

$\Xi_c(3055)$ as a scaling point to establish the excited $\Xi_c^{(\prime)}$ family

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The low-lying orbital excitations of $\Xi_c^{(\prime)}$ baryons are studied within the chiral quark model combined with the $^3P_0$ decay mechanism. Motivated by the LHCb observation that $\Xi_c(3055)$ is a λ -mode $1D$ state with $J^P = 3/2^+$, we take it as a reference to constrain model parameters and perform a systematic analysis of states below 3.1 GeV. Our results provide a consistent interpretation of the observed Ξ_c spectrum: $\Xi_c(2790)$ and $\Xi_c(2815)$ are well described as a λ -mode $1P$ doublet, the structures around 2.9 GeV can be interpreted as P -wave excitations with mixed λ/ρ modes, and $\Xi_c(2970)$ is consistent with a $2S$ assignment. Furthermore, $\Xi_c(3055)$ together with $\Xi_c(3080)$ forms a λ -mode D -wave doublet, while $\Xi_c(3123)$ favors a $1D$ assignment. These results provide a coherent picture of the low-lying Ξ_c spectrum and call for further experimental tests.

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I. INTRODUCTION

As one of the fundamental problems of strong interaction, decoding how interactions arise between quarks decides the follow-up behaviors of hadrons. Among the development history of the theory of strong interaction, the study of baryons, which are considered to be a kind of hadron composed of three constituent quarks, gave birth to the color degree of freedom. Thus, studies of baryon systems are a very interesting topic in hadron physics, not only because they will deepen our understanding on strong interaction, but also due to their properties as the simplest few-body system, which can help us further on to recognize few-body interactions.

Among baryon systems, singly heavy baryons play a special role, as they offer an ideal platform to study the interplay between heavy quark symmetry and chiral symmetry. In particular, the $\Xi_c^{(\prime)}$ family, composed of one charm quark and two light quarks with different masses, provides a unique environment where both SU(3) flavor symmetry and chiral symmetry are explicitly broken, which provides a great platform to examine the

inner Goldstone boson exchanges. Within this system, excitations can be classified into two modes: the λ mode, corresponding to the excitation between the heavy quark and the light diquark, and the ρ mode, corresponding to the excitation within the light-quark subsystem. These modes are shown in Fig 1.

Experimentally, a number of excited $\Xi_c^{(\prime)}$ states have been observed in recent years [1–7], as summarized in Table I. However, the quantum numbers of many of these states remain undetermined, especially for the structures around 2.9–3.1 GeV, where different theoretical approaches, including lattice QCD [8], QCD sum rules [9,10], quark models [11–14], and flux-tube models [15], often lead to conflicting interpretations, as summarized in Table II. This situation calls for further systematic studies.

Thus, a consistent interpretation of the observed spectrum is still lacking, and to study this project, a QCD-inspired quark model is still one of the most commonly used approaches. The chiral quark model, which incorporates Goldstone boson exchanges between light quarks, has been successfully applied to describe

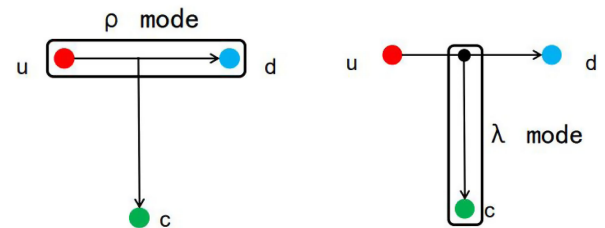


FIG. 1. $\Xi_c^{(\prime)}$ system with λ - or ρ -mode excitations.

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TABLE I. The basic experimental information of the excited Ξ_c baryons observed so far includes the J^P , mass, total width, and decay mode.

State	J^P [1]	Mass (MeV) [1]	Width (MeV) [1]	Decay modes [1]
$\Xi_c(2790)^+$	$\frac{1}{2}^-$	2791.9 ± 0.5	8.9 ± 1.0	$\Xi_c' \pi, \Xi_c^0 \gamma, \Xi_c^+ \gamma$
$\Xi_c(2790)^0$	$\frac{1}{2}^-$	2793.9 ± 0.5	10.0 ± 1.1	$\Xi_c' \pi, \Xi_c^0 \gamma, \Xi_c^+ \gamma$
$\Xi_c(2815)^+$	$\frac{3}{2}^-$	2816.51 ± 0.25	2.43 ± 0.26	$\Xi_c' \pi, \Xi_c(2645) \pi, \Xi_c^0 \gamma, \Xi_c^+ \gamma$
$\Xi_c(2815)^0$	$\frac{3}{2}^-$	2819.79 ± 0.30	2.54 ± 0.25	$\Xi_c' \pi, \Xi_c(2645) \pi, \Xi_c^0 \gamma, \Xi_c^+ \gamma$
$\Xi_c(2923)^0$	$?^?$ [20]	2923.04 ± 0.35 [20]	7.1 ± 2.0 [20]	$\Lambda_c K$ [20]
$\Xi_c(2939)^0$	$?^?$ [20]	2938.55 ± 0.30 [20]	10.2 ± 1.4 [20]	$\Lambda_c K$ [20]
$\Xi_c(2965)^0$	$?^?$ [20]	2964.88 ± 0.33 [20]	14.1 ± 1.6 [20]	$\Lambda_c K$ [20]
$\Xi_c(2970)^+$	$\frac{1}{2}^+$	2964.3 ± 1.5	$20.9^{+2.4}_{-3.5}$	$\Lambda_c K \pi, \Sigma_c(2455) K, \Xi_c' \pi, \Xi_c(2645) \pi, \Xi_c \pi \pi$
$\Xi_c(2970)^0$	$\frac{1}{2}^+$	2967.1 ± 1.7	$14.1 \pm 0.9 \pm 1.3$	$\Lambda_c K \pi, \Sigma_c(2455) K, \Xi_c' \pi, \Xi_c(2645) \pi, \Xi_c \pi \pi$
$\Xi_c(3055)^+$	$?^?$	3055.9 ± 0.4	7.8 ± 1.9	$\Sigma_c(2455) K, \Lambda D$
$\Xi_c(3080)^+$	$?^?$	3077.2 ± 0.4	3.6 ± 1.1	$\Lambda_c K \pi, \Sigma_c(2455) K, \Sigma_c(2520) K, \Lambda D$
$\Xi_c(3080)^0$	$?^?$	3079.9 ± 1.4	5.6 ± 2.2	$\Lambda_c K \pi, \Sigma_c(2455) K, \Sigma_c(2520) K, \Lambda D$
$\Xi_c(3123)^+$	$?^?$	3122.9 ± 1.3	4 ± 4	$\Sigma_c(2520) K$

the hadron spectra [16–19], hadron-hadron interactions [21–24], and multiquark structures [25–27]. Notably, in baryon sectors, the chiral quark model has been used to study the spectra and decays of excited N and Σ [28–30], and to successfully explain the internal structures of several excited states, such as $N(1535)$, the Roper resonance $N(1440)$, and $\Sigma(1750)$. In addition, their results do indicate that Goldstone boson exchange plays a very important role in understanding baryon properties. This makes it a suitable framework for the present study.

Recently, the LHCb Collaboration determined that $\Xi_c(3055)$ is a $\bar{3}_F \lambda$ -mode $1D$ state with $J^P = 3/2^+$ [31]. Such a result obviously provides an important reference point for constraining model parameters and organizing the $\Xi_c^{(\prime)}$ spectrum. Motivated by this, in this work we perform a systematic study of the low-lying $2S$, $1P$, and $1D$ states of $\Xi_c^{(\prime)}$ baryons within the chiral quark model combined with the $^3P_0$ decay mechanism. By comparing the calculated mass spectra and decay widths with experimental data, we aim to provide a coherent interpretation of the observed $\Xi_c^{(\prime)}$ states.

The paper is organized as follows: In Sec. II, we briefly introduce the theoretical framework. Section III presents the numerical results and discussions. Finally, a summary is given in Sec. IV.

II. THEORETICAL FRAMEWORK

A. Chiral quark model

As an application of the chiral symmetry, the chiral quark model contains a kinematic term, confinement, one-gluon

exchange, and Goldstone-boson exchange as

$$H = \sum_{i=1}^3 \left(m_i + \frac{p_i^2}{2m_i} \right) - T_{\text{CM}} + \sum_{j>i=1}^3 \left[V_{\text{CON}}(\mathbf{r}_{ij}) + V_{\text{OGE}}(\mathbf{r}_{ij}) + V_{\text{GBE}}(\mathbf{r}_{ij}) \right], \quad (1)$$

where m_i is the constituent mass of the quark (antiquark); $\mathbf{p}_i$ is the momentum of quark i ; T_{cm} is the kinetic energy of the center of mass; $\mathbf{r}_{ij}$ means the relative coordinate between quark i and j ; and V_{CON} , V_{OGE} , V_{GBE} are the color-confinement, one-gluon-exchange, and Goldstone-boson-exchange potentials, respectively. These three kinds of potentials reveal the most relevant features of QCD in a low-energy regime—i.e., color confinement, asymptotic freedom, and spontaneous chiral symmetry breaking [16].

For color-confinement potential, in this work, we adopt the linear form, which refers to the very famous Cornell potential as

$$V_{\text{CON}}^C(\mathbf{r}_{ij}) = \lambda_i^c \cdot \lambda_j^c (-a_c r_{ij} - \Delta), \quad (2)$$

$$V_{\text{CON}}^{\text{SO}}(\mathbf{r}_{ij}) = -(\lambda_i^c \cdot \lambda_j^c) \frac{a_c r_{ij}}{4m_i^2 m_j^2} \left[((m_i^2 + m_j^2)(1 - 2a_s) + 4m_i m_j (1 - a_s))(S_+ \cdot L) + (m_j^2 - m_i^2)(1 - 2a_s)(S_- \cdot L) \right]. \quad (3)$$

Here, $V_{\text{CON}}^{\text{SO}}(\mathbf{r}_{ij})$ denotes the Thomas-precession effect, a_c and Δ are model parameters, $S_{\pm} = \mathbf{S}_i \pm \mathbf{S}_j$, and λ^c represents the SU(3) Gell-Mann matrices.

For one-gluon-exchange interaction, the model contains the so-called Coulomb and color-magnetism interactions, in addition to the spin-orbit potential and tensor potential, which arise from QCD perturbation effects and low-order relativistic corrections, as

$$V_{\text{OGE}}^C(\mathbf{r}_{ij}) = \frac{\alpha_s}{4} \lambda_i^c \cdot \lambda_j^c \left[\frac{1}{r_{ij}} - \frac{\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j}{6m_i m_j} \frac{e^{-r_{ij}/r_0(\mu)}}{r_{ij} r_0^2(\mu)} \right], \quad (4)$$

$$V_{\text{OGE}}^{\text{SO}}(\mathbf{r}_{ij}) = -\frac{\alpha_s}{16m_i^2 m_j^2} \lambda_i^c \cdot \lambda_j^c \left[\frac{1}{r_{ij}^3} - \frac{e^{-r_{ij}/r_g(\mu)}}{r_{ij}^3} \right] \times \left(1 + \frac{r_{ij}}{r_g(\mu)} \right) \times [((m_i + m_j)^2 + 2m_i m_j) \times (\mathbf{S}_+ \cdot \mathbf{L}) + (m_j^2 - m_i^2)(\mathbf{S}_- \cdot \mathbf{L})], \quad (5)$$

$$V_{\text{OGE}}^T(\mathbf{r}_{ij}) = -\frac{\alpha_s}{16m_i m_j} \lambda_i^c \cdot \lambda_j^c \left[\frac{1}{r_{ij}^3} - \frac{e^{-r_{ij}/r_g(\mu)}}{r_{ij}} \right] \times \left(\frac{1}{r_{ij}^2} + \frac{1}{3r_g^2(\mu)} + \frac{1}{r_{ij} r_g(\mu)} \right) S_{ij}. \quad (6)$$

Here, μ is the reduced mass of two interacting quarks; $\boldsymbol{\sigma}$ represents the SU(2) Pauli matrices; S_{ij} is the tensor operator; $r_0(\mu) \equiv \hat{r}_0/\mu$, $r_g(\mu) \equiv \hat{r}_g/\mu$, with $\hat{r}_0$ and $\hat{r}_g$ being parameters; and α_s denotes the effective flavor-dependent strong coupling constant.

