Theoretical interpretation of $\Xi_c(2970)$

Ze Zhao^{*}

CAS Key Laboratory of Theoretical Physics, Institute of Theoretical Physics,
Chinese Academy of Sciences, Beijing 100190, China

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The open charm strong decay widths and certain ratio of branching fractions of a charmed strange baryon $\Xi_c(2970)$ are calculated in a 3P_0 model. The results are compatible with the latest experimental data. The theoretical ratio of decay branching fractions $R = \mathcal{B}[\Xi_c(2970)^+ \rightarrow \Xi_c(2645)^0 \pi^+] / \mathcal{B}[\Xi_c(2970)^+ \rightarrow \Xi_c^0 \pi^+] \approx 1.0$. The spin parity $J^P = 1/2^+$ and $3/2^+$ for different assignments are analyzed. From the results of our calculation, $\Xi_c(2970)$ can be interpreted as a $2S$ -wave state with $J^P(s_l) = 1/2^+(0)$. The distinctions between the $2S$ -wave n_{ρ^-} and n_{λ^-} -excitation states and between states with $s_l = 0$ and $s_l = 1$ and between states with total spin $1/2$ and $3/2$ ($s_l = 1$) are also discussed.

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I. INTRODUCTION

In the convention of a quark model [1,2], the Ξ_c baryon consists of one u or d , one strange quark, and one charmed quark, which is also known as the charmed-strange baryon. The low lying charmed-strange baryons are confirmed with their J^P numbers measured experimentally. However, with the increasing energy, more and more highly excited charmed-strange baryons have been observed. In the Ξ_c sector, $\Xi_c(2970)$ [was $\Xi_c(2980)$] was first observed by the Belle Collaboration in the $\Lambda_c^+ K^- \pi^+$ channel [3], and then confirmed by the BABAR Collaboration in the $\Xi_c(2645)^0 \pi^+$ decay channel [4]. With its quantum numbers unmeasured, calculations and debates of $\Xi_c(2970)$ have been carried out.

Recently, the Belle Collaboration reported the results from a study of the spin and parity of $\Xi_c(2970)^+$ [5]. The angular distributions strongly favor $\Xi_c(2970)$ to be spin $J = 1/2$. And they also measured the ratio of decay branching fractions,

$$R = \frac{\mathcal{B}[\Xi_c(2970)^+ \rightarrow \Xi_c(2645)^0 \pi^+]}{\mathcal{B}[\Xi_c(2970)^+ \rightarrow \Xi_c^0 \pi^+]}$$

$$= 1.67 \pm 0.29(\text{stat})_{-0.09}^{+0.15}(\text{syst}) \pm 0.25(\text{IS}).$$

where IS refers to the uncertainty due to possible isospin-symmetry-breaking effects. This R value favors the spin

parity $J^P = 1/2^+$ with the spin of the light-quark degrees of freedom $s_l = 0$.

In experiments, J^P quantum numbers for most of the observed excited charmed baryons have not yet been measured so far. How to identify the observed baryons is an important topic in baryon spectroscopy. The spectroscopy of charmed baryons has been studied in many models. Ebert *et al.* calculated the mass spectra of heavy baryons in the heavy quark–light quark picture in the QCD-motivated relativistic quark model and they suggested that $\Xi_c(2970)$ be assigned as the $2S$ excitation with $J^P = 1/2^+$ [6]. Bing Chen *et al.* investigated the Λ_c and Ξ_c in the heavy quark–light diquark picture and they also concluded that $\Xi_c(2970)$ can be assigned to the first radial excitations with $J^P = 1/2^+$ [7]. For more on the spectrum study, one can see Ref. [2] and references therein.

Hadronic decays of $\Xi_c(2970)$ have been studied in a heavy hadron chiral perturbation theory [8], where $\Xi_c(2970)$ is suggested as a positive-parity excitation of Ξ_c . It has also been studied in a chiral quark model [9], in which $\Xi_c(2970)$ is suggested as one of the orbital excitations of Ξ_c . There are never certain conclusions about these excited baryons before their quantum numbers can be measured experimentally. Since the report of the spin parity of $\Xi_c(2970)^+$, one of the remaining questions is to ascertain its radial quantum number, that is, to decide whether it is an $2S$ -wave or $1D$ -wave state. One of the purposes of this article is to solve this question theoretically by calculating the hadronic decay of $\Xi_c(2970)^+$ under different assignments, and the other is to predict the properties of other Ξ_c baryons that may carry similar masses or quantum numbers to be observed.

