Newly observed $\Omega_c(3327)$: A good candidate for a D-wave charmed baryon

Si-Qiang Luo[1,2,3,4,5,*] and Xiang Liu[1,3,4,5,†]

[1]*School of Physical Science and Technology, Lanzhou University, Lanzhou 730000, China*
[2]*School of Mathematics and Statistics, Lanzhou University, Lanzhou 730000, China*
[3]*Research Center for Hadron and CSR Physics, Lanzhou University and Institute of Modern Physics of CAS, Lanzhou 730000, China*
[4]*Lanzhou Center for Theoretical Physics, Key Laboratory of Theoretical Physics of Gansu Province, and Frontiers Science Center for Rare Isotopes, Lanzhou University, Lanzhou 730000, China*
[5]*Key Laboratory of Quantum Theory and Applications of MoE, Lanzhou University, Lanzhou 730000, China*

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The newly observed $\Omega_c(3327)$ gives us a good chance to construct the Ω_c charmed baryon family. In this work, we carry out the mass spectrum analysis by a nonrelativistic potential model using the Gaussian expansion method, and the study of its two-body Okubo-Zweig-Iizuka–allowed strong decay behavior. Our results imply that the $\Omega_c(3327)$ is a good candidate of the $\Omega_c(1D)$ state with $J^P = 5/2^+$. We also predict the spectroscopy behavior of other $\Omega_c(1D)$ states, which may provide further clues to their search.

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Very recently, the LHCb Collaboration observed two new hadronic states, $\Omega_c(3185)$ and $\Omega_c(3327)$, in the $\Xi_c^+ K^-$ invariant spectrum [1]. Their resonance parameters are given by

$$\begin{aligned} M_{\Omega_c(3185)} &= 3185.1 \pm 1.7^{+7.4}_{-0.9} \pm 0.2 \text{ MeV}, \\ \Gamma_{\Omega_c(3185)} &= 50 \pm 7^{+10}_{-20} \text{ MeV}, \\ M_{\Omega_c(3327)} &= 3327.1 \pm 1.2^{+0.1}_{-1.3} \pm 0.2 \text{ MeV}, \\ \Gamma_{\Omega_c(3327)} &= 20 \pm 5^{+13}_{-1} \text{ MeV}. \end{aligned} \tag{1}$$

In this experimental analysis [1], LHCb also confirmed the existence of the five narrow Ω_c states including the $\Omega_c(3000)$, $\Omega_c(3050)$, $\Omega_c(3065)$, $\Omega_c(3090)$, and $\Omega_c(3119)$, which were first reported in 2017 [2]. Furthermore, the $\Omega_c(3000)$, $\Omega_c(3050)$, $\Omega_c(3065)$, and $\Omega_c(3090)$ states were also confirmed by the Belle Collaboration via the e^+e^- collision [3], and by LHCb in the $\Omega_b^- \to \Omega_c^0(X)\pi^- \to \Xi_c^+ K^- \pi^-$ process [4]. Obviously, by associating these excited states with the two $1S$ states $\Omega_c(2695)$ and $\Omega_c(2700)$, these new observations of the Ω_c states give us a good chance to construct the Ω_c charmed baryon family.

There have been some theoretical studies focusing on the $\Omega_c(3000)$, $\Omega_c(3050)$, $\Omega_c(3065)$, $\Omega_c(3090)$, and $\Omega_c(3119)$ states, which suggest that these five Ω_c states are good candidates of $\Omega_c(1P)$ or $\Omega_c(2S)$ [5–18]. For the newly observed $\Omega_c(3185)$, its resonance parameter is close to that of the $\Omega_c(3188)$ discovered by LHCb and Belle [2,3]. In principle, we can treat the $\Omega_c(3185)$ and the $\Omega_c(3188)$ states in the same procedures. These efforts have made great progress in constructing the Ω_c charmed baryon family, where there are suitable candidates for the $1S$, $1P$, and $2S$ states of Ω_c (see Refs. [19–22] for review articles). However, our knowledge of higher states in the Ω_c family is still lacking. Further efforts should therefore be made.