Due to chiral symmetry breaking, Goldstone-boson-exchange potentials will appear between light quarks (u , d , and s), which have the following expressions:

$$V_{\text{GBE}}(\mathbf{r}_{ij}) = V_\pi(\mathbf{r}_{ij}) + V_K(\mathbf{r}_{ij}) + V_\eta(\mathbf{r}_{ij}) + V_{\text{sc}}(\mathbf{r}_{ij}), \quad (7)$$

$$V_\pi(\mathbf{r}_{ij}) = \frac{g_{\text{ch}}^2}{4\pi} \frac{m_\pi^2}{12m_i m_j} \frac{\Lambda_\pi^2 m_\pi}{\Lambda_\pi^2 - m_\pi^2} \sum_{a=1}^3 \lambda_i^a \lambda_j^a \times \left\{ (\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j) \left[Y(m_\pi r_{ij}) - \frac{\Lambda_\pi^3}{m_\pi^3} Y(\Lambda_\pi r_{ij}) \right] + \left[H(m_\pi \mathbf{r}_{ij}) - \frac{\Lambda_\pi^3}{m_\pi^3} H(\Lambda_\pi r_{ij}) \right] S_{ij} \right\}, \quad (8)$$

$$V_K(\mathbf{r}_{ij}) = \frac{g_{\text{ch}}^2}{4\pi} \frac{m_K^2}{12m_i m_j} \frac{\Lambda_K^2 m_K}{\Lambda_K^2 - m_K^2} \sum_{a=4}^7 \lambda_i^a \lambda_j^a \times \left\{ (\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j) \left[Y(m_K r_{ij}) - \frac{\Lambda_K^3}{m_K^3} Y(\Lambda_K r_{ij}) \right] + \left[H(m_K \mathbf{r}_{ij}) - \frac{\Lambda_K^3}{m_K^3} H(\Lambda_K r_{ij}) \right] S_{ij} \right\}, \quad (9)$$

$$V_\eta(\mathbf{r}_{ij}) = \frac{g_{\text{ch}}^2}{4\pi} \frac{m_\eta^2}{12m_i m_j} \frac{\Lambda_\eta^2 m_\eta}{\Lambda_\eta^2 - m_\eta^2} \times \left[\cos \theta_P (\lambda_i^8 \lambda_j^8) - \sin \theta_P (\lambda_i^0 \lambda_j^0) \right] \times \left\{ (\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j) \left[Y(m_\eta r_{ij}) - \frac{\Lambda_\eta^3}{m_\eta^3} Y(\Lambda_\eta r_{ij}) \right] + \left[H(m_\eta \mathbf{r}_{ij}) - \frac{\Lambda_\eta^3}{m_\eta^3} H(\Lambda_\eta r_{ij}) \right] S_{ij} \right\}, \quad (10)$$

$$Y(x) = e^{-x}/x, \quad H(x) = \left(1 + \frac{3}{x} + \frac{3}{x^2} \right) Y(x), \quad (11)$$

where λ^a are the Gell-Mann matrices, Λ_χ ($\chi = \pi, K, \eta$) are the cutoffs, m_χ are the masses of Goldstone bosons, and g_{ch}^2 is the chiral field coupling constant, which is determined from the $NN\pi$ interaction through

TABLE II. Quantum number interpretations of excited Ξ_c under different models.

Resonances	HHCPT [32]	RQM [11]	NQM [12]	QSR [9,10]	RTF [15]	$^3P_0$ [33]	LQCD [8]
$\Xi_c(2790)$	$\frac{1}{2}^-$	$\frac{1}{2}^-$	$\frac{1}{2}^-$	$\frac{1}{2}^-$	$\frac{1}{2}^-$	$\frac{1}{2}^-$	$\frac{1}{2}^-$
$\Xi_c(2815)$	$\frac{3}{2}^-$	$\frac{3}{2}^-$	$\frac{3}{2}^-$	$\frac{3}{2}^-$	$\frac{3}{2}^-$	$\frac{3}{2}^-$	$\frac{3}{2}^-$
$\Xi_c(2923)$	...	$(\frac{1}{2}, \frac{3}{2}, \frac{5}{2})^-$	...	$\frac{1}{2}^-$	...	...	$\frac{1}{2}^-$
$\Xi_c(2939)$	...	$(\frac{1}{2}, \frac{3}{2}, \frac{5}{2})^-$	...	$\frac{1}{2}^-$	...	...	$\frac{1}{2}^-$
$\Xi_c(2965)$	...	$(\frac{1}{2}, \frac{3}{2}, \frac{5}{2})^-$	...	$\frac{1}{2}^-$	...	...	$\frac{1}{2}^-$
$\Xi_c(2970)$	$\frac{1}{2}^+$	$\frac{1}{2}^+$	...	$\frac{1}{2}^-$	$\frac{1}{2}^+$	D -wave	$(\frac{1}{2}^\pm, \frac{3}{2}^\pm, \frac{5}{2}^\pm)$
$\Xi_c(3055)$	...	$\frac{3}{2}^+$	...	$\frac{3}{2}^+$	$\frac{3}{2}^+$	...	$\frac{1}{2}^-$
$\Xi_c(3080)$	$\frac{5}{2}^+$	$\frac{5}{2}^+$	$\frac{5}{2}^+$	$\frac{5}{2}^+$	$\frac{5}{2}^+$	D -wave	$\frac{1}{2}^+$
$\Xi_c(3123)$	...	$\frac{7}{2}^+$	...	...	$(\frac{1}{2}, \frac{3}{2})^-$	...	...

$$\frac{g_{\text{ch}}^2}{4\pi} = \frac{9}{25} \frac{g_{\pi NN}^2}{4\pi} \frac{m_{u,d}^2}{m_N^2}. \quad (12)$$

Additionally, as the extension of the σ -meson exchange, the scalar nonet exchange V_{sc} is also included as

$$V_{\text{sc}}(\mathbf{r}_{ij}) = V_{a_0}(\mathbf{r}_{ij}) \sum_{a=1}^3 \lambda_i^a \lambda_j^a + V_{\kappa}(\mathbf{r}_{ij}) \sum_{a=4}^7 \lambda_i^a \lambda_j^a + V_{f_0}(\mathbf{r}_{ij}) \lambda_i^8 \lambda_j^8 + V_{\sigma}(\mathbf{r}_{ij}) \lambda_i^0 \lambda_j^0, \quad (13)$$

$$V_s(\mathbf{r}_{ij}) = -\frac{g_{\text{ch}}^2}{4\pi} \frac{\Lambda_s^2 m_s}{\Lambda_s^2 - m_s^2} \left[Y(m_s r_{ij}) - \frac{\Lambda_s}{m_s} Y(\Lambda_s r_{ij}) \right] + \frac{m_s^3}{2m_i m_j} \left[G(m_s r_{ij}) - \frac{\Lambda_s^3}{m_s^3} G(\Lambda_s r_{ij}) \right] \times \mathbf{L} \cdot \mathbf{S}(s = a_0, \kappa, f_0, \sigma), \quad (14)$$

$$G(x) = \left(1 + \frac{1}{x} \right) \frac{Y(x)}{x}, \quad (15)$$

where m_s and Λ_s are the mass and cutoff that correspond to the scalar meson s , respectively.

To determine the model parameters of our work, we perform a combined fit on the well-established ground mesons and baryons relative to our next calculations. The model parameters are listed in Table III, and the fitted baryon and meson masses are presented in Table IV along with the experimental values. Since it is difficult to use the same set of parameters to simultaneously describe the baryon and meson spectra well, we use different values of α_s for quark-quark and quark-antiquark pairs. As we can see from Table IV, most of our fitted masses are close to the experimental values. We want to emphasize here that for the purpose of unification, the flavor functions of all the states appearing in this work are described in the SU(3) symmetry. However, during the fit, we surprisingly find some possible competitions between one-gluon-exchange and one-boson-exchange potentials, which will break the common-sense assumption in quantum chromodynamics that α_s will decrease with momentum transfer, as Table III shows. We will present a discussion of this issue in detail in Appendix C.

B. Method to calculate mass spectra

To correspond to the intrinsic chiral symmetry within our model, the flavor wave functions of $\Xi_c^{(l)}$ are constructed under the SU(3) symmetry, although the masses of u/d and s quarks are different. In addition, due to the much larger mass of the charm quark, chiral symmetry is approximately obeyed at this time. Thus, Ξ_c can belong to the $\bar{3}_F$ representation as

TABLE III. Quark model parameters used in the calculation, where the superscript “*” means that a number was previously fixed during the fit.

Quark masses	$m_{u,d}$ (MeV)	313*
	m_s (MeV)	555*
	m_c (MeV)	1800*
Goldstone bosons	Λ_{π} (fm $^{-1}$)	4.20*
	$\Lambda_{\eta,K}$ (fm $^{-1}$)	5.20*
	m_{π} (fm $^{-1}$)	0.70*
	m_K (fm $^{-1}$)	2.51*
	m_{η} (fm $^{-1}$)	2.77*
	$g_{\text{ch}}^2/(4\pi)$	0.54*
	$\theta_P(^{\circ})$	-15*
Confinement	a_c (MeV $\cdot$ fm $^{-1}$)	108.34 ± 0.16
	Δ (MeV)	-82.99 ± 0.15
	a_s	0.777*
Scalar nonet	m_{σ} (fm $^{-1}$)	3.42*
	Λ_{σ} (fm $^{-1}$)	4.20*
	Λ_{a_0,κ,f_0} (fm $^{-1}$)	5.20*
	m_{a_0,κ,f_0} (fm $^{-1}$)	4.97*
OGE	$\hat{r}_0 = \hat{r}_g$ (MeV $\cdot$ fm)	24.7*
	α_{uu}	0.477 ± 0.0014
	α_{us}	0.566 ± 0.0017
	α_{ss}	0.502 ± 0.0015
	α_{uc}	0.713 ± 0.0011
	α_{sc}	0.668 ± 0.0010
	$\alpha_{u\bar{u}}$	0.566 ± 0.0015
	$\alpha_{u\bar{s}}$	0.534 ± 0.0013
	$\alpha_{s\bar{s}}$	0.395 ± 0.0015
	$\alpha_{u\bar{c}}$	0.626 ± 0.0009
	$\alpha_{s\bar{c}}$	0.530 ± 0.0008

$$|\Xi_c\rangle_f = \frac{1}{\sqrt{2}}(us - su)c, \quad (16)$$

while Ξ'_c can be accounted for in the 6_F representation as

$$|\Xi'_c\rangle_f = \frac{1}{\sqrt{2}}(us + su)c. \quad (17)$$

Then, taking into account the antisymmetric color wave function of any baryon as

$$|\Xi_c^{(l)}\rangle_c = \frac{1}{\sqrt{6}}(rgb + gbr + brg - grb - bgr - rbg), \quad (18)$$

under the $S-L$ coupling representation, the total wave function of $\Xi_c^{(l)}$ with total angular momentum J can be represented as

$$|\Xi_c^{(l)}\rangle_J = |\Xi_c^{(l)}\rangle_c \otimes |\Xi_c^{(l)}\rangle_f \otimes [|\Xi_c^{(l)}\rangle_s \otimes |\Xi_c^{(l)}\rangle_L]_J, \quad (19)$$

TABLE IV. The masses of ground-state baryons and mesons in units of MeV.

