}{2}^-)$	306.83	304.83	297.21
$\Xi_{c1}'(\frac{1}{2}^-)$	94.23	98.22	249.94
$\Xi_{c1}'(\frac{3}{2}^-)$	72.39	78.42	87.88
$\Xi_{c2}'(\frac{3}{2}^-)$	8.56	10.66	15.01
$\Xi_{c2}'(\frac{5}{2}^-)$	8.24	10.25	14.42
Experiments	$7.1 \pm 0.8 \pm 1.8$	$10.2 \pm 0.8 \pm 1.1$	$14.1 \pm 0.9 \pm 1.3$

candidates of these $\Xi_c'(1P)$ states. Although the $\Xi_c(2965)^0$ lies higher than the predicted masses and can be assigned as the $\Xi_c'(2S)$ state, the possibility of $\Xi_c(2965)^0$ as $\Xi_c'(1P)$ states are also calculated. The total decay widths with various assignments are presented in Table 6. For the $j = 0$ state, the predicted total decay width is rather large, which can be fully excluded. For the two $j = 1$ states, the total decay widths also seem larger than the experimental data and the $\Lambda_c \bar{K}$ decay mode is forbidden due to the quantum number conservation. For the two $j = 2$ states, the calculated total decay widths agree well with the experimental data, which indicate that all the $\Xi_c(2923)^0$, $\Xi_c(2939)^0$, and $\Xi_c(2965)^0$ structures can be regarded as the $\Xi_{c2}'(\frac{3}{2}^-)$ and $\Xi_{c2}'(\frac{5}{2}^-)$ states. To describe these three resonances simultaneously, we prefer the normal mass order and assign the $\Xi_c(2923)^0$, $\Xi_c(2939)^0$, and $\Xi_c(2965)^0$ as $\Xi_{c2}'(\frac{3}{2}^-)$, $\Xi_{c2}'(\frac{5}{2}^-)$, and $\Xi_c'(2S)$ states, respectively.

Moreover, the physical structures can be the mixing of the quark model states with same J^P , that is to say

$$\begin{pmatrix} |1P \ 1/2^- \rangle_1 \\ |1P \ 1/2^- \rangle_2 \end{pmatrix} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} |1/2^-, j=0 \rangle \\ |1/2^-, j=1 \rangle \end{pmatrix}, \quad (21)$$

$$\begin{pmatrix} |1P \ 3/2^- \rangle_1 \\ |1P \ 3/2^- \rangle_2 \end{pmatrix} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} |3/2^-, j=1 \rangle \\ |3/2^-, j=2 \rangle \end{pmatrix}. \quad (22)$$

In the heavy quark limit, these mixing angles should be zero and the heavy quark symmetry is preserved. The finite charm quark mass may break this symmetry explicitly, and the physical states and quark model states may have a small diver-

Fig. 2 The total decay widths under various assignments as functions of the mixing angle θ in the range of $-30^\circ \sim 30^\circ$. The red solid lines stand for the $|1P \ 1/2^- \rangle_1$ and $|1P \ 3/2^- \rangle_1$ states, and the blue dashed curves are the $|1P \ 1/2^- \rangle_2$ and $|1P \ 3/2^- \rangle_2$ states. The green bands stand for the experimental total decay widths

gence with a nonzero mixing angle. The dependence on the mixing angle θ in the range of $-30^\circ \sim 30^\circ$ are presented in Fig. 2. It is shown that the two $J^P = 1/2^-$ states can be excluded, while the $J^P = 3/2^-$ assignments are allowed. From the mixing scheme, all the $\Xi_c(2923)^0$, $\Xi_c(2939)^0$, and $\Xi_c(2965)^0$ may belong to the narrower $|1P \ 3/2^- \rangle_2$ state. Actually, compared with the experimental data, the mixing angle should be extremely small, and the $|1P \ 3/2^- \rangle_2$ state is almost same as the pure $\Xi_{c2}'(\frac{3}{2}^-)$ state. Thus, the mixing effects can be neglected here, and our above assignments of these three resonances remain.

These interpretations on the $\Xi_c(2923)^0$, $\Xi_c(2939)^0$, and $\Xi_c(2965)^0$ are different with the results within QCD sum rules, where all the resonances are clarified into the $\Xi_c'(1P)$ states [2]. It can be noticed that the quite different interpretations between two approaches arise from the different predictions of two $j = 1$ states and $J^P = 5/2^-$ state. Moreover, these features also appear in other flavor 6_F states of singly heavy baryons, such as $\Sigma_b(1P)$ states [45, 53]. It is very interesting to find out the underlying reasons, but the huge technical difference between these two approaches makes the direct comparisons rather difficult. Since both approaches claim

Table 7 Strong decays of the $\Xi_c(2923)^0$ and $\Xi_c(2939)^0$ under $j = 2$ assignments in MeV