Against this research background, the newly observed $\Omega_c(3327)$ state is timely, since deciphering the nature of the $\Omega_c(3327)$ may provide useful clues to establish the $1D$ states of the Ω_c family, which will be a major task of this work.

To achieve this goal, we perform the mass spectrum analysis and the study of its two-body Okubo-Zweig-Iizuka (OZI)-allowed strong decay behavior. When performing the mass spectrum analysis, we adopt a nonrelativistic potential model [23,24] with the help of the Gaussian expansion method (GEM) [25], which can promote the accuracy of the calculation. Obtaining the mass spectrum of the Ω_c family is only one aspect of deciphering the property of the $\Omega_c(3327)$. In the following, we should focus on its

*luosq15@lzu.edu.cn
†xiangliu@lzu.edu.cn

two-body OZI-allowed strong decay behavior. The numerical spatial wave function obtained by the mass spectrum analysis can be used as input, by which we can avoid the uncertainty of simply applying the simple harmonic oscillator (SHO) wave function to deal with the spatial wave function. In the concrete calculation of its strong decay behavior, the quark pair creation model [26] is adopted, which is an effective approach to estimate the partial widths of the strong decay of the baryon. Later, we will briefly present some details of the QPC model. In general, we can finally suggest that the newly observed $\Omega_c(3327)$ is a $1D$ state of Ω_c with spin parity quantum number $J^P = 5/2^+$. Taking this opportunity, we also give some further predictions of its strong decay mode, which can be used to test this assignment. In fact, there are six $1D$ states of Ω_c. In this work, their masses and two-body OZI-allowed decay behaviors are predicted, which is useful for future searches for them.

As a first step, we need the mass spectrum of the singly heavy baryons. Here, a nonrelativistic potential model has been adopted. The corresponding Hamiltonian is [23,24,27]

$$\hat{H} = \sum_i \left(m_i + \frac{p_i^2}{2m_i} \right) + \sum_{i<j} V_{ij}, \tag{2}$$

where m_i and p_i are the mass and momentum of the ith constituent quark, respectively. The last term, V_{ij}, in Eq. (2) denotes the quark-quark interaction, which is expressed by

$$V_{ij} = H_{ij}^{\rm conf} + H_{ij}^{\rm hyp} + H_{ij}^{\rm so(cm)} + H_{ij}^{\rm so(tp)}. \tag{3}$$

In Eq. (3), the first term is spin independent—i.e.,

$$H_{ij}^{\rm conf} = -\frac{2}{3}\frac{\alpha_s}{r_{ij}} + \frac{b}{2} r_{ij} + \frac{1}{2} C. \tag{4}$$

Here, the values α_s, b, and C are the coupling constant of the one-gluon-exchange (OGE), the strength of the linear confinement, and the renormalized mass constant, respectively. The remaining parts of Eq. (3) are spin-dependent potentials, including the hyperfine interaction $H_{ij}^{\rm hyp}$, the color-magnetic term $H_{ij}^{\rm so(cm)}$, and the Thomas-precession piece $H_{ij}^{\rm so(tp)}$, which are written as

$$H_{ij}^{\rm hyp} = \frac{2\alpha_s}{3m_i m_j} \left[\frac{8\pi}{3} \tilde{\delta}(r_{ij}) \mathbf{s}_i \cdot \mathbf{s}_j + \frac{1}{r_{ij}^3} S(\mathbf{r}, \mathbf{s}_i, \mathbf{s}_j) \right], \tag{5}$$

$$H_{ij}^{\rm so(cm)} = \frac{2\alpha_s}{3r_{ij}^3} \left(\frac{\mathbf{r}_{ij} \times \mathbf{p}_i \cdot \mathbf{s}_i}{m_i^2} - \frac{\mathbf{r}_{ij} \times \mathbf{p}_j \cdot \mathbf{s}_j}{m_j^2} - \frac{\mathbf{r}_{ij} \times \mathbf{p}_j \cdot \mathbf{s}_i - \mathbf{r}_{ij} \times \mathbf{p}_i \cdot \mathbf{s}_j}{m_i m_j} \right), \tag{6}$$

TABLE I. The parameters involved in the adopted potential model.