	N	Δ	Λ	Σ	Σ^*
CQM	940 ± 10	1285 ± 7	1119 ± 8	1143 ± 9	1385 ± 7
Exp.	939	1232	1116	1189	1383
	Ξ	Ξ^*	Ω	Λ_c	Σ_c
CQM	1350 ± 7	1501 ± 6	1656 ± 6	2274 ± 7	2475 ± 6
Exp.	1318	1533	1672	2286	2455
	Σ_c^*	Ξ_c	Ξ_c'	$\Xi_c'^*$	Ω_c
CQM	2541 ± 6	2473 ± 7	2565 ± 6	2637 ± 6	2689 ± 5
Exp.	2520	2471	2579	2645	2695
	Ω_c^*	π	ρ	K	K^*
CQM	2765 ± 5	140 ± 8	821 ± 3	494 ± 4	975 ± 2
Exp.	2770	140	775	495	892
	ω	η'	ϕ	D	D^*
CQM	701 ± 3	958 ± 5	1040 ± 5	1863 ± 7	2063 ± 4
Exp.	782	958	1020	1864	2007
	D_s	D_s^*			
CQM	1967 ± 5	2203 ± 2			
Exp.	1968	2112			

where $\Xi_c^{(l)}\rangle_S$ and $|\Xi_c^{(l)}\rangle_L$ are spin and spatial wave functions that expand as

$$|\Xi_c^{(l)}\rangle_S = [[\psi_{S_1}^{\text{spin}} \otimes \psi_{S_2}^{\text{spin}}]_{S_\rho} \otimes \psi_{S_3}^{\text{spin}}]_S, \quad (20)$$

$$|\Xi_c^{(l)}\rangle_L = [\psi_{L_\rho}^{\text{orbit}} \otimes \psi_{L_\lambda}^{\text{orbit}}]_L. \quad (21)$$

Here, S_ρ means the total spin of the two light quarks in the $\Xi_c^{(l)}$ baryon, S is the total spin, L_ρ is the relative orbital angular momentum between the two light quarks, L_λ is the relative orbital angular momentum between the charm quark and the light quark pair, and L is the total angular momentum.

For the spatial wave functions, we adopt the Rayleigh-Ritz variational method to solve the eigenvalue problem, where a basis expansion of the trial spatial wave function is performed. In this work, we select the widely used Gaussian expansion method (GEM) [34] to expand each relative motion in the system. The GEM has proven to be an accurate and universal few-body calculation method [35–37], whose critical point is to expand the radial part of the orbital wave function with a set of Gaussian functions as

$$\psi_l^{\text{orbit}} = \sum_{n=1}^{n_{\max}} C_n N_{nl}^r e^{-\nu_n r^2} \mathcal{Y}_l(\mathbf{r}), \quad (22)$$

where $\mathcal{Y}_l(\mathbf{r})$ is the solid spherical harmonic function, N_{nl} is the normalization constant,

$$N_{nl} = \left(\frac{2^{l+2} (2\nu_n)^{l+3/2}}{\sqrt{\pi} (2l+1)!!} \right)^{\frac{1}{2}}, \quad (23)$$

and C_n are the variational parameters, which are determined by the dynamics of the system. The Gaussian size is chosen by the following geometric progression:

$$\nu_n = \frac{1}{r_n^2}, \quad r_n = r_{\min} \left(\frac{r_{\max}}{r_{\min}} \right)^{\frac{n-1}{n_{\max}-1}}, \quad (24)$$

where $r_{\min}$ and $r_{\max}$ are parameters, and $n_{\max}$ is the number of Gaussian functions, which are determined by the convergence of the results. In this work, we find that after setting $r_{\min} = 0.1$ fm, $r_{\max} = 2$ fm, and $n_{\max} = 8$, the spectra of the low-lying excited $\Xi_c^{(l)}$ baryons can be sufficiently convergent.

Finally, to use the language of heavy quark symmetry, a representation transformation is performed, which is explicitly expressed as

$$\begin{aligned}
[\psi_{J_l} \otimes \psi_{S_Q}^{\text{spin}}]_J &= (-1)^{L+S_Q+J+\frac{1}{2}} \sum_S \sqrt{2J_l+1} \\
&\times \sqrt{2S+1} \begin{Bmatrix} L & S_Q & J_l \\ S_Q & J & S \end{Bmatrix} \\
&\times [\psi_S^{\text{spin}} \otimes \psi_L^{\text{orbit}}]_J. \quad (25)
\end{aligned}$$

Here, S_Q is the spin of the heavy quark, and $J_l = L \otimes S_\rho$ is the light degree of freedom, which is a good quantum number in heavy quark symmetry. Actually, under the heavy quark limit, the heavy quark spin S_Q is approximately frozen, which means that the interactions between the heavy quark and the two light quarks are strongly suppressed by the heavy quark mass. This indicates that, for a singly heavy baryon, the state constructed by the $J_l - S_Q$ coupling may be closer to the physical state than that constructed by the $S - L$ scheme, although the masses may be different under different schemes.

C. Two-body decay mechanism

After calculating the mass spectra, we use the ${}^3P_0$ model to calculate the two-body decays of the initial $\Xi_c^{(\prime)}$ baryons, because under the quark level, it has been widely applied and has proved strongly effective in the studies of the strong decay problems of hadrons [33,38,39] allowed by the Okubo-Zweig-Iizuka rule. This model was first proposed by Micu in 1969 [40] and was further developed by Le Yaouanc, Ackleh, and Roberts [41–43], whose corresponding applicable scope has also been expanded from traditional hadrons to multi-quark states.

According to this model, a pair of quarks with $J^{PC} = 0^{++}$ is first created from the vacuum. Then, by the quark rearrangement process, this new $q\bar{q}$ pair from the vacuum combines with the three quarks within the initial baryon, resulting in the creation of the outgoing meson and baryon. When considering the case of a baryon A decaying to a baryon B and a meson C , there are usually three types of recombination, as shown in Fig. 2 [44].

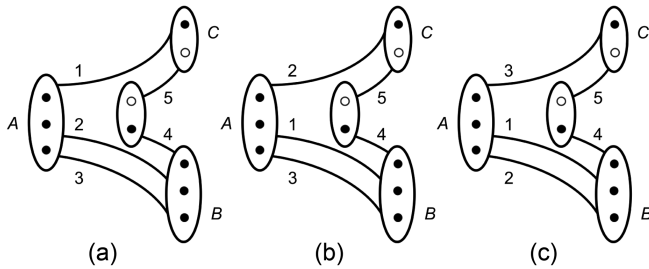


FIG. 2. Baryon decay process of $A \rightarrow B + C$ in the ${}^3P_0$ model, taken from our previous work [44]. Here, the three panels denote different quark recombinations, where (a) represents that the antiquark generated from vacuum captures the first quark of baryon to form the final meson, while (b) and (c) denote that the second and the third quark are captured, respectively.

The original transition operator of the decay process $A \rightarrow B + C$ through the ${}^3P_0$ model can be expressed under the momentum representation as [45]

$$\begin{aligned}
T &= -3\gamma \sum_m \langle 1m; 1-m | 00 \rangle \int d\mathbf{p}_4 d\mathbf{p}_5 \delta(\mathbf{p}_4 + \mathbf{p}_5) \\
&\times \mathcal{Y}_1^m \left(\frac{\mathbf{p}_4 - \mathbf{p}_5}{2} \right) \chi_{45}^{1-m} \phi_{45}^0 \omega_{45}^0 b_4^\dagger(\mathbf{p}_4) d_5^\dagger(\mathbf{p}_5), \quad (26)
\end{aligned}$$

where γ describes the probability of creating a quark-antiquark pair with momenta $\mathbf{p}_4$ and $\mathbf{p}_5$, respectively, from the vacuum. The solid harmonic polynomial $\mathcal{Y}_1^m = |p| Y_1^m(\theta_p, \phi_p)$ reflects the P -wave distribution of the created quark pair in the momentum space. The values $\phi_{45}^0 = (u\bar{u} + d\bar{d} + s\bar{s})/\sqrt{3}$, $\omega_{45}^0 = (r\bar{r} + g\bar{g} + b\bar{b})/\sqrt{3}$, and χ_{45}^{1-m} are the flavor, color, and spin wave functions of the created quark pair, respectively.

However, when this original transition operator was used to calculate the mass shift of light mesons, a very large mass shift beyond expectation would occur [46]. To avoid this problem, in Refs. [27,46], the convergence

factor $e^{-\frac{r^2}{4f^2}}$ and damping factor $e^{-\frac{R_{AV}^2}{R_0^2}}$ are introduced, which reflect the cutoffs on the momentum and distance—i.e., the created quark pair should not have too large a momentum, and the position it creates should not be too far away from the initial hadron. Thus, after performing a Fourier transformation on the original transition operator and multiplying the above two form factors, the transition operator can be modified as [46]

$$\begin{aligned}
T &= -3\gamma \sum_m \langle 1m; 1-m | 00 \rangle \int d\mathbf{r}_4 d\mathbf{r}_5 \left(\frac{1}{2\pi} \right)^{\frac{3}{2}} \\
&\times 2^{-\frac{5}{2}} f^{-5} \mathcal{Y}_1^m(\mathbf{r}) e^{-\frac{r^2}{4f^2}} e^{-\frac{R_{AV}^2}{R_0^2}} \chi_{45}^{1-m} \\
&\times \phi_{45}^0 \omega_{45}^0 b_4^\dagger(\mathbf{r}_4) d_5^\dagger(\mathbf{r}_5), \quad (27)
\end{aligned}$$

where $\mathbf{r}_4$, $\mathbf{r}_5$, and $\mathbf{r}$ are the coordinates of the vacuum-created quark and antiquark, and the relative coordinate between them, respectively.