Mode	$\Xi_c(2923)^0$ as $\Xi'_{c2}(\frac{3}{2}^-)$	$\Xi_c(2939)^0$ as $\Xi'_{c2}(\frac{5}{2}^-)$
$\Xi_c\pi$	4.79	5.72
$\Xi'_c\pi$	0.76	0.44
$\Xi_c^*\pi$	0.18	0.42
$\Lambda_c\bar{K}$	2.83	3.67
Total width	8.56	10.25
Experiments	$7.1 \pm 0.8 \pm 1.8$	$10.2 \pm 0.8 \pm 1.1$

that the heavy quark symmetry is approximatively preserved in their frameworks, the heavy quark symmetry may become a bridge to connect them. More sophisticated investigations are needed to clarify the differences and underlying reasons between the 3P_0 model and QCD sum rules.

The partial decay widths for the $\Xi_c(2923)^0$ and $\Xi_c(2939)^0$ under $j = 2$ assignments are also presented in Table 7 for reference. It is shown that the $\Xi_c\pi$, and $\Lambda_c\bar{K}$ are the dominating decay modes for these two states. Under our present interpretations, three P -wave states, $\Xi'_{c0}(\frac{1}{2}^-)$, $\Xi'_{c1}(\frac{1}{2}^-)$ and $\Xi'_{c1}(\frac{3}{2}^-)$, have not been observed. For the $j = 0$ state, it may be hardly found due to its larger total decay width. For the two $j = 1$ states, the $\Xi_c\pi$ and $\Lambda_c\bar{K}$ channels are forbidden, and other final states, such as $\Xi'_c\pi$ and $\Xi_c^*\pi$, can help us to hunt for them. Moreover, the similarities among Σ_c , Ξ'_c and Ω_c spectra may also provide valuable clues, and more experimental information and theoretical efforts on these flavor 6_F states are needed.

In the Review of Particle Physics [3], there also exist two states, $\Xi_c(2930)$ and $\Xi_c(2970)$. The $\Xi_c(2930)^+$ and $\Xi_c(2930)^0$ have total widths of 15 and 26 MeV, respectively, which can not be clarified into our present arrangement. We agree with the suggestion of LHCb Collaboration that the $\Xi_c(2930)$ is the overlap of two structures $\Xi_c(2923)$ and $\Xi_c(2939)$ [1]. The $\Xi_c(2970)$ have a nearly identical mass with $\Xi_c(2965)$, and the measured widths by different collaborations show large divergence. Theoretically, it has been interpreted as the $\Xi_c(2S)$, $\Xi'_c(2S)$, and $\Xi'_c(1P)$ states. Based on our calculations, the predicted total decay width of $\Xi_c(2S)$ state is rather small, which does not support the $\Xi_c(2970)$ as $\Xi_c(2S)$ state. Moreover, the mass gap between $\Xi_c(2970)$ and $\Xi_c(2965)$ contradicts with the mass splitting of $\Xi_c(2S)$ and $\Xi'_c(2S)$ states. In the P -wave states, there is also no room left for the $\Xi_c(2970)$ under our assignments. Together with the mass and total width, we suggest that the $\Xi_c(2970)$ should be the same state as $\Xi_c(2965)$. More information on spin-parity and branching ratios can help us to clarify its nature.

4 Summary

In this work, we estimate the strong decays of three newly observed resonances $\Xi_c(2923)^0$, $\Xi_c(2939)^0$, and $\Xi_c(2965)^0$ by the LHCb Collaboration. Given the Ξ_c and Ξ'_c spectra predicted by constituent quark models, these three resonances can be tentatively treated as the λ -mode $\Xi_c(2S)$, $\Xi'_c(2S)$, $\Xi_c^*(2S)$, and $\Xi'_c(1P)$ states. Their strong decay behaviors are calculated within the 3P_0 model. Compared with the experimental data, our results indicate that the $\Xi_c(2923)^0$ and $\Xi_c(2939)^0$ should be $J^P = 3/2^-$ and $5/2^-$ $\Xi'_c(1P)$ states respectively, and the $\Xi_c(2965)^0$ can be assigned as the $J^P = 1/2^+$ $\Xi'_c(2S)$ state. Also, we suggest that the previous observed $\Xi_c(2930)$ may be the overlap of two structures $\Xi_c(2923)$ and $\Xi_c(2939)$, and the $\Xi_c(2970)$ should be the same state as $\Xi_c(2965)$. Other theoretical results of the missing $\Xi_c(2S)$, $\Xi_c^*(2S)$, and $\Xi'_c(1P)$ states may be helpful for future experiments.

During the study, it can be noticed that the Ξ_c and Ξ'_c systems are more complicated than other singly heavy baryons because the flavor configurations can not be determined by the isospin quantum number. Fortunately, there exist some similarities and connections among the Σ_c , Ξ'_c and Ω_c baryons, which can provide valuable clues for us. More theoretical and experimental studies on these three families are needed to further understand their inner structures and establish the low-lying spectra.

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