System	α_s	b (GeV^2)	σ (GeV)	C (GeV)
Ξ_c/Ξ_c'	0.548	0.144	1.732	−0.711
Ω_c	0.578	0.144	1.732	−0.688
Meson	0.578	0.144	1.020	−0.685
$m_{u/d} = 0.370$ GeV, $m_s = 0.600$ GeV, $m_c = 1.880$ GeV				

and

$$H_{ij}^{\rm so(tp)} = -\frac{1}{2r_{ij}} \frac{\partial H_{ij}^{\rm conf}}{\partial r_{ij}} \left(\frac{\mathbf{r}_{ij} \times \mathbf{p}_i \cdot \mathbf{s}_i}{m_i^2} - \frac{\mathbf{r}_{ij} \times \mathbf{p}_j \cdot \mathbf{s}_j}{m_j^2} \right). \tag{7}$$

The Gaussian smearing function $\tilde{\delta}(r_{ij})$ and tensor operator $S(\mathbf{r}, \mathbf{s}_i, \mathbf{s}_j)$ in Eq. (5) are defined as

$$\tilde{\delta}(r) = \frac{\sigma^3}{\pi^{3/2}} e^{-\sigma^2 r^2}, \quad S(\mathbf{r}, \mathbf{s}_i, \mathbf{s}_j) = \frac{3\mathbf{s}_i \cdot \mathbf{r}_{ij} \mathbf{s}_j \cdot \mathbf{r}_{ij}}{r_{ij}^2} - \mathbf{s}_i \cdot \mathbf{s}_j, \tag{8}$$

respectively. For the quark-antiquark potential $V_{ij}^{q\bar{q}}$ in the meson system, we simply take $V_{ij}^{q\bar{q}} = 2V_{ij}^{qq}$, since the color factor of the quark-(anti)quark within a meson is exactly twice that of the baryon system.

It is convenient to use the ρ mode and λ mode to distinguish the different excited modes of the singly charmed baryon.[1] The basis

$$|JM\rangle = |[[[s_{q_1} s_{q_2}]_{s_\ell} [n_\rho n_\lambda l_\rho l_\lambda]_L]_{j_\ell} s_Q]_{JM}\rangle \tag{9}$$

is used to calculate the masses of singly charmed baryons. Here, s_{q_1} and s_{q_2} are the spins of the light flavor quarks, while s_Q is the spin of the heavy flavor quark. The value s_ℓ in Eq. (9) denotes the total spin of the two light flavor quarks, while $n_{\rho/\lambda}$ and $l_{\rho/\lambda}$ are the radial and orbital quantum numbers, respectively. L is the total orbital angular momentum of the system, and j_ℓ stands for the total angular momentum of the light degree of freedom.

In this work, we employ the GEM [25] to solve the Schrödinger equations of the mesons and singly charmed baryons. In our calculation, the values of α_s, b, σ, C, and the consistent quark masses in the quark potential model are constrained by the well-established mesons and charm baryons. The concrete values of the parameters are listed in Table I.

The numerical results of the mass spectrum of a singly charmed baryon are shown in Fig. 1. So far, all observed

[1] The ρ mode denotes the excitation between two light quarks (q_1 and q_2), while the λ mode represents the excitation between the light quark cluster and the heavy quark (Q).