There are a lot of theoretical approaches to study the properties of hadrons. The 3P_0 model is one of the phenomenological methods to calculate the Okubo-Zweig-Iizuka (OZI)-allowed hadronic decays of hadrons.

^{*}zhaoze@mail.itp.ac.cn

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In addition to mesons, it is employed successfully to explain the hadronic decays of baryons [10–15]. In this paper, we will study the hadronic decays of $\Xi_c(2970)^+$ in the framework of the 3P_0 model.

This work is organized as follows. In Sec. II, we give a brief review of the 3P_0 model while in Sec. III we present our numerical results. In the last section, we give our conclusions and discussions.

II. THE FRAMEWORK

The 3P_0 model was first proposed by Micu [16] and further developed by Yaouanc *et al.* [17–19]. It is also known as a quark pair creation model, in whose framework it is assumed that a pair of quarks $q\bar{q}$ is created from the vacuum and thus with quantum numbers $J^{PC} = 0^{++}(^2S+1L_J = ^3P_0)$. It was first proposed to calculate the open strong decays of two-body mesons. Furthermore, the model has been subsequently employed and developed to study the OZI-allowed hadronic decays of three-body baryons by many authors not cited here.

In the model, the created quark-antiquark $q\bar{q}$ then regroups with the quarks from the initial hadron A to form two daughter hadrons, B and C. The interaction Hamiltonian for the creating process has the form [20–22]

$$\mathcal{H}_{q\bar{q}} = \gamma \sum_f 2m_f \int d^3\mathbf{r} \bar{\psi}_f \psi_f, \quad (1)$$

where ψ_f is a Dirac quark field with flavor f . m_f is the constituent quark mass. The strength of the quark pair creation is represented by the dimensionless parameter γ .

For meson decays, the created quark regroups with the antiquark of the initial meson, the created antiquark

FIG. 1. Baryon decay process of $A \rightarrow B + C$ in the 3P_0 model.

regroups with the quark of the initial meson, and two mesons appear in the final states. For baryon decays, one quark of the initial baryon regroups with the created antiquark to form a meson, and the rest of the two quarks regroup with the created quark to form a daughter baryon. The process of a baryon decay is shown in Fig. 1.

In the 3P_0 model, the hadronic decay width Γ of a process $A \rightarrow B + C$ is as follows [19]:

$$\Gamma = \pi^2 \frac{|\vec{p}|}{m_A^2} \frac{1}{2J_A + 1} \sum_{M_{J_A} M_{J_B} M_{J_C}} |\mathcal{M}^{M_{J_A} M_{J_B} M_{J_C}}|^2. \quad (2)$$

In the equation, $\vec{p}$ is the momentum of the daughter baryon in the A's center of mass frame,

$$|\vec{p}| = \frac{\sqrt{[m_A^2 - (m_B - m_C)^2][m_A^2 - (m_B + m_C)^2]}}{2m_A}, \quad (3)$$

and m_A and J_A are the mass and total angular momentum of the initial baryon A, respectively. m_B and m_C are the masses of the final hadrons. $\mathcal{M}^{M_{J_A} M_{J_B} M_{J_C}}$ is the helicity amplitude, which has the relation [15]