Then, the matrix element for the transition $A \rightarrow B + C$ can be calculated as

$$\langle BC | T | A \rangle = \delta^3(\mathbf{P}_A - \mathbf{P}_B - \mathbf{P}_C) \mathcal{M}^{M_A M_B M_C}, \quad (28)$$

where $\mathbf{P}_B$ and $\mathbf{P}_C$ are the momenta of the final B and C hadrons in the center-of-mass frame of baryon A . $\mathcal{M}^{M_A M_B M_C}$ is the helicity amplitude, as

$$\begin{aligned}
 & \mathcal{M}^{M_{J_A} M_{J_B} M_{J_C}}(A \rightarrow BC) \\
 &= \sqrt{8E_A E_B E_C} \sum_{\substack{M_{L_A} M_{S_A}, \\ M_{L_B} M_{S_B}, \\ M_{L_C} M_{S_C}, m}} \langle 1m1 - m | 00 \rangle \\
 & \times \langle \chi_{S_C M_{S_C}}^{235} \chi_{S_B M_{S_B}}^{14} | \chi_{S_A M_{S_A}}^{123} \chi_{1-m}^{45} \rangle \\
 & \times \langle L_A M_{L_A} S_A M_{S_A} | J_A M_{J_A} \rangle \\
 & \times \langle L_B M_{L_B} S_B M_{S_B} | J_B M_{J_B} \rangle \\
 & \times \langle L_C M_{L_C} S_C M_{S_C} | J_C M_{J_C} \rangle \\
 & \times \langle \varphi_C^{235} \varphi_B^{14} | \varphi_A^{123} \varphi_0^{45} \rangle I_{M_{L_B} M_{L_C}}^{M_{L_A}, m}, \quad (29)
 \end{aligned}$$

where the spatial integral $I_{M_{L_B} M_{L_C}}^{M_{L_A}, m}$ can be written as

$$\begin{aligned}
 I_{M_{L_B} M_{L_C}}^{M_{L_A}, m} &= -3i\gamma \left(\frac{1}{2\pi}\right)^3 2^{-\frac{5}{2}} f^{-5} \int \psi_{L_C M_{L_C}}^*(\mathbf{r}_C, \mathbf{R}_C) \\
 & \times \psi_{L_B M_{L_B}}^*(\mathbf{r}_B) \mathcal{Y}_1^m(\mathbf{r}_\nu) e^{-i\mathbf{r}_{BC} \cdot \mathbf{p}} e^{-\frac{r_\nu^2}{4f^2}} e^{-\frac{R_{AV}^2}{R_0^2}} \\
 & \times \psi_{L_A M_{L_A}}(\mathbf{r}_A, \mathbf{R}_A) d\mathbf{r}_A d\mathbf{R}_A d\mathbf{r}_\nu d\mathbf{R}_{AV}. \quad (30)
 \end{aligned}$$

Here, E_i is the on-shell energy of hadron i ; ψ_{LM_L} is the spatial wave function of hadrons in coordinate representation; $\langle \chi_{S_C M_{S_C}}^{235} \chi_{S_B M_{S_B}}^{14} | \chi_{S_A M_{S_A}}^{123} \chi_{1-m}^{45} \rangle$ and $\langle \varphi_C^{235} \varphi_B^{14} | \varphi_A^{123} \varphi_0^{45} \rangle$ denote the spin and flavor overlap matrix elements, respectively; $\mathbf{r}_A$ and $\mathbf{r}_C$ are the relative coordinates between two quarks in baryons A and C ; $\mathbf{R}_A$ and $\mathbf{R}_C$ are the relative coordinates between the third quark and the remaining quark pair in baryons A and C ; $\mathbf{r}_B$ represents the relative coordinate between the quark and antiquark in the meson; $\mathbf{r}_\nu$ is the relative coordinate between the created quark pair from the vacuum; $\mathbf{R}_{AV}$ is the relative coordinate between the baryon A and the vacuum-created quark pair; $\mathbf{r}_{BC}$ is the relative coordinate between the final B and C ; and $\mathbf{p}$ represents the momentum of the final hadron B or C in the center-of-mass frame of A , whose modulus is

$$|\mathbf{p}| = \frac{\sqrt{[M_A^2 - (M_B + M_C)^2][M_A^2 - (M_B - M_C)^2]}}{2M_A}, \quad (31)$$

with M_A, M_B, M_C being the masses of the hadrons A, B, C , respectively.

Finally, the hadronic decay width of a process $A \rightarrow B + C$ is calculated as follows:

$$\Gamma = \pi^2 \frac{|\mathbf{p}|}{M_A^2} \frac{\mathcal{S}}{2J_A + 1} \sum_{M_{J_A} M_{J_B} M_{J_C}} |\mathcal{M}^{M_{J_A} M_{J_B} M_{J_C}}|^2, \quad (32)$$

where $\mathcal{S}$ is a statistical factor for identical particles, according to $\mathcal{S} \equiv 1/(1 + \delta_{BC})$.

As for γ, f , and R_0 , in this work, we take the same values as Ref. [46], which can both reproduce the decay

width of the $\rho \rightarrow \pi\pi$ process and avoid the mass shift problem:

$$\gamma = 32, \quad f = 0.2 \text{ fm}, \quad R_0 = 1.0 \text{ fm}. \quad (33)$$

III. RESULTS AND DISCUSSIONS

In this section, we present the mass spectra of the $2S, 1P$, and $1D \Xi_c^{(\prime)}$ states calculated through the chiral quark model, as well as the corresponding decay widths under the $^3P_0$ decay mechanism.

The experimental values of several excited baryons with high status are listed in Table I, and the mass spectra of Ξ_c and Ξ_c' with the corresponding quantum numbers are shown in Tables V and VI, respectively, where n_λ, L_ρ , and S_ρ denote the radial quantum number, the relative orbital angular momentum, and the total spin of the two light quarks (us), respectively. L is the total orbital angular momentum of the baryon, J_l is the light degree of freedom, and J denotes the total angular momentum.

A. $\Xi_c(2790)$ and $\Xi_c(2815)$

Both of these two excited Ξ_c baryons were first discovered by the CLEO Collaboration as $J^P = 1/2^-$ and $3/2^-$ states [47]. The $\Xi_c(2790)$ was observed in the decay channel $\Xi_c' \pi$ [48], while $\Xi_c(2815)^0$ and $\Xi_c(2815)^+$ were observed in the final states of $\Xi_c^{0(+)} \pi^+ \pi^-$ via the intermediate states $\Xi_c(2645)^0$ and $\Xi_c(2645)^+$ [47], respectively. These two states would later be confirmed by the Belle Collaboration in 2016 with resonance parameters as [5]

$$\Xi_c(2790)^+: M = 2791.6 \pm 0.2 \pm 0.1 \pm 0.4 \text{ MeV},$$

$$\Gamma = 8.9 \pm 0.6 \pm 0.8 \text{ MeV};$$

$$\Xi_c(2790)^0: M = 2794.9 \pm 0.3 \pm 0.1 \pm 0.4 \text{ MeV},$$

$$\Gamma = 10.0 \pm 0.7 \pm 0.8 \text{ MeV};$$

$$\Xi_c(2815)^+: M = 2816.65 \pm 0.03 \pm 0.03 \pm 0.23 \text{ MeV},$$

$$\Gamma = 2.07 \pm 0.08 \pm 0.12 \text{ MeV};$$

$$\Xi_c(2815)^0: M = 2820.20 \pm 0.08 \pm 0.07 \text{ MeV},$$

$$\Gamma = 2.54 \pm 0.18 \pm 0.17 \text{ MeV}.$$

Furthermore, the mass and width of $\Xi_c(2815)^+$ have been measured by the LHCb Collaboration in $\Xi_c^+ \pi^- \pi^+$ [7].

Until now, almost all the theoretical works generally hold that these two particles are ρ -mode P -wave excitations of Ξ_c with the established quantum numbers. In Ref. [8], the authors studied the charmed baryon spectrum within the lattice QCD and found that the masses of λ -mode excited $\Xi_{c1}(\frac{1}{2}^-, 1P)$ and $\Xi_{c1}(\frac{3}{2}^-, 1P)$ states should be 2770 MeV and 2797 MeV. In Refs. [9,10], QCD sum rules have been used, and the masses of these two states are found to be

TABLE V. The quantum number of Ξ_c baryons in the $1S$, $2S$, $1P$, and $1D$ states, and the corresponding masses in units of MeV.

State	Mass	L_ρ	L_λ	L	S_ρ	J_l	J	State	Mass	L_ρ	L_λ	L	S_ρ	J_l	J
$\Xi_c(\frac{1}{2}^+, 1S)$	2473 ± 7	0	0	0	0	0	$\frac{1}{2}$	$\Xi_{c2}(\frac{3}{2}^+, 1D)$	3043 ± 8	0	2	2	0	2	$\frac{3}{2}$
$\Xi_c(\frac{1}{2}^+, 2S)$	2970 ± 8	0	0	0	0	0	$\frac{1}{2}$	$\Xi_{c2}(\frac{5}{2}^+, 1D)$	3078 ± 8	0	2	2	0	2	$\frac{5}{2}$
$\Xi_{c1}(\frac{1}{2}^-, 1P)$	2783 ± 7	0	1	1	0	1	$\frac{1}{2}$	$\Xi_{c2}(\frac{3}{2}^+, 1D)$	3353 ± 9	2	0	2	0	2	$\frac{3}{2}$
$\Xi_{c1}(\frac{3}{2}^-, 1P)$	2830 ± 7	0	1	1	0	1	$\frac{3}{2}$	$\Xi_{c2}(\frac{5}{2}^+, 1D)$	3373 ± 9	2	0	2	0	2	$\frac{5}{2}$
$\Xi_{c0}(\frac{1}{2}^-, 1P)$	2950 ± 4	1	0	1	1	0	$\frac{1}{2}$	$\Xi_{c1}(\frac{1}{2}^+, 1D)$	3217 ± 8	1	1	2	1	1	$\frac{1}{2}$
$\Xi_{c1}(\frac{1}{2}^-, 1P)$	2910 ± 3	1	0	1	1	1	$\frac{1}{2}$	$\Xi_{c1}(\frac{3}{2}^+, 1D)$	3255 ± 4	1	1	2	1	1	$\frac{3}{2}$
$\Xi_{c1}(\frac{3}{2}^-, 1P)$	3057 ± 5	1	0	1	1	1	$\frac{3}{2}$	$\Xi_{c2}(\frac{3}{2}^+, 1D)$	3237 ± 4	1	1	2	1	2	$\frac{3}{2}$
$\Xi_{c2}(\frac{3}{2}^-, 1P)$	3037 ± 5	1	0	1	1	2	$\frac{3}{2}$	$\Xi_{c2}(\frac{5}{2}^+, 1D)$	3303 ± 6	1	1	2	1	2	$\frac{5}{2}$
$\Xi_{c2}(\frac{5}{2}^-, 1P)$	3116 ± 8	1	0	1	1	2	$\frac{5}{2}$	$\Xi_{c3}(\frac{5}{2}^+, 1D)$	3289 ± 6	1	1	2	1	3	$\frac{5}{2}$
								$\Xi_{c3}(\frac{7}{2}^+, 1D)$	3334 ± 9	1	1	2	1	3	$\frac{7}{2}$

2.79 ± 0.15 GeV and 2.83 ± 0.15 GeV. It is worth noting that the mass difference between the doublets in this work is 42 MeV, which is in agreement with our results. In addition, quark models [11,12], flux tube models [15], and the $^3P_0$ model [33] have all conducted studies on the spectra of these two particles, and they reached consistent qualitative conclusions.

In our work, mass spectra and decay widths of ρ -mode P -wave excitation of Ξ_c are shown in Tables V and VII.

- (1) $\Xi_c(2790)$: The theoretical mass of $\Xi_{c1}(\frac{1}{2}^-)$ is 2783 MeV, extremely close to $\Xi_c(2790)$, and its decay width to $\Xi'_c\pi$ is 21.13 MeV. Due to the symmetry, we cannot distinguish the u and d quarks. Therefore, in the calculation, $\Xi_c(2790)^0$

and $\Xi_c(2790)^+$ are the same. Namely, the decay width should be the sum of $\Xi_c(2790)^0$ and $\Xi_c(2790)^+$, which is 18.9 MeV in the experiment and very close to our theoretical results. In Ref. [33], the author studied the strong decays of $\Xi_c(2790)$ and $\Xi_c(2815)$, and the result showed that the total width of $\Xi_c(2790)$ decay to the $\Xi'_c\pi$ mode can be 20.2 MeV. Therefore, $\Xi_c(2790)$ can be identified as a ρ -mode P -wave state.