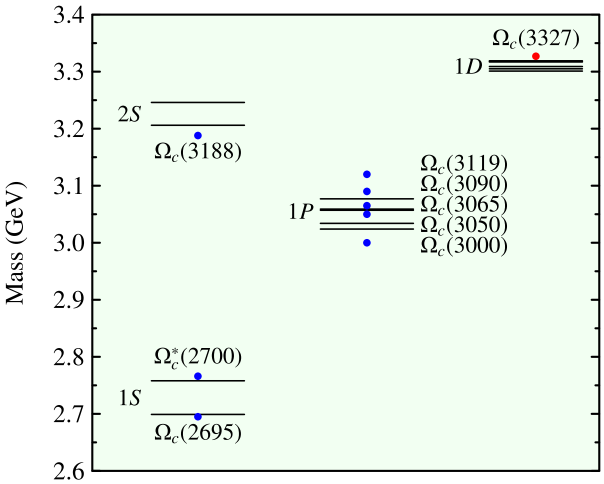

FIG. 1. The calculated mass spectrum of the Ω_c and the comparison with experimental data. The short lines represent the calculated results, while the blue points are obtained from the experimental data taken from the Particle Data Group (PDG) [37]. The newly observed $\Omega_c(3327)$ [1] is marked by the red point.

singly charmed baryons belong to the λ-mode excited state [28,29], which is the reason why in this work we mainly focus on the assignment of the λ-mode exited state to $\Omega_c(3327)$. Thus, six of the λ-mode $1D$ Ω_c states are $\Omega_{c1}(1D, 1/2^+)$, $\Omega_{c1}(1D, 3/2^+)$, $\Omega_{c2}(1D, 3/2^+)$, $\Omega_{c2}(1D, 5/2^+)$, $\Omega_{c3}(1D, 5/2^+)$, and $\Omega_{c3}(1D, 7/2^+)$, where the subscripts 1, 2, 3, denote the j_ℓ quantum number of the corresponding states. The same notation is also applied to denote other Ω_c states in Table II. Here, most of the calculated results are in good agreement with the experimental data. In this way, we test the feasibility of the adopted potential model used to represent the mass spectrum of a singly charmed baryon. Furthermore, in order to refer to the details of the Ω_c mass spectrum, we also collect our results and make comparisons with those of different theoretical groups in Table II, and similar results have also been obtained in Refs. [27,30–36]. We find that the mass of the newly observed $\Omega_c(3327)$ is close to the calculated mass range of the $\Omega_c(1D)$ states, suggesting that the $\Omega_c(3327)$ can be a good $\Omega_c(1D)$ candidate. However, since the mass splits of the six $\Omega_c(1D)$ states are too small, it is difficult to determine the spin-parity quantum number of the $\Omega_c(3327)$ directly from this mass spectrum analysis. We need to further unravel its nature by investigating its two-body OZI-allowed strong decay behaviors.

TABLE II. The comparisons of our calculated mass spectrum of a Ω_c charmed baryon with the results from other theoretical groups.

States	PDG [37]	This work	Ref. [30]	Ref. [31]	Ref. [27]
$\Omega_c(1S, 1/2^+)$	2695	2699	2698	2699	2731
$\Omega_c(2S, 1/2^+)$		3206	3088	3150	3227
$\Omega_c(1S, 3/2^+)$	2766	2758	2768	2762	2779
$\Omega_c(2S, 3/2^+)$		3246	3123	3197	3257
$\Omega_{c0}(1P, 1/2^-)$		3034	2966	3057	3030
$\Omega_{c1}(1P, 1/2^-)$		3024	3055	3045	3048
$\Omega_{c1}(1P, 3/2^-)$		3059	3029	3062	3033
$\Omega_{c2}(1P, 3/2^-)$		3057	3054	3039	3056
$\Omega_{c2}(1P, 5/2^-)$		3077	3051	3067	3057
$\Omega_{c1}(1D, 1/2^+)$		3301	3287	3304	3292
$\Omega_{c1}(1D, 3/2^+)$		3305	3282	3313	3285
$\Omega_{c2}(1D, 3/2^+)$		3318	3298	3304	...
$\Omega_{c2}(1D, 5/2^+)$		3319	3286	3314	3288
$\Omega_{c3}(1D, 5/2^+)$		3309	3297	3304	3299
$\Omega_{c3}(1D, 7/2^+)$		3317	3283	3315	...