$$\begin{aligned} \delta^3(\vec{p}_B + \vec{p}_C - \vec{p}_A) \mathcal{M}^{M_{J_A} M_{J_B} M_{J_C}} &= -2\gamma \sqrt{8E_A E_B E_C} \sum_{M_{\rho_A}} \sum_{M_{L_A}} \sum_{M_{\rho_B}} \sum_{M_{L_B}} \sum_{M_{S_1}, M_{S_3}, M_{S_4}, m} \langle J_{I_A} M_{J_{I_A}} S_3 M_{S_3} | J_A M_{J_A} \rangle \\ &\times \langle L_{\rho_A} M_{L_{\rho_A}} L_{\lambda_A} M_{L_{\lambda_A}} | L_A M_{L_A} \rangle \langle L_A M_{L_A} S_{12} M_{S_{12}} | J_{I_A} M_{J_{I_A}} \rangle \langle S_1 M_{S_1} S_2 M_{S_2} | S_{12} M_{S_{12}} \rangle \\ &\times \langle J_{I_B} M_{J_{I_B}} S_3 M_{S_3} | J_B M_{J_B} \rangle \langle L_{\rho_B} M_{L_{\rho_B}} L_{\lambda_B} M_{L_{\lambda_B}} | L_B M_{L_B} \rangle \langle L_B M_{L_B} S_{14} M_{S_{14}} | J_{I_B} M_{J_{I_B}} \rangle \\ &\times \langle S_1 M_{S_1} S_4 M_{S_4} | S_{14} M_{S_{14}} \rangle \langle 1m; 1-m | 00 \rangle \langle S_4 M_{S_4} S_5 M_{S_5} | 1-m \rangle \langle L_C M_{L_C} S_C M_{S_C} | J_C M_{J_C} \rangle \\ &\times \langle S_2 M_{S_2} S_5 M_{S_5} | S_C M_{S_C} \rangle \times \langle \varphi_B^{1,4,3} \varphi_C^{2,5} | \varphi_A^{1,2,3} \varphi_0^{4,5} \rangle \times I_{M_{L_B}, M_{L_C}}^{M_{L_A}, m}(\vec{p}). \end{aligned} \quad (4)$$

In the equation above, $\langle \varphi_B^{1,4,3} \varphi_C^{2,5} | \varphi_A^{1,2,3} \varphi_0^{4,5} \rangle$ is the flavor matrix, and to calculate the flavor matrix element, equations from Ref. [19] are employed,

$$\langle \varphi_B^{1,4,3} \varphi_C^{2,5} | \varphi_A^{1,2,3} \varphi_0^{4,5} \rangle = \mathcal{F}^{(I_A; I_B I_C)} \langle I_B I_B I_C i_C | I_A i_A \rangle \quad (5)$$

and taking into account that $I_P = 0$ (isospin of the created quark pair) we have

$$\begin{aligned} \mathcal{F}^{(I_A; I_B I_C)} &= f \cdot (-1)^{I_{12} + I_C + I_A + I_3} \left[\frac{1}{2} (2I_C + 1)(2I_B + 1) \right]^{1/2} \\ &\times \begin{Bmatrix} I_{12} & I_B & I_4 \\ I_C & I_3 & I_A \end{Bmatrix} \end{aligned} \quad (6)$$

where f takes the value of $(\frac{2}{3})^{1/2}$ or $-(\frac{1}{3})^{1/2}$ according to isospin $\frac{1}{2}$ or 0 of the created quarks. I_A , I_B , and I_M represent

the isospins of the initial baryon, the final baryon, and the final meson. I_{12} , I_3 , I_4 are the isospins of relevant quarks, respectively.

The core of the calculation lies in the space integral in Eq. (4),

$$I_{M_{LB}, M_{LC}}^{M_{LA}, m}(\vec{p}) = \int d\vec{p}_1 d\vec{p}_2 d\vec{p}_3 d\vec{p}_4 d\vec{p}_5 \times \delta^3(\vec{p}_1 + \vec{p}_2 + \vec{p}_3 - \vec{p}_A) \delta^3(\vec{p}_4 + \vec{p}_5) \times \delta^3(\vec{p}_1 + \vec{p}_4 + \vec{p}_3 - \vec{p}_B) \delta^3(\vec{p}_2 + \vec{p}_5 - \vec{p}_C) \times \Psi_B^*(\vec{p}_1, \vec{p}_4, \vec{p}_3) \Psi_C^*(\vec{p}_2, \vec{p}_5) \times \Psi_A(\vec{p}_1, \vec{p}_2, \vec{p}_3) y_{1m} \left(\frac{\vec{p}_4 - \vec{p}_5}{2} \right). \quad (7)$$