- (2) $\Xi_c(2815)$: For $\Xi_c(2815)$, our results are similar to those obtained in $\Xi_c(2790)$. The theoretical mass of $\Xi_{c1}(\frac{3}{2}^-)$ is 2830 MeV, close to experimental value. There are two decay modes with nonzero numbers, $\Xi'_c\pi$ and $\Xi_c^{*}\pi$, which is consistent with the

TABLE VI. The quantum number of Ξ'_c baryons in the $1S$, $2S$, $1P$, and $1D$ states, and the corresponding masses in units of MeV.

State	Mass	L_ρ	L_λ	L	S_ρ	J_l	J	State	Mass	L_ρ	L_λ	L	S_ρ	J_l	J
$\Xi'_c(\frac{1}{2}^+, 1S)$	2565 ± 6	0	0	0	1	1	$\frac{1}{2}$	$\Xi_{c1}(\frac{1}{2}^+, 1D)$	3136 ± 8	0	2	2	1	1	$\frac{1}{2}$
$\Xi'_c(\frac{3}{2}^+, 1S)$	2637 ± 6	0	0	0	1	1	$\frac{3}{2}$	$\Xi_{c1}(\frac{3}{2}^+, 1D)$	3143 ± 4	0	2	2	1	1	$\frac{3}{2}$
$\Xi'_c(\frac{1}{2}^+, 2S)$	3054 ± 8	0	0	0	1	1	$\frac{1}{2}$	$\Xi_{c2}(\frac{3}{2}^+, 1D)$	3172 ± 4	0	2	2	1	2	$\frac{3}{2}$
$\Xi'_c(\frac{3}{2}^+, 2S)$	3101 ± 8	0	0	0	1	1	$\frac{3}{2}$	$\Xi_{c2}(\frac{5}{2}^+, 1D)$	3153 ± 5	0	2	2	1	2	$\frac{5}{2}$
$\Xi'_{c0}(\frac{1}{2}^-, 1P)$	2874 ± 4	0	1	1	1	0	$\frac{1}{2}$	$\Xi_{c3}(\frac{5}{2}^+, 1D)$	3170 ± 5	0	2	2	1	3	$\frac{5}{2}$
$\Xi'_{c1}(\frac{1}{2}^-, 1P)$	2908 ± 4	0	1	1	1	1	$\frac{1}{2}$	$\Xi_{c3}(\frac{7}{2}^+, 1D)$	3176 ± 8	0	2	2	1	3	$\frac{7}{2}$
$\Xi'_{c1}(\frac{3}{2}^-, 1P)$	2915 ± 5	0	1	1	1	1	$\frac{3}{2}$	$\Xi_{c1}(\frac{1}{2}^+, 1D)$	3281 ± 8	2	0	2	1	1	$\frac{1}{2}$
$\Xi'_{c2}(\frac{3}{2}^-, 1P)$	2924 ± 5	0	1	1	1	2	$\frac{3}{2}$	$\Xi_{c1}(\frac{3}{2}^+, 1D)$	3336 ± 4	2	0	2	1	1	$\frac{3}{2}$
$\Xi'_{c2}(\frac{5}{2}^-, 1P)$	2948 ± 7	0	1	1	1	2	$\frac{5}{2}$	$\Xi_{c2}(\frac{3}{2}^+, 1D)$	3302 ± 4	2	0	2	1	2	$\frac{3}{2}$
$\Xi'_{c1}(\frac{1}{2}^-, 1P)$	3018 ± 7	1	0	1	0	1	$\frac{1}{2}$	$\Xi_{c2}(\frac{5}{2}^+, 1D)$	3368 ± 6	2	0	2	1	2	$\frac{5}{2}$
$\Xi'_{c1}(\frac{1}{2}^-, 1P)$	3038 ± 7	1	0	1	0	1	$\frac{3}{2}$	$\Xi_{c3}(\frac{5}{2}^+, 1D)$	3362 ± 6	2	0	2	1	3	$\frac{5}{2}$
								$\Xi_{c3}(\frac{7}{2}^+, 1D)$	3393 ± 9	2	0	2	1	3	$\frac{7}{2}$
								$\Xi_{c2}(\frac{3}{2}^+, 1D)$	3261 ± 8	1	1	2	0	2	$\frac{3}{2}$
								$\Xi_{c2}(\frac{5}{2}^+, 1D)$	3282 ± 8	1	1	2	0	2	$\frac{5}{2}$

TABLE VII. The decay widths (in MeV) of $\Xi_c(2790)$ and $\Xi_c(2815)$ as candidates for a $1P$ -wave state, where the states are represented with the J^P quantum number, radial and orbital excitation, and mass (in MeV). Here, “ ~ 0 ” means that the corresponding partial decay width is less than 0.01 MeV.

State	$\Xi_c \pi$	$\Xi'_c \pi$	$\Xi_c^{*/} \pi$	$\Lambda_c \bar{K}$	Γ_{total}
$\Xi_{c1}(\frac{1}{2}^-, 1P, 2783)$	~ 0	21.13 ± 1.64	~ 0	~ 0	21.13 ± 1.64
$\Xi_{c1}(\frac{3}{2}^-, 1P, 2830)$	~ 0	0.01 ± 0.0005	8.11 ± 0.93	~ 0	8.12 ± 0.93

conclusion of the Review of Particle Physics (RPP) [1]. The width of the main decay channel is 8.11 MeV and is very close to the sum of $\Xi_c(2815)^0$ and $\Xi_c(2815)^+$. Hence, $\Xi_c(2815)$ can be identified as the P -wave excited state and form a doublet $\Xi_{c1}(\frac{1}{2}^-, \frac{3}{2}^-)$ with $\Xi_c(2790)$.

B. $\Xi_c(2923)$, $\Xi_c(2939)$, and $\Xi_c(2965)$

In 2020, the LHCb Collaboration announced that three Ξ_c resonances— $\Xi_c(2923)^0$, $\Xi_c(2939)^0$, and $\Xi_c(2965)^0$ —were observed in the $\Lambda_c^+ K^-$ spectrum, whose masses and widths are shown below as [20]

$$\Xi_c(2923)^0: M = 2923.04 \pm 0.25 \pm 0.20 \pm 0.14 \text{ MeV},$$

$$\Gamma = 7.1 \pm 0.8 \pm 1.8 \text{ MeV};$$

$$\Xi_c(2939)^0: M = 2939.55 \pm 0.21 \pm 0.17 \pm 0.14 \text{ MeV},$$

$$\Gamma = 10.2 \pm 0.8 \pm 1.1 \text{ MeV};$$

$$\Xi_c(2965)^0: M = 2964.88 \pm 0.26 \pm 0.14 \pm 0.14 \text{ MeV},$$

$$\Gamma = 14.1 \pm 0.9 \pm 1.3 \text{ MeV}.$$

Also, the LHCb Collaboration pointed out that the $\Xi_c(2930)^0$ state [2,3] should be a superposition state due to the overlap of $\Xi_c(2923)^0$ and $\Xi_c(2939)^0$, while the $\Xi_c(2970)^0$ state [4,5,49] may be different from $\Xi_c(2965)^0$ due to the significant difference in decay width.

The above results have led to heated discussion, since the quantum numbers of these resonances are still unknown. In the framework of the QCD sum rule, these three states can

be explained as λ -mode P -wave Ξ'_c states with quantum numbers $\frac{1}{2}^-$ or $\frac{3}{2}^-$ [50]. In Ref. [51], these three Ξ_c^0 states and their two-body strong decays were evaluated within a chiral quark model, and their results showed that $\Xi_c(2923)^0$ and $\Xi_c(2938)^0$ are most likely to be $1P$ Ξ'_c states with $J^P = \frac{3}{2}^-$, while the $\Xi_c(2965)^0$ should be a $1P$ Ξ'_c state with $J^P = \frac{5}{2}^-$. After studying the decay widths through the $^3P_0$ model, Ref. [52] pointed out that $\Xi_c(2923)^0$ and $\Xi_c(2938)^0$ might be $1P$ Ξ'_c states, but $\Xi_c(2965)^0$ may be a $2S$ Ξ'_c state. Lattice simulations also give theoretical investigations of these heavy flavored baryons [8,53,54]. In addition, several theoretical works have described these three states as molecular states [55–59], including our previous work [35]. Considering that these three states are very close to the $2S$ and $1P$ states of Ξ_c and $1P$ states of Ξ'_c , all the other $2S$ and $1P$ $\Xi_c^{(*)}$ configurations have been studied, and the mass spectra in addition to decay widths are shown in Tables VIII and IX.

(1) $\Xi_c(2923)$: According to Tables VIII and IX, the mass of $\Xi'_c(\frac{3}{2}^-)$ is almost the same as that of $\Xi_c(2923)$. However, its decay width to $\Lambda_c \bar{K}$ is very small, which is contrary to the experimental results. Thus, $\Xi'_c(\frac{3}{2}^-)$ may be excluded. Similarly, $\Xi'_c(\frac{3}{2}^-)$, $\Xi_{c0}(\frac{1}{2}^-)$, and $\Xi_{c1}(\frac{1}{2}^-)$ should also be ruled out. However, for $\Xi_{c1}(\frac{3}{2}^-)$, $\Xi_{c2}(\frac{3}{2}^-)$, $\Xi_{c2}(\frac{5}{2}^-)$, $\Xi'_{c1}(\frac{1}{2}^-)$, and $\Xi'_{c1}(\frac{3}{2}^-)$, these states also should be excluded due to their too-large masses. Then, since the mass of $\Xi'_{c1}(\frac{1}{2}^-)$ is 2908 MeV and its partial decay width to $\Lambda_c \bar{K}$ final state is 21.6 MeV, and considering that our work does not account for unquenched effects, the

TABLE VIII. The decay widths (in MeV) of $\Xi_c(2923)$, $\Xi_c(2930)$, $\Xi_c(2939)$, $\Xi_c(2965)$, and $\Xi_c(2970)$ as the candidates for the $1P$ or $2S$ states of Ξ_c . The symbol “ $\times$ ” means that this decay cannot happen due to the threshold, while “ ~ 0 ” means that the corresponding partial decay width is less than 0.01 MeV.