In this work, the quark pair creation (QPC) model [26,38–41] is employed to calculate the strong decays of the $\Omega_c(1D)$ states. The QPC model has been widely used to study the strong decays of the singly charmed baryons [13,14,28,42–58]. The transition operator of the QPC model is

$$\hat{\mathcal{T}} = -3\gamma\sum_m \langle 1, m; 1, -m|0, 0\rangle \int \mathrm{d}^3\mathbf{p}_i \mathrm{d}^3\mathbf{p}_j \delta(\mathbf{p}_i + \mathbf{p}_j) \times \mathcal{Y}_1^m\left(\frac{\mathbf{p}_i - \mathbf{p}_j}{2}\right)\omega_0^{(i,j)}\phi_0^{(i,j)}\chi_{1,-m}^{(i,j)} b_i^\dagger(\mathbf{p}_i) d_j^\dagger(\mathbf{p}_j), \quad (10)$$

where ω, ϕ, χ, and $\mathcal{Y}$ are the color, flavor, spin, and spatial functions of the quark pair, respectively. The values $b_i^\dagger$ and $d_j^\dagger$ are the quark and antiquark creation operators, respectively. The dimensionless parameter γ describes the strength of a quark-antiquark pair created from the vacuum, which is fixed as $\gamma = 9.58$ by fitting the experimental width of the $\Sigma_c^*(2520)$ state [37]. The partial wave amplitude for a decay process $A \to BC$ with relative spin S_{BC} and orbital angular momentum L_{BC} between BC could be expressed by

$$\mathcal{M}_{A\to BC}^{L_{BC}S_{BC}}(p) = \langle BC, L_{BC}, S_{BC}, p|\hat{\mathcal{T}}|A\rangle, \quad (11)$$

where p is the momentum of the final-state B. The partial width could be calculated by

$$\Gamma_{A\to BC}^{L_{BC}S_{BC}} = 2\pi\frac{\sqrt{M_B^2 + p^2}\sqrt{M_C^2 + p^2}}{M_A} p|\mathcal{M}_{A\to BC}^{L_{BC}S_{BC}}(p)|^2. \quad (12)$$

In the calculations of meson decays [40,41,59,60], it is convenient to employ the simple harmonic oscillator (SHO) wave functions to depict the spatial structures of hadrons—i.e.,

$$R_{nlm}^p(\beta, \mathbf{P}) = \frac{(-1)^n(-\mathrm{i})^l}{\beta^{\frac{3}{2}+l}}\sqrt{\frac{2n!}{\Gamma(n + l + \frac{3}{2})}} L_n^{l+\frac{1}{2}}(P^2/\beta^2) \times \mathrm{e}^{-\frac{P^2}{2\beta^2}} P^l Y_{lm}(\Omega_{\mathbf{P}}), \quad (13)$$

where n, l, and m represent the radial, orbital, and magnetic quantum numbers, respectively. The β value in Eq. (13) is a

TABLE III. The β values (in units of GeV) of these involved mesons and singly charmed baryons.