Simple harmonic oscillator wave functions are employed to model the baryon wave functions [10,12,13]

$$\Psi_A(\vec{p}_A) = N \Psi_{n_{\rho_A} L_{\rho_A} M_{L_{\rho_A}}}(\vec{p}_{\rho_A}) \Psi_{n_{\lambda_A} L_{\lambda_A} M_{L_{\lambda_A}}}(\vec{p}_{\lambda_A}), \quad (8)$$

$$\Psi_B(\vec{p}_B) = N \Psi_{n_{\rho_B} L_{\rho_B} M_{L_{\rho_B}}}(\vec{p}_{\rho_B}) \Psi_{n_{\lambda_B} L_{\lambda_B} M_{L_{\lambda_B}}}(\vec{p}_{\lambda_B}), \quad (9)$$

where N represents a normalization coefficient of the total wave function and

$$\Psi_{nLM_L}(\vec{p}) = \frac{(-1)^n (-i)^L}{\beta^{3/2}} \sqrt{\frac{2n!}{\Gamma(n+L+\frac{3}{2})}} \left(\frac{\vec{p}}{\beta} \right)^L \times \exp\left(-\frac{\vec{p}^2}{2\beta^2}\right) L_n^{L+1/2} \left(\frac{\vec{p}^2}{\beta^2} \right) Y_{LM_L}(\Omega_p). \quad (10)$$

$L_n^{L+1/2}(\frac{\vec{p}^2}{\beta^2})$ denotes the Laguerre polynomial function and $Y_{LM_L}(\Omega_p)$ is a spherical harmonic function. The relation between the solid harmonica polynomial $y_{LM}(\vec{p})$ and $Y_{LM_L}(\Omega_p)$ is $y_{LM}(\vec{p}) = |\vec{p}|^L Y_{LM_L}(\Omega_p)$.

III. NUMERICAL RESULTS

A. Notations of baryons and relevant parameters

For the hadronic decays of $\Xi_c(2970)$, the quantum numbers of the initial state baryons and final state baryons are presented in Tables I and II, respectively. In these two tables, n_ρ , L_ρ , and S_ρ denote the nodal quantum number, the orbital angular momentum, and the spin of the two light quarks, respectively, while n_λ and L_λ correspond to the nodal quantum number and the orbital angular momentum between the heavy quark and the two-light-quark system, respectively. L is the total orbital angular momentum of the baryon, which has the relation $\vec{L} = \vec{L}_\rho + \vec{L}_\lambda$. J_l is the total spin of S_ρ and L , which is $\vec{J}_l = \vec{L} + \vec{S}_\rho$. Finally,

TABLE I. Quantum numbers of 2S- and 1D-wave excitations. The $\bar{3}_F$ indicates that it is an SU(3) flavor antitriplet and 6_F indicates a symmetric sextet.