State	$\Xi_c \pi$	$\Xi'_c \pi$	$\Xi_c^{*/} \pi$	$\Lambda_c \bar{K}$	$\Sigma_c \bar{K}$	$\Sigma_c^{*} \bar{K}$	ΛD	ΣD	Γ_{total}
$\Xi_c(\frac{1}{2}^+, 2S, 2970)$	~ 0	0.74 ± 0.02	27.31 ± 0.90	~ 0	0.01 ± 0.05	$\times$	$\times$	$\times$	28.06 ± 0.90
$\Xi_{c0}(\frac{1}{2}^-, 1P, 2950)$	68.71 ± 1.15	65.85 ± 1.37	0.02 ± 0.0006	65.93 ± 1.63	$\times$	$\times$	$\times$	$\times$	200.51 ± 2.42
$\Xi_{c1}(\frac{1}{2}^-, 1P, 2910)$	126.69 ± 2.35	114.15 ± 2.75	0.01 ± 0.0004	127.54 ± 3.91	$\times$	$\times$	$\times$	$\times$	368.39 ± 5.32
$\Xi_{c1}(\frac{3}{2}^-, 1P, 3057)$	1.75 ± 0.02	5.83 ± 0.09	13.97 ± 0.27	1.65 ± 0.03	0.28 ± 0.01	2.99 ± 0.60	~ 0	~ 0	26.48 ± 0.66
$\Xi_{c2}(\frac{3}{2}^-, 1P, 3037)$	1.51 ± 0.02	4.66 ± 0.07	37.69 ± 0.78	1.41 ± 0.02	0.14 ± 0.01	2.20 ± 1.83	~ 0	~ 0	47.61 ± 1.99
$\Xi_{c2}(\frac{5}{2}^-, 1P, 3116)$	68.94 ± 0.87	19.58 ± 0.29	40.82 ± 0.74	64.38 ± 0.95	2.19 ± 0.08	2.00 ± 0.13	~ 0	~ 0	197.91 ± 1.52

TABLE IX. The decay widths (in MeV) of $\Xi_c(2923)$, $\Xi_c(2930)$, $\Xi_c(2939)$, $\Xi_c(2965)$, and $\Xi_c(2970)$ as the candidates for the $1P$ or $2S$ state of Ξ'_c , where the states are represented with J^P quantum numbers, radial and orbital excitations, and masses (in MeV). Here, the symbol “ $\times$ ” means that this decay cannot happen due to the threshold, and “ ~ 0 ” means that the corresponding partial decay width is less than 0.01 MeV.

State	$\Xi_c \pi$	$\Xi'_c \pi$	$\Xi'_c{}^* \pi$	$\Lambda_c \bar{K}$	$\Sigma_c \bar{K}$	$\Sigma_c^* \bar{K}$	ΛD	ΣD	Γ_{total}
$\Xi'_c(\frac{1}{2}^+, 2S, 3054)$	3.58 ± 0.05	1.96 ± 0.03	22.20 ± 0.50	57.33 ± 1.05	2.80 ± 0.17	0.21 ± 0.06	36.11 ± 3.21	2.22 ± 0.31	126.41 ± 3.44
$\Xi_c^*(\frac{3}{2}^+, 2S, 3101)$	9.19 ± 0.12	1.35 ± 0.02	35.42 ± 0.68	72.33 ± 1.12	2.90 ± 0.11	2.02 ± 0.16	44.33 ± 2.33	4.71 ± 0.33	172.25 ± 2.70
$\Xi'_{c0}(\frac{1}{2}^-, 1P, 2874)$	54.73 ± 1.19	31.05 ± 0.95	~ 0	54.04 ± 2.30	$\times$	$\times$	$\times$	$\times$	139.82 ± 2.75
$\Xi'_{c1}(\frac{1}{2}^-, 1P, 2908)$	23.72 ± 0.46	18.47 ± 0.47	~ 0	23.02 ± 0.74	$\times$	$\times$	$\times$	$\times$	65.21 ± 0.99
$\Xi'_{c1}(\frac{3}{2}^-, 1P, 2915)$	0.13 ± 0.003	0.26 ± 0.007	14.47 ± 0.57	0.10 ± 0.003	$\times$	$\times$	$\times$	$\times$	14.96 ± 0.57
$\Xi'_{c2}(\frac{3}{2}^-, 1P, 2924)$	0.17 ± 0.003	0.33 ± 0.008	23.52 ± 0.87	0.12 ± 0.004	$\times$	$\times$	$\times$	$\times$	24.14 ± 0.87
$\Xi'_{c2}(\frac{5}{2}^-, 1P, 2948)$	13.58 ± 0.26	1.75 ± 0.04	2.14 ± 0.08	12.54 ± 0.36	$\times$	$\times$	$\times$	$\times$	30.01 ± 0.45
$\Xi'_{c1}(\frac{1}{2}^-, 1P, 3018)$	~ 0	98.08 ± 1.84	~ 0	~ 0	32.53 ± 3.30	$\times$	0.04 ± 0.007	~ 0	130.65 ± 3.77
$\Xi'_{c1}(\frac{3}{2}^-, 1P, 3038)$	~ 0	~ 0	89.03 ± 2.03	~ 0	~ 0	$\times$	~ 0	~ 0	89.03 ± 2.03

theoretical results will be higher than the experimental values. Therefore, we are inclined to consider $\Xi'_{c1}(\frac{1}{2}^-)$ as a candidate for $\Xi_c(2923)$.

- (2) **$\Xi_c(2939)$** : Since its mass and decay width are very close to those of $\Xi_c(2923)$, we obtain similar circumstances during our analysis. After excluding several states whose masses and widths are significantly different from the experimental values, we found that $\Xi'_{c2}(\frac{5}{2}^-)$ can be a good candidate for $\Xi_c(2939)$, because our theoretical mass and width are both extremely close to experimental results.
- (3) **$\Xi_c(2965)$** : The results shown in Tables VIII and IX indicate that there are two states that can be candidates for $\Xi_c(2965)$, $\Xi_c(\frac{1}{2}^+, 2S)$, and $\Xi_{c0}(\frac{1}{2}^-, 1P)$ from the perspective of mass. However, the decay of $\Xi_c(\frac{1}{2}^+, 2S)$ to $\Lambda_c \bar{K}$ is strictly forbidden. Therefore, $\Xi_c(2965)$ tends to be identified as a ρ -mode P -wave excitation of Ξ_c with a quantum number of $J^P = \frac{1}{2}^-$.

It is important to highlight here that we also discovered a $\Xi'_{c0}(\frac{1}{2}^-)$ state and its mass is 2874 MeV, which is very close to the $\Xi_c(2882)$ observed by the LHCb Collaboration in 2023 [60]. We hope that subsequent experiments will be able to find this state and thereby confirm our conclusion, although the status of $\Xi_c(2882)$ is not so clear at present.

C. $\Xi_c(2970)$

The $\Xi_c(2970)$ state was observed by the Belle Collaboration in the $\Lambda_c^+ K^- \pi^+$ and $\Lambda_c^+ K_S^0 \pi^-$ invariant mass spectra in 2006 [49], and it was confirmed later by Belle in the $\Xi_c^* \pi$ channel [6]. In 2020, the Belle experiment determined its quantum number to be $\frac{1}{2}^+$ by measuring the angular distribution of $\Xi_c(2970)^+ \rightarrow \Xi_c(2645)^0 \pi^+ \rightarrow \Xi_c^+ \pi^- \pi^+$ [61], which is the first determination of the spin and parity of a charmed-strange baryon. Furthermore, the

decay branching ratio of $\Xi_c(2970)$ is also presented by Belle as

$$\frac{\Gamma_{\Xi_c(2970)^+ \rightarrow \Xi_c(2645)^0 \pi^+}}{\Gamma_{\Xi_c(2970)^+ \rightarrow \Xi_c^0 \pi^+}} = 1.67 \pm 0.29(\text{stat})^{+0.15}_{-0.09}(\text{sys}) \pm 0.25(\text{IS}), \quad (34)$$

where IS refers to the uncertainty due to possible isospin symmetry-breaking effects. In addition, this R value favors the spin of the light-quark degrees of freedom, $S_\rho = 0$. Here, we take the decay width of $\Xi_c(2970)^+$ from RPP as $20.9^{+2.4}_{-3.5}$ MeV [1].

Since the quantum number $J^P = \frac{1}{2}^+$ of $\Xi_c(2970)$ is already clear, it can only be a $2S$ state or $1D$ state. Several quark-model-based calculations are consistent with the experimental results. In Ref. [11], the mass of the $\Xi_c(2S)$ state was calculated to be 2983 MeV in the heavy-quark–light-diquark picture in the framework of the QCD-motivated relativistic quark model, suggesting that $\Xi_c(2970)$ can be a $2S$ state of Ξ_c . In Ref. [15], $\Xi_c(2970)$ was studied by the relativistic flux tube model and assigned to the first radial excitations with $J^P = \frac{1}{2}^+$. In Refs. [62,63], the hypercentral description of a three-body system and the relativistically covariant quark model based on the Bethe-Salpeter equation are both used to investigate the $\Xi_c(2970)$ state, and to show that it is indeed possible for it to be a $2S$ state. Furthermore, the $^3P_0$ model is also used to study the decay widths and certain ratio of branching fractions of $\Xi_c(2970)$, and its results are compatible with the experimental data [64].

- (1) **$\Xi_c(2970)$** : From the perspective of the mass spectrum, according to Tables V and VI, the mass of $\Xi_c(\frac{1}{2}^+, 2S)$ at 2970 MeV is the same as that of $\Xi_c(2970)$, while other excitations with positive parity are all over 3000 MeV, which must be

TABLE X. The decay widths (in MeV) of $\Xi_c(3055)$ and $\Xi_c(3080)$ as candidates for $1D$ states, where the states are represented with J^P quantum numbers, radial and orbital excitations, and masses (in MeV). Here, “ ~ 0 ” means that the corresponding partial decay width is less than 0.01 MeV.

State	$\Xi_c\pi$	$\Xi'_c\pi$	$\Xi_c^*\pi$	$\Lambda_c\bar{K}$	$\Sigma_c\bar{K}$	$\Sigma_c^*\bar{K}$	ΛD	ΣD	Γ_{total}
$\Xi_{c2}(\frac{3}{2}^+, 1D, 3043)$	~ 0	9.10 ± 0.17	2.00 ± 0.05	~ 0	1.22 ± 0.09	0.01 ± 0.007	0.70 ± 0.07	0.80 ± 0.15	13.83 ± 0.25
$\Xi_{c2}(\frac{5}{2}^+, 1D, 3078)$	~ 0	2.36 ± 0.04	5.32 ± 0.11	~ 0	0.09 ± 0.004	0.57 ± 0.07	0.24 ± 0.02	0.27 ± 0.03	8.85 ± 0.14

excluded. The decay of $\Xi_c(2970)$ into $\Lambda_c\bar{K}$ or $\Xi_c\pi$ has never been seen in experiments, which is consistent with our results. The latest experimental data shows that the width of $\Xi_c(2970)$ is $\Gamma = 20.9^{+2.4}_{-3.5}$ MeV [1], close to our results. Considering the mass spectrum and decay width, we tend to interpret $\Xi_c(2970)$ as the $\Xi_c(\frac{1}{2}^+, 2S)$ state.