States	β_ρ	β_λ	States	β_ρ	β_λ	States	β_ρ	β_λ
$\Xi_c(1S)$	0.304	0.384	$\Xi_c'(1S)$	0.252	0.384	$\Omega_c(1S)$	0.288	0.420
$\cdots$	$\cdots$	$\cdots$	$\Xi_c^*(1S)$	0.243	0.358	$\Omega_c^*(1S)$	0.275	0.389
$\Xi_c(2S)$	0.262	0.207	$\Xi_c'(2S)$	0.214	0.210	$\Omega_c(2S)$	0.230	0.231
$\cdots$	$\cdots$	$\cdots$	$\Xi_c^*(2S)$	0.217	0.201	$\Omega_c^*(2S)$	0.236	0.218
$\Xi_c(1P)$	0.278	0.258	$\Xi_c'(1P)$	0.229	0.258	$\Omega_c(1P)$	0.257	0.279
$\Xi_c(1D)$	0.267	0.201	$\Xi_c'(1D)$	0.219	0.199	$\Omega_c(1D)$	0.244	0.212
Ξ	0.287	0.317	$\beta_\pi = 0.409$ $\beta_{s\bar{s}(1^1S_0)} = 0.402$ $\beta_K = 0.385$					
Ξ^*	0.258	0.265	$\beta_D = 0.357$ $\beta_{D^*} = 0.307$					

parameter for scaling the SHO wave function, which could be calculated from the GEM. By solving the Schrödinger equations with the GEM, one could obtain the spatial wave function $\phi^r_{n_\rho n_\lambda l_\rho l_\lambda m_\rho m_\lambda}(\boldsymbol{\rho},\boldsymbol{\lambda})$, which is the summation of a series of Gaussian wave functions. Since a singly charmed baryon contains two spatial degrees of freedom, two β values (β_ρ and β_λ) are introduced in the SHO wave functions to reduce $\phi^r_{n_\rho n_\lambda l_\rho l_\lambda m_\rho m_\lambda}(\boldsymbol{\rho},\boldsymbol{\lambda})$, which can be extracted with

$$\frac{1}{\beta_\rho^2} = \int |\phi^r_{n_\rho n_\lambda l_\rho l_\lambda m_\rho m_\lambda}(\boldsymbol{\rho},\boldsymbol{\lambda})|^2\boldsymbol{\rho}^2 \mathrm{d}^3\boldsymbol{\rho}\mathrm{d}^3\boldsymbol{\lambda},$$
$$\frac{1}{\beta_\lambda^2} = \int |\phi^r_{n_\rho n_\lambda l_\rho l_\lambda m_\rho m_\lambda}(\boldsymbol{\rho},\boldsymbol{\lambda})|^2\boldsymbol{\lambda}^2 \mathrm{d}^3\boldsymbol{\rho}\mathrm{d}^3\boldsymbol{\lambda}. \quad (14)$$

Here, the formula for calculating the β value is slightly different from that in Refs. [59,60], but the calculations for the decay widths of singly heavy baryons [14,28,43–45,58] suggest that this scheme is also an effective approach. Then the spatial wave functions could be written by the following approximation:

$$\phi^r_{n_\rho n_\lambda l_\rho l_\lambda m_\rho m_\lambda}(\boldsymbol{\rho},\boldsymbol{\lambda}) \approx R^r_{n_\rho l_\rho m_\rho}(\beta_\rho,\boldsymbol{\rho})R^r_{n_\lambda l_\lambda m_\lambda}(\beta_\lambda,\boldsymbol{\lambda}). \quad (15)$$

Since it is convenient to calculate decay widths in the momentum space with the QPC model, we transform the wave function into the momentum representation—i.e.,

$$\phi^p_{n_\rho n_\lambda l_\rho l_\lambda m_\rho m_\lambda}(\mathbf{p}_\rho,\mathbf{p}_\lambda) \approx R^p_{n_\rho l_\rho m_\rho}(\beta_\rho,\mathbf{p}_\rho)R^p_{n_\lambda l_\lambda m_\lambda}(\beta_\lambda,\mathbf{p}_\lambda). \quad (16)$$

With preparations above, we calculate the β values and present them in Table III. There are six $1D$ states of the Ω_c charmed baryon, as shown in Fig. 1. The mass spectrum analysis only shows that the newly discovered $\Omega_c(3327)$ has a relation to the $1D$ states of Ω_c. The information of the total and partial decay widths of six $\Omega_c(1D)$ charmed baryons is crucial to decoding the nature of the $\Omega_c(3327)$. In this subsection, we focus on the study of the partial decay widths of these discussed $\Omega_c(1D)$ charmed baryons.