Assignments	J	J_l	n_ρ	L_ρ	n_λ	L_λ	L	S_ρ
$\tilde{\Xi}_{c0}^{(1/2^+)} \bar{3}_F$	$\frac{1}{2}$	0	1	0	0	0	0	0
$\tilde{\Xi}_{c1}^{(1/2^+)} 6_F$	$\frac{1}{2}$	1	1	0	0	0	0	1
$\tilde{\Xi}_{c1}^{*(3/2^+)} 6_F$	$\frac{3}{2}$	1	1	0	0	0	0	1
$\tilde{\Xi}_{c0}^{(1/2^+)} \bar{3}_F$	$\frac{1}{2}$	0	0	0	1	0	0	0
$\tilde{\Xi}_{c1}^{(1/2^+)} 6_F$	$\frac{1}{2}$	1	0	0	1	0	0	1
$\tilde{\Xi}_{c1}^{*(3/2^+)} 6_F$	$\frac{3}{2}$	1	0	0	1	0	0	1
$\tilde{\Xi}_{c1}^{(1/2^+, 3/2^+)} 6_F$	$\frac{1}{2}, \frac{3}{2}$	1	0	0	0	2	2	1
$\tilde{\Xi}_{c2}^{(3/2^+, 5/2^+)} 6_F$	$\frac{3}{2}, \frac{5}{2}$	2	0	0	0	2	2	1
$\tilde{\Xi}_{c3}^{(5/2^+, 7/2^+)} 6_F$	$\frac{5}{2}, \frac{7}{2}$	3	0	0	0	2	2	1
$\tilde{\Xi}_{c2}^{(3/2^+, 5/2^+)} \bar{3}_F$	$\frac{3}{2}, \frac{5}{2}$	2	0	0	0	2	2	0
$\tilde{\Xi}_{c1}^{(1/2^+, 3/2^+)} 6_F$	$\frac{1}{2}, \frac{3}{2}$	1	0	2	0	0	2	1
$\tilde{\Xi}_{c2}^{(3/2^+, 5/2^+)} 6_F$	$\frac{3}{2}, \frac{5}{2}$	2	0	2	0	0	2	1
$\tilde{\Xi}_{c3}^{(5/2^+, 7/2^+)} 6_F$	$\frac{5}{2}, \frac{7}{2}$	3	0	2	0	0	2	1
$\tilde{\Xi}_{c2}^{(3/2^+, 5/2^+)} \bar{3}_F$	$\frac{3}{2}, \frac{5}{2}$	2	0	2	0	0	2	0
$\tilde{\Xi}_{c0}^{(1/2^+)} 6_F$	$\frac{1}{2}$	0	0	1	0	1	0	0
$\tilde{\Xi}_{c1}^{(1/2^+, 3/2^+)} 6_F$	$\frac{1}{2}, \frac{3}{2}$	1	0	1	0	1	1	0
$\tilde{\Xi}_{c2}^{(3/2^+, 5/2^+)} 6_F$	$\frac{3}{2}, \frac{5}{2}$	2	0	1	0	1	2	0
$\tilde{\Xi}_{c1}^{(1/2^+, 3/2^+)} \bar{3}_F$	$\frac{1}{2}, \frac{3}{2}$	1	0	1	0	1	0	1
$\tilde{\Xi}_{c0}^{(1/2^+)} \bar{3}_F$	$\frac{1}{2}$	0	0	1	0	1	1	1
$\tilde{\Xi}_{c1}^{(1/2^+, 3/2^+)} \bar{3}_F$	$\frac{1}{2}, \frac{3}{2}$	1	0	1	0	1	1	1
$\tilde{\Xi}_{c2}^{(3/2^+, 5/2^+)} \bar{3}_F$	$\frac{3}{2}, \frac{5}{2}$	2	0	1	0	1	1	1
$\tilde{\Xi}_{c1}^{(1/2^+, 3/2^+)} \bar{3}_F$	$\frac{1}{2}, \frac{3}{2}$	1	0	1	0	1	2	1
$\tilde{\Xi}_{c2}^{(3/2^+, 5/2^+)} \bar{3}_F$	$\frac{3}{2}, \frac{5}{2}$	2	0	1	0	1	2	1
$\tilde{\Xi}_{c3}^{(5/2^+, 7/2^+)} \bar{3}_F$	$\frac{5}{2}, \frac{7}{2}$	3	0	1	0	1	2	1

J equals the total spin of the baryon, $\vec{J} = \vec{J}_l + \vec{S}_Q$. Here $S_Q = \frac{1}{2}$ is the spin of the heavy quark. Notations for the excited D-wave Ξ_c baryons are the same as those in Ref. [15]. For the first radially excited Ξ_c , there are two kinds of excitations, $(n_\rho, n_\lambda) = (1, 0)$ and $(0, 1)$, here we call them “ n_ρ excitation” and “ n_λ excitation,” respectively. We use $\tilde{\Xi}_{cJ_l}^{(l,*)}$ and $\tilde{\Xi}_{cJ_l}^{(l,*)}$ to represent them.

As reported by the Belle Collaboration [5], the J^P quantum numbers of $\Xi_c(2970)$ favor $J^P(s_l) = 1/2^+(0)$.

TABLE II. Quantum numbers of baryons in the final states.

	J	J_l	L_ρ	L_λ	L	S_ρ
$\Xi_c^{0(+)}$	$\frac{1}{2}$	0	0	0	0	0
$\Xi_c^{0(+)}$	$\frac{1}{2}$	1	0	0	0	1
$\Xi_c(2645)^{0(+)}$	$\frac{3}{2}$	1	0	0	0	1
$\Sigma_c(2455)^{+(++)}$	$\frac{1}{2}$	1	0	0	0	1
Λ_c^+	$\frac{1}{2}$	0	0	0	0	0

TABLE III. Masses of involved mesons and baryons in the decays [1].