D. $\Xi_c(3055)$ and $\Xi_c(3080)$

The $\Xi_c(3080)$ state was also discovered by the Belle Collaboration in the $\Lambda_c^+ K^- \pi^+$ and $\Lambda_c^+ K_s^0 \pi^-$ invariant mass spectra in 2006 [49]. Later, it was discovered in the $\Sigma_c(2455)^{++} K^-$ and $\Sigma_c(2520)^{++} K^-$ decay channels by the BABAR Collaboration in 2008 [4]. In 2016, the Belle Collaboration reviewed the $\Xi_c(3055)$ and $\Xi_c(3080)$ states in the ΛD decay mode and provided the masses and decay widths of all the states as [65]

$$\begin{aligned}
 \Xi_c(3055)^0: M &= 3059.0 \pm 0.5 \pm 0.6 \text{ MeV}, \\
 \Gamma &= 6.4 \pm 2.1 \pm 1.1 \text{ MeV}; \\
 \Xi_c(3055)^+: M &= 3055.8 \pm 0.4 \pm 0.2 \text{ MeV}, \\
 \Gamma &= 7.0 \pm 1.2 \pm 1.5 \text{ MeV}; \\
 \Xi_c(3080)^+: M &= 3079.6 \pm 0.4 \pm 0.1 \text{ MeV}, \\
 \Gamma &= 3.0 \pm 0.7 \pm 0.4 \text{ MeV}. \quad (35)
 \end{aligned}$$

It is worth noting that the spin and parity of $\Xi_c(3055)$ have been determined by the LHCb Collaboration to be $J^P = 3/2^+$, which suggests it to be the first identified λ -mode D -wave excitation of Ξ_c [31]. And for $\Xi_c(3080)^+$, its width and mass have also been measured in the invariant mass spectrum of $\Xi_c^+ \pi^- \pi^+$ by the LHCb Collaboration as [7]

$$\begin{aligned}
 \Xi_c(3080)^+: M &= 3076.8 \pm 0.7 \pm 1.3 \pm 0.2 \text{ MeV}, \\
 \Gamma &= 6.8 \pm 2.3 \pm 0.9 \text{ MeV}. \quad (36)
 \end{aligned}$$

Due to the fact that the specific quantum numbers of $\Xi_c(3080)$ have not been fully determined, various works with different models have been used to study its quantum number. For example, Ref. [66] considers it to be an excitation of Ξ_c with $J^P = \frac{3}{2}^+$. In Refs. [11,15,67–69], the authors regarded $\Xi_c(3080)$ as a D -wave state with $J^P = \frac{5}{2}^+$.

In Refs. [9,10], the authors consider $\Xi_c(3080)$ to be a $\Xi'_c(1P)$ state with $J^P = \frac{5}{2}^-$, or a $\Xi_c(1D)$ state with $J^P = \frac{5}{2}^+$, while Ref. [70] suggests it is a $\Xi_c(2S)$ state with $J^P = \frac{1}{2}^+$. In Refs. [71,72], the $\Xi_c(3080)$ state has been investigated as a D -wave baryon state in the framework of the QCD sum rule.

- (1) $\Xi_c(3055)$: According to Tables V and VI, both $\Xi'_c(\frac{1}{2}^+, 2S)$ and $\Xi_{c2}(\frac{3}{2}^+, 1D)$ are close to $\Xi_c(3055)$ with positive parity. However, the decay width of $\Xi'_c(\frac{1}{2}^+, 2S)$ is much higher than the experimental value, and it cannot be a good candidate of $\Xi_c(3055)$. We further calculated the decay width of $\Xi_{c2}(\frac{3}{2}^+, 1D)$ according to the $^3P_0$ model, and the results are shown in Table X. The total decay width is 13.83 MeV, very close to the sum of the central values of the decay widths of $\Xi_c(3055)^0$ and $\Xi_c(3055)^+$. Therefore, $\Xi_c(3055)$ can be interpreted as a λ -mode $1D$ -wave Ξ_c baryon, which is consistent with the experimental conclusion [31].
- (2) $\Xi_c(3080)$: Based on our research on $\Xi_c(3055)$, we found that the mass of $\Xi_{c2}(\frac{5}{2}^+, 1D)$ is 3078 MeV, which is almost the same as that of $\Xi_c(3080)$. For $\Xi_c(3080)^0$, its total decay width is 5.6 ± 2.2 MeV [1], and the sum of this width and that of $\Xi_c(3080)^+$ is around 8.6 MeV, which is almost the same as our calculation at 8.86 MeV. Therefore, we consider $\Xi_{c2}(\frac{5}{2}^+, 1D)$ to be a good arrangement for $\Xi_c(3080)$, which can form a doublet as $\Xi_{c2}(\frac{3}{2}^+, \frac{5}{2}^+)$ with the $\Xi_c(3055)$ state.

E. Σ -type D -wave Ξ'_c states

We also studied the λ -mode D -wave excitation of Ξ'_c , and the masses and corresponding decay width are shown in Table XI, where the masses of these states are very close to that of $\Xi_c(3123)$. In addition, their decay widths are all around several MeV. The $\Xi_c(3123)$ state was observed by the BABAR experiment in the mass spectra of $\Lambda_c^+ K^- \pi^+$ in 2008 [4], and its mass and decay width were reported as follows:

$$\begin{aligned}
 \Xi_c(3123)^+: M &= 3122.9 \pm 1.3 \pm 0.3 \text{ MeV}, \\
 \Gamma &= 4.4 \pm 3.4 \pm 1.7 \text{ MeV}. \quad (37)
 \end{aligned}$$

TABLE XI. The decay widths (in MeV) of λ -mode D -wave excitation of Ξ'_c , where the states are represented with J^P quantum numbers, radial and orbital excitations, and masses (in MeV). Here, “ ~ 0 ” means that the corresponding partial decay width is less than 0.01 MeV.

State	$\Xi_c \pi$	$\Xi'_c \pi$	$\Xi_c^* \pi$	$\Lambda_c \bar{K}$	$\Sigma_c \bar{K}$	$\Sigma_c^* \bar{K}$	ΛD	ΣD	Γ_{total}
$\Xi'_{c1}(\frac{1}{2}^+, 1D, 3136)$	~ 0	0.1 ± 0.001	~ 0	~ 0	~ 0	~ 0	2.46 ± 0.10	1.32 ± 0.07	3.78 ± 0.12
$\Xi'_{c1}(\frac{3}{2}^+, 1D, 3143)$	1.12 ± 0.01	0.45 ± 0.005	2.73 ± 0.04	0.16 ± 0.002	0.15 ± 0.004	0.60 ± 0.02	0.30 ± 0.01	0.03 ± 0.001	5.54 ± 0.05
$\Xi'_{c2}(\frac{5}{2}^+, 1D, 3153)$	0.05 ± 0.0005	0.22 ± 0.003	2.03 ± 0.03	0.05 ± 0.0006	0.02 ± 0.0005	0.35 ± 0.01	0.60 ± 0.02	0.04 ± 0.002	3.36 ± 0.04
$\Xi'_{c3}(\frac{5}{2}^+, 1D, 3170)$	0.05 ± 0.0005	0.23 ± 0.003	2.09 ± 0.03	1.10 ± 0.01	0.50 ± 0.01	1.85 ± 0.06	0.93 ± 0.03	0.05 ± 0.002	6.80 ± 0.07
$\Xi'_{c2}(\frac{3}{2}^+, 1D, 3172)$	0.72 ± 0.007	0.40 ± 0.004	2.64 ± 0.03	0.01 ± 0.0001	0.15 ± 0.003	0.70 ± 0.02	0.27 ± 0.01	0.02 ± 0.001	5.91 ± 0.04
$\Xi'_{c3}(\frac{7}{2}^+, 1D, 3176)$	~ 0	~ 0	~ 0	~ 0	~ 0	~ 0	0.92 ± 0.03	0.06 ± 0.002	0.98 ± 0.03

Then, in 2014, the Belle experiment attempted to find the signal of $\Xi_c(3123)$ in the final state of $\Sigma_c(2520)^{++}K^-$ but did not observe it [73]. On the Review of Particle Physics (RPP) [1], the statistical significance of $\Xi_c(3123)$ is 3.6σ , indicating that the experimental information is still insufficient to confirm it as a new particle state. On the theoretical side, in Ref. [15], the authors suggest that it is a $\Xi_c(2P)$ state with $J^P = \frac{1}{2}^-$ or $\frac{3}{2}^-$.

However, based on our calculation of the mass spectra and partial decay width, it is highly likely that $\Xi_c(3123)$ is a Σ -type D -wave excitation of Ξ'_c , although its spin parity is unknown. From our results in Table XI, the decay widths of all D -wave excitations of Ξ'_c to the $\Sigma_c \bar{K}$ are very small. For both $\Xi'_{c1}(\frac{1}{2}^+)$ and $\Xi'_{c3}(\frac{7}{2}^+)$, the main decay channels are ΛD and ΣD . For $\Xi'_{c1}(\frac{3}{2}^+)$, the main decay channels are $\Xi_c \pi$ and $\Xi_c^* \pi$, while for $\Xi'_{c2}(\frac{5}{2}^+)$ and $\Xi'_{c2}(\frac{3}{2}^+)$, the main decay channel is $\Xi_c^* \pi$. Finally, for $\Xi'_{c3}(\frac{5}{2}^+)$, the main decay channels are $\Xi_c^* \pi$, $\Lambda_c \bar{K}$, and $\Sigma_c^* \bar{K}$. Thus, although their mass positions are close to each other, their dominant decay modes are very different. For $\Xi'_{c1}(\frac{1}{2}^+)$, which is interpreted as $\Xi_c(3123)$ in this work, the experiment can attempt to find it in the ΛD and ΣD decay modes. However, it is not easily detectable in the $\Sigma_c^* \bar{K}$ decay mode due to fact that the corresponding decay width we calculated is 0, which is consistent with the conclusions in Ref. [73]. Similarly, for other Σ -type D -wave Ξ'_c states, the experiment can also search for them using the same method—namely, utilizing the dominant decay modes. Therefore, we hope that our results will help the experiment to further identify the nature of $\Xi_c(3123)$, and to discover more D -wave excitation of Ξ'_c in the future as a verification of our model.

IV. SUMMARY

Due to its special constituent quark components, the $\Xi_c^{(\prime)}$ family becomes a great platform to study the heavy quark symmetry and chiral symmetry. In particular, the explicit breaking of chiral symmetry makes exchanges of massive Goldstone bosons between light quarks possible, and it provides an excellent environment for the examination of the chiral constituent quark model.

Presently, there already exist many $\Xi_c^{(\prime)}$ in RPP [1]. However, the properties of most of them still remain unclear—although there already exist many studies, the classification of these states is still confused [8–12,15].

However, things may change with the measurements carried out by the LHCb Collaboration, which determines that $\Xi_c(3055)$ is a $\bar{3}_F \lambda$ -mode $1D$ state with quantum number $\frac{3}{2}^+$. In our view, this result can allow $\Xi_c(3055)$ to serve as a scaling point, which can be used to restrict the model parameters for further studies on the $\Xi_c^{(\prime)}$ family. Thus, inspired by this, in this work, we investigate the $2S$, $1P$, and $1D$ states of $\Xi_c^{(\prime)}$ baryons in the framework of the chiral quark model and the $^3P_0$ decay mechanism with the help of the Gaussian expansion method. By comparing the results of the mass spectra and decay widths with the experimental values, we give interpretations for the quantum numbers of these states as follows:

- (1) $\Xi_c(2790)$ and $\Xi_c(2815)$ are probably λ -mode $1P$ states and form a doublet $\Xi_{c1}(\frac{1}{2}^-, \frac{3}{2}^-)$. The decay widths of the dominant decay channels of our calculations are very close to experimental values.
- (2) $\Xi_c(2923)$ and $\Xi_c(2939)$ can be $\Xi'_{c1}(\frac{1}{2}^-, 1P)$ and $\Xi'_{c2}(\frac{5}{2}^-, 1P)$, respectively. $\Xi_c(2965)$ can be a ρ -mode P -wave excited state with quantum number $J^P = \frac{1}{2}^-$. In addition, another P -wave excited state $\Xi'_{c0}(\frac{1}{2}^-)$ with a mass of 2874 MeV is obtained, and it can be a good candidate for $\Xi_c(2882)$.
- (3) $\Xi_c(2970)$ can be interpreted as $\Xi_c(\frac{1}{2}^+, 2S)$, which is the only possibility in our model, in terms of both mass and decay width.
- (4) $\Xi_c(3055)$ can be arranged as $\Xi_{c2}(\frac{3}{2}^+, 1D)$, which is the same as the experimental result [31], and it can form a doublet $\Xi_{c2}(\frac{3}{2}^+, \frac{5}{2}^+)$ with $\Xi_c(3080)$, as is the case with $\Xi_c(2790)$ and $\Xi_c(2815)$.
- (5) $\Xi_c(3123)$ might be arranged as a Σ -type D -wave $\Xi'_{c1}(\frac{1}{2}^+, 1D)$ state, but to determine its detailed quantum number, experimental measurements on the ΛD and ΣD (its dominant decay modes by our calculations) are critical.