In Table IV, we list the calculated partial and total decay widths of six $1D$ states of Ω_c and make a comparison with the experimental data of the $\Omega_c(3327)$ [1]. We should note that the masses of the six $1D$ states of Ω_c are assumed to be the mass of $\Omega_c(3327)$ for ease of comparison. We find that the measured width of the $\Omega_c(3327)$ is very close to the obtained total decay width of the $\Omega_{c3}(1D,5/2^+)$ state. In addition, the $\Xi_c(2470)\bar{K}$ channel has the largest contribution to the total decay width, which can be reflected by the corresponding branching ratio

$$\mathrm{BR}[\Omega_{c3}(1D,5/2^+)\to\Xi_c(2470)\bar{K}]\approx 55\%, \quad (17)$$

which also explains why the $\Omega_c(3327)$ was first observed in its $\Xi_c^+(2470)K^-$ channel. Thus, according to this study, we may conclude that assigning the $\Omega_c(3327)$ as the $\Omega_{c3}(1D,5/2^+)$ state is suitable. If the $\Omega_c(3327)$ is the $\Omega_{c3}(1D,5/2^+)$ state, the partial widths of the $\Omega_c(3327)$ decays into $\Xi_c'(2580)\bar{K}$, ΞD, $\Xi_c^*(2645)\bar{K}$, and $\Xi_c(2790)\bar{K}$ are sizable. In Ref. [61], the decay widths of the $\Omega_c(1D)$ states were predicted by the chiral quark model. According to the numerical results of Ref. [61], the $\Omega_c(3327)$ is also consistent with the $\Omega_c(1D)$ assignment.

We should introduce the decay behaviors of the other two $1D$ states of Ω_c. Here, $\Omega_{c1}(1D,1/2^+)$ is a very broad state, where ΞD and $\Xi_c(2790)\bar{K}$ have dominant contributions to the width of $\Omega_{c1}(1D,1/2^+)$. Although the total decay width of $\Omega_{c1}(1D,3/2^+)$ is close to that of $\Omega_{c2}(1D,3/2^+)$, their decay behaviors are different. Here, $\Xi_c(2815)\bar{K}$ and ΞD are the dominant decay modes of $\Omega_{c1}(1D,3/2^+)$ and $\Omega_{c2}(1D,3/2^+)$, respectively. The $\Omega_{c2}(1D,5/2^+)$ cases have a total width of 60.5 MeV, coming mainly from the ΞD, $\Xi_c^*(2645)\bar{K}$, and ΞD^* channels. There exists $\Omega_{c3}(1D,7/2^+)$, where ΞD is the dominant contributor to the total decay width and $\Xi_c(2470)\bar{K}$ is sizable. This obtained decay information is valuable for further experimental searches.

In reality, the mixing between $\Omega_{c1}(1D,3/2^+)$ and $\Omega_{c2}(1D,3/2^+)$ can happen—i.e.,

$$\begin{pmatrix} |\Omega_c(1D,3/2^+)_a\rangle \\ |\Omega_c(1D,3/2^+)_b\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta_1 & \sin\theta_1 \\ -\sin\theta_1 & \cos\theta_1 \end{pmatrix}\begin{pmatrix} |\Omega_{c1}(1D,3/2^+)\rangle \\ |\Omega_{c2}(1D,3/2^+)\rangle \end{pmatrix}. \quad (18)$$

TABLE IV. The partial and total decay widths of the λ-mode excited $\Omega_c(1D)$ state in units of MeV. The forbidden couplings are denoted by the symbol "×." The number "0.0" implies that the partial decay width is less than 0.1 MeV. Here, we do not consider the mixture between $\Omega_{c1}(1D,3/2^+)$ and $\Omega_{c2}(1D,3/2^+)$ or the mixture between $\Omega_{c2}(1D,5/2^+)$ and $\Omega_