State	Mass (MeV)	State	Mass (MeV)
$\pi^\pm$	139.570	$\Xi_c(2645)^0$	2646.38
π^0	134.977	$\Xi_c(2645)^+$	2645.56
$K^\pm$	493.677	$\Xi_c(2790)^0$	2794.1
K^0	497.611	$\Xi_c(2790)^+$	2793.4
Ξ_c^0	2470.90	$\Xi_c(2815)^0$	2820.25
Ξ_c^+	2467.94	$\Xi_c(2815)^+$	816.74
$\Xi_c'^0$	2579.2	$\Sigma_c(2455)^+$	2452.9
$\Xi_c'^+$	2578.4	$\Sigma_c(2455)^{++}$	2453.97
Λ_c^+	2286.46		

From Table II we see that the possible assignments for $\Xi_c(2970)$ are the 2S-wave $\tilde{\Xi}_{c0}(\frac{1}{2}^+)$ and $\tilde{\Xi}_{c0}(\frac{1}{2}^+)$ and the 1D-wave $\check{\Xi}_{c0}^0(\frac{1}{2}^+)$ and $\check{\Xi}_{c1}^1(\frac{1}{2}^+)$.

Masses of relevant mesons and baryons involved in the calculation are listed in Table III [1]. Parameters γ and β are taken as those in Refs. [15,23]. $\gamma = 13.4$. β is chosen as 476 MeV for meson π and K . For baryons, a universal value $\beta = 600$ MeV is employed. The mass of $\Xi_c(2970)^+$ is taken as 2966.34 MeV.

B. Decays of $\Xi_c(2970)^+$ as 2S- and 1D-wave states

In general, $u\bar{u}$, $d\bar{d}$, and $s\bar{s}$ could be created from the vacuum. However, there exists no experimental signal for the decay mode with an $s\bar{s}$ creation. On the other hand, according to the decaying threshold the decay mode with an $s\bar{s}$ creation does not open for $\Xi_c(2970)^+$. Thus, we consider that the OZI-allowed channels are all from the $u\bar{u}$ and $d\bar{d}$ pairs creation. Possible decay modes and corresponding hadronic decay widths of $\Xi_c(2970)^+$ as 2S- and 1D-wave state baryons in different assignments are computed and

presented in Table IV. The vanish modes in the table indicate forbidden channels due to the conservation of certain quantum numbers.

$\Xi_c(2970)$ was first observed by the Belle Collaboration in the $\Lambda_c^+ K^- \pi^+$ channel with $\Gamma = 43.5 \pm 7.5 \pm 7.0$ MeV and confirmed by the BABAR Collaboration in the intermediate resonant mode $\Sigma_c(2455)^+ K^-$. In Ref. [24] some new measurements were reported. The branching fraction ratio of $B(\Xi_c(2970)^+ \rightarrow \Xi_c^0 \pi^+)/B(\Xi_c(2815)^+ \rightarrow \Xi_c(2645)^0 \pi^+, \Xi_c(2645)^0 \rightarrow \Xi_c^+ \pi^-) \approx 75\%$ indicates that $\Xi_c(2970)$ decays significantly into $\Xi_c' \pi^+$. The decay of $\Xi_c(2970)$ into the $\Lambda_c K$ or $\Xi_c \pi$ channel has never been observed in experiments. The latest experimental data shows that the width of $\Xi_c(2970)^+$ is $\Gamma = 20.9_{-3.5}^{+2.4}$ MeV.

From Table IV we can see that for the four states with $s_l(S_\rho) = 0$, the D-wave $\check{\Xi}_{c0}^0(\frac{1}{2}^+)$ and $\check{\Xi}_{c1}^1(\frac{1}{2}^+)$ and the 2S-wave $\tilde{\Xi}_c^+(\frac{1}{2}^+)$ and $\tilde{\Xi}_c^+(\frac{1}{2}^+)$ both have very different decay behaviors. The $\check{\Xi}_{c1}^1(\frac{1}{2}^+)$ does not decay to any of the channels. This may indicate that this state may never exist because of the model itself or because of the problem of the spin coupling scheme in the baryons; however, here we do not discuss it in detail. The state $\check{\Xi}_{c0}^0(\frac{1}{2}^+)$ has the ratio $R \approx 1$, which is near the lower bound of experimental value. On the other hand, it also has a total decay width of 93.3 MeV, which is about five times the experimental measurement.

For the 2S-wave states, the n_ρ -excited state $\tilde{\Xi}_c^+(\frac{1}{2}^+)$ also has the ratio $R \approx 1$ and has an even larger total decay width, which is about seven times the experimental measurement. On the other hand, the n_λ -excited state $\tilde{\Xi}_c^+(\frac{1}{2}^+)$ has a relatively smaller total decay width 15.5 MeV, which is near the lower threshold of the experimental data. The R value is also ≈ 1 .