Thus, we hope that future experiments can carry out relevant measurements to verify our conclusions, which not only will help in further determinations on the properties of the currently unclear $\Xi_c^{(\prime)}$ states, but also will deepen our understandings on the symmetry, strong interaction, and few-body system.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

APPENDIX A: CALCULATION ON THE ERRORS OF THE MASS SPECTRUM

During the fit on the mesons and baryons given in Table IV, we can get not only the values of parameters, but also their errors. Thus, we can use these values to calculate the errors of the mass spectrum.

We start from the definition of energy in quantum mechanics—i.e., if we already have a wave function ψ of the system that obeys the Hamiltonian $H(\lambda_s)$, with λ_s being the parameters in the Hamiltonian, the energy of the system can be calculated as

$$E(\lambda_s) = \langle \psi(\lambda_s) | H(\lambda_s) | \psi(\lambda_s) \rangle, \quad (\text{A1})$$

where $\psi(\lambda_s)$ can be expanded by a series of basis functions ψ_i with λ_s -dependent coefficients as

$$\psi(\lambda_s) = \sum_i C_i(\lambda_s) \psi_i. \quad (\text{A2})$$

Then, following the thinking of perturbation theory, we think that the leading-order errors may be sufficient. Thus, we can estimate the error of energy as

$$\delta E = \sum_{s,i,j} C_i(\lambda_s) C_j^*(\lambda_s) \langle \psi_j | \frac{\partial}{\partial \lambda_s} H(\lambda_s) | \psi_i \rangle \delta \lambda_s. \quad (\text{A3})$$

Here, we want to emphasize that to get the above equation, we introduce an assumption that expansion coefficients $C_i(\lambda_s)$ change little when the parameters vary—i.e., $\frac{\partial}{\partial \lambda_s} C_i(\lambda_s) \approx 0$ when $\delta \lambda_s$ is small. However, according to our cross-check, the error obtained with this method is not the same but very close to that from another strategy, where we vary the model parameters within their permitted ranges to make a dense calculation on the spectra, and then extract the minimum and maximum values to obtain the error.

Thus, when it comes to practical calculation, the masses of quarks, the contribution from meson exchange, and the a_s , r_0 , r_g values in the noncentral potential are fixed as in Table III. Thus, the error of the mass spectrum only comes from α_s in the OGE potential, in addition to a_c , and Δ in confinement; then, we will have

$$\delta V_{\text{CON}}^C = \lambda_i^c \cdot \lambda_j^c [-r_{ij} \delta a_c - \delta \Delta], \quad (\text{A4})$$

$$\begin{aligned} \delta V_{\text{CON}}^{\text{SO}} = & -\lambda_i^c \cdot \lambda_j^c \frac{r_{ij} \delta a_c}{4m_i^2 m_j^2} \left[((m_i^2 + m_j^2)(1 - 2a_s) \right. \\ & + 4m_i m_j (1 - a_s)) (\mathbf{S}_+ \cdot \mathbf{L}) \\ & \left. + (m_j^2 - m_i^2)(1 - 2a_s) (\mathbf{S}_- \cdot \mathbf{L}) \right], \end{aligned} \quad (\text{A5})$$

$$\delta V_{\text{OGE}}^C = \frac{\delta \alpha_s}{4} \lambda_i^c \cdot \lambda_j^c \left[\frac{1}{r_{ij}} - \frac{\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j}{6m_i m_j} \frac{e^{-r_{ij}/r_0(\mu)}}{r_{ij} r_0^2(\mu)} \right], \quad (\text{A6})$$

$$\begin{aligned} \delta V_{\text{OGE}}^T = & -\frac{1}{16} \frac{\delta \alpha_s}{m_i m_j} \lambda_i^c \cdot \lambda_j^c \left[\frac{1}{r_{ij}^3} - \frac{e^{-r_{ij}/r_g(\mu)}}{r_{ij}} \right. \\ & \left. \times \left(\frac{1}{r_{ij}^2} + \frac{1}{3r_g^2(\mu)} + \frac{1}{r_{ij} r_g(\mu)} \right) \right] S_{ij}, \end{aligned} \quad (\text{A7})$$

$$\begin{aligned} \delta V_{\text{OGE}}^{\text{SO}} = & -\frac{1}{16} \frac{\delta \alpha_s}{m_i^2 m_j^2} \lambda_i^c \cdot \lambda_j^c \left[\frac{1}{r_{ij}^3} - \frac{e^{-r_{ij}/r_g(\mu)}}{r_{ij}^3} \right. \\ & \left. \times \left(1 + \frac{r_{ij}}{r_g(\mu)} \right) \right] \left[((m_i + m_j)^2 + 2m_i m_j) \right. \\ & \left. \times (\mathbf{S}_+ \cdot \mathbf{L}) + (m_j^2 - m_i^2) (\mathbf{S}_- \cdot \mathbf{L}) \right]. \end{aligned} \quad (\text{A8})$$

Thus, the Hamiltonian dependence on the parameters is

$$\sum_s \frac{\partial}{\partial \lambda_s} H(\lambda_s) \delta \lambda_s = \delta V_{\text{CON}} + \delta V_{\text{OGE}}. \quad (\text{A9})$$

Finally, to avoid the uncertainties of the signs of errors of parameters, we calculate the errors as

$$\delta E = \sqrt{\sum_{s,i,j} \left(C_i C_j^* \langle \psi_j | \frac{\partial}{\partial \lambda_s} H(\lambda_s) | \psi_i \rangle \right)^2 (\delta \lambda_s)^2}. \quad (\text{A10})$$

APPENDIX B: CALCULATION ON THE ERRORS OF TWO-BODY DECAYS

For the two-body partial decay width of the process $A \rightarrow B + C$, we have

$$\Gamma_{A \rightarrow B+C} \equiv \Gamma_{2,i} \sim \frac{p(M_A, M_B, M_C)}{M_A^2} |\mathcal{M}_{A \rightarrow B+C}|^2, \quad (\text{B1})$$

where p is the module of the three-momentum of final particles in the center-of-mass system, and $\mathcal{M}_{A \rightarrow B+C}$ is the transition amplitude.

Ordinarily, in the quark model, $\mathcal{M}_{A \rightarrow B+C}$ can be symbolically expressed as

$$\mathcal{M}_{A \rightarrow B+C} \sim \langle \psi_B \psi_C | \hat{T} | \psi_A \rangle, \quad (\text{B2})$$

where ψ_i is the wave function of particle i , and $\hat{T}$ is the transition operator. Because in the quark pair creation model, the parameters in $\hat{T}$ are previously fixed, if we still follow the assumption that $C_i(\lambda_s)$ remains unchanged if $\delta \lambda_s$ is small, we can intermediately infer that $(\mathcal{M}_{A \rightarrow B+C})$ will be a constant in error calculation. Thus, we can approximately estimate the error of the two-body decay as

$$(\delta \Gamma_{2,i})^2 = \left(\frac{\partial \Gamma_{2,i}}{\partial M_A} \right)^2 (\delta M_A)^2 + \left(\frac{\partial \Gamma_{2,i}}{\partial M_B} \right)^2 (\delta M_B)^2 + \left(\frac{\partial \Gamma_{2,i}}{\partial M_C} \right)^2 (\delta M_C)^2, \quad (\text{B3})$$

where δM_i is just the error of the mass of particle i from the previous appendix. Finally, the error of the total two-body decay width is calculated as

$$\delta \Gamma_2 = \sqrt{\sum_i (\delta \Gamma_{2,i})^2}. \quad (\text{B4})$$

APPENDIX C: POSSIBLE COMPETITIONS BETWEEN ONE-GLUON EXCHANGE AND ONE-BOSON EXCHANGE

In the early stages of this work, we tried to fit the ground baryon spectra with one-gluon exchange only under SU(3) symmetry, and the model parameters and fit results are presented in Tables XII and XIII, respectively.

It is easy to see that when considering the one-gluon exchange only, the behavior of α_s does decrease with the

TABLE XII. Quark model parameters used in the calculation, where the superscript “*” means that a number was previously fixed during the fit.

Quark masses	$m_{u,d}$ (MeV)	313*
	m_s (MeV)	555*
	m_c (MeV)	1800*
Confinement	a_c (MeV · fm ⁻¹)	105.44 ± 0.48469
	Δ (MeV)	-79.501 ± 0.67998
OGE	$\hat{r}_0 = \hat{r}_g$ (MeV · fm)	30.633 ± 0.21361
	α_{uu}	0.878 ± 0.0044
	α_{us}	0.799 ± 0.0039
	α_{ss}	0.758 ± 0.0042
	α_{uc}	0.750 ± 0.0038
	α_{sc}	0.691 ± 0.0035
	α_{cc}	0.666 ± 0.0029

momentum transfer, which obeys the requirement of quantum chromodynamics. However, at this time, Λ and Σ will have the same mass. Such a thing is actually understandable, since the gluon exchange cannot distinguish the isospin of the hadron if we use SU(3) symmetry to describe Λ and Σ , which makes us realize the necessity of the introduction of Goldstone exchange in baryon calculation if we want to adopt a unified SU(3) symmetry to describe both light and single heavy baryons. In addition, we also find that such a thing also happens in the meson sector. For example, ρ and ω will also have the same mass when considering gluon exchange only, which shares the same reason as the baryon fit.

Thus, following the chiral quark model, we add into the Goldstone exchanges, and to obey the conclusion of chiral symmetry, all the cutoffs appeared in the potentials of Goldstone meson exchanges are previously fixed around 1 GeV. However, at this time, we find that the fit on the ground baryon spectra will violate the usual behavior of α_s . It is, in our view, because when the cutoffs of the Goldstone exchange are previously fixed, their contributions are also previously fixed, and then during the fit, the behavior of α_s is sacrificed by the program. In other words, there may exist some mysterious competitions that we have not figured out between gluon and Goldstone exchange contributions in light quark interactions when fitting the ground baryon spectra. Thus, in the next step, we make all the cutoffs in the Goldstone exchanges free and fit the ground baryon spectra again, and we find that although the behavior of α_s can be revealed, some of the cutoffs are smaller than the masses of the exchanged bosons, which we think is unacceptable, since in our view, it is not physically permitted. Finally, to obey the requirements of physics, we use the model parameters along with the fit result given in Tables III and IV.

TABLE XIII. The masses of ground-state baryons in units of MeV.

	N	Δ	Λ	Σ	Σ^*	Ξ
ChQM	942.12	1227.97	1153.30	1153.30	1386.69	1328.21
Expt	939	1232	1116	1189	1383	1318
	Ξ^*	Ω	Λ_c	Σ_c	Σ_c^*	Ξ_c
ChQM	1531.73	1662.10	2276.85	2453.55	2514.81	2466.67
Expt	1533	1672	2286	2455	2520	2471
	Ξ'_c	Ξ'^*_c	Ω_c	Ω^*_c		
ChQM	2582.66	2647.04	2696.18	2765.14		
Expt	2579	2645	2695	2770		

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