TABLE IV. Decay widths (MeV) of $\Xi_c(2970)^+$ as different states.

States	$\check{\Xi}_{c0}^0(\frac{1}{2}^+)$	$\check{\Xi}_{c1}^1(\frac{1}{2}^+)$	$\tilde{\Xi}_c^+(\frac{1}{2}^+)$	$\tilde{\Xi}_c^+(\frac{1}{2}^+)$	$\tilde{\Xi}_c^{*+}(\frac{3}{2}^+)$	$\tilde{\Xi}_c^+(\frac{1}{2}^+)$	$\tilde{\Xi}_c^+(\frac{1}{2}^+)$	$\tilde{\Xi}_c^{*+}(\frac{3}{2}^+)$
$\Xi_c^0 \pi^+$	0	0	0	71.7	71.7	0	8.0	8.0
$\Xi_c^0 \pi^+$	22.3	0	33.4	44.6	11.1	3.7	5.0	1.2
$\Xi_c(2645)^0 \pi^+$	22.1	0	33.2	11.1	27.7	3.7	1.2	3.1
$\Xi_c(2790)^0 \pi^+$	0	0	0	4.9	6.0×10^{-5}	0	7.0	1.3×10^{-3}
$\Xi_c(2815)^0 \pi^+$	0	0	0	1.6×10^{-6}	1.8	0	3.3×10^{-5}	2.7
$\Xi_c^+ \pi^0$	0	0	0	73.3	73.3	0	8.1	8.1
$\Xi_c^+ \pi^0$	22.7	0	34.0	45.4	11.3	3.8	5.0	1.3
$\Xi_c(2645)^+ \pi^0$	22.8	0	34.2	11.4	28.5	3.8	1.3	3.2
$\Xi_c(2790)^+ \pi^0$	0	0	0	5.3	9.1×10^{-5}	0	7.6	1.9×10^{-3}
$\Xi_c(2815)^+ \pi^0$	0	0	0	1.2×10^{-5}	2.8	0	2.5×10^{-4}	4.0
$\Sigma_c(2455)^+ K^0$	1.5	0	2.2	3.0	0.7	0.2	0.3	0.1
$\Sigma_c(2455)^{++} K^-$	1.9	0	2.8	3.8	0.9	0.3	0.4	0.1
$\Lambda_c^+ K^0$	0	0	0	81.6	81.6	0	9.1	9.1
Total	93.3	0	140.0	356.1	311.4	15.5	53.0	40.9

On the other hand, as mentioned in the experimental paper [5], heavy-quark spin symmetry predicts $R = 1.06(0.26)$ for a $1/2^+$ state with the spin of the light-quark degrees of freedom $s_l = 0(1)$ as calculated in Ref [8]. The R value in this work is in consistent with their result, which is $R \approx 1$.

As we all know, the results of phenomenological models depend heavily on the parameters. Reference [25] calculated the decay widths of Ξ_c baryons by using different groups of parameters β . The results in their paper shows how the decay width and relative branching fractions vary according to the different sets of parameters.

Furthermore, we also calculated the hadronic decays of the $2S$ -wave Ξ_c baryons with quantum numbers $s_l = 1$, the n_ρ excitations $\tilde{\Xi}_c^{'+}(1/2^+)$ and $\tilde{\Xi}_c^{*+}(3/2^+)$, and the n_λ excitations $\tilde{\Xi}_c^{'+}(1/2^+)$ and $\tilde{\Xi}_c^{*+}(3/2^+)$. From Table IV we can see that the decay channels $\Xi_c\pi$ and $\Lambda_c K$ are open. Both these two channels have relatively larger decay widths than other channels. It can be taken as the distinction between a state with $s_l = 0$ and $s_l = 1$. It is obvious that the total decay widths of $\tilde{\Xi}_c^{'+}(1/2^+)$ and $\tilde{\Xi}_c^{*+}(3/2^+)$ are much more larger than that of the $\tilde{\Xi}_c^{'+}(1/2^+)$ and $\tilde{\Xi}_c^{*+}(3/2^+)$; that is, the n_ρ -excited states are much broader than the n_λ -excited states. The total decay widths will be the distinction between them. Finally, the branching ratios

$$\frac{\tilde{\Xi}_c^{'+}(1/2^+) \rightarrow \Xi_c(2645)^0 \pi^+}{\tilde{\Xi}_c^{'+}(1/2^+) \rightarrow \Xi_c^0 \pi^+} = \frac{11.1}{44.6} \approx 0.25 < 0.5,$$

$$\frac{\tilde{\Xi}_c^{*+}(3/2^+) \rightarrow \Xi_c(2645)^0 \pi^+}{\tilde{\Xi}_c^{*+}(3/2^+) \rightarrow \Xi_c^0 \pi^+} = \frac{27.7}{11.1} \approx 2.5 > 2.$$

This may be help to distinguish the $2S$ -wave states with total spin $1/2$ from $3/2$.

IV. CONCLUSIONS AND DISCUSSIONS

In this work, the hadronic decays of $\Xi_c(2970)^+$ are studied in a 3P_0 model. We calculate the decay widths and some ratios of branching fractions of $\Xi_c(2970)^+$ as possible assignments related to a recent Belle experiment. In comparison with experimental data, we make an

identification of this charmed-strange baryon. Our theoretical predictions are consistent with experiments.

$\Xi_c(2970)$ was first observed by the Belle Collaboration in the $\Lambda_c^+ K^- \pi^+$ channel and the latest experimental data shows that its decay width is about 20 MeV. Our results of the branching fraction ratios are consistent with the results that considered the heavy-quark spin symmetry effects. Our conclusion of $\Xi_c(2970)^+$ is that it is a $2S$ -wave n_λ -excitation state $\tilde{\Xi}_c^{'+}(1/2^+)$, whose $J^P(s_l)$ is $1/2^+(0)$. It is compatible with the latest experimental measurement.

The $1D$ -wave $\tilde{\Xi}_{c0}^{'+}(1/2^+)$ and $\tilde{\Xi}_{c1}^{'+}(1/2^+)$ assignments are not suitable for $\Xi_c(2970)$ either for over the large total decay width or for no decays at all. The $2S$ -wave $\tilde{\Xi}_c^{'+}(1/2^+)$ assignment is not suitable for $\Xi_c(2970)$ either. The large difference of total decay widths may indicate different inner pictures of the n_ρ and n_λ excitations. However, the dynamics between these two pictures still requires deeper investigations to reveal it.

We also calculate the hadronic decays of the $2S$ -wave Ξ_c baryons with quantum numbers $s_l = 1$, the n_ρ excitations $\tilde{\Xi}_c^{'+}(1/2^+)$ and $\tilde{\Xi}_c^{*+}(3/2^+)$, and the n_λ excitations $\tilde{\Xi}_c^{'+}(1/2^+)$ and $\tilde{\Xi}_c^{*+}(3/2^+)$. The particular difference is that the decay channels $\Xi_c\pi$ and $\Lambda_c K$ are open, compared to the fact that the decay of $\Xi_c(2970)$ into the $\Xi_c\pi$ or $\Lambda_c K$ channel has never been observed in experiments. It can be taken as the distinction between states with $s_l = 0$ and states with $s_l = 1$. Another feature we can see is that the n_ρ -excitation states $\tilde{\Xi}_c^{'+}(1/2^+)$ and $\tilde{\Xi}_c^{*+}(3/2^+)$ have much larger total decay widths than those of the n_λ -excitation states $\tilde{\Xi}_c^{'+}(1/2^+)$ and $\tilde{\Xi}_c^{*+}(3/2^+)$. This can also be a distinction between them. Finally, the branching fraction ratio $\frac{\Xi_c^{'+}(1/2^+) \rightarrow \Xi_c(2645)^0 \pi^+}{\Xi_c^{'+}(1/2^+) \rightarrow \Xi_c^0 \pi^+}$ and $\frac{\Xi_c^{*+}(3/2^+) \rightarrow \Xi_c(2645)^0 \pi^+}{\Xi_c^{*+}(3/2^+) \rightarrow \Xi_c^0 \pi^+}$ can be a dominant factor to distinguish the $2S$ -wave $\tilde{\Xi}_c^{'+}(1/2^+)$ and $\tilde{\Xi}_c^{*+}(3/2^+)$ with $s_l = 1$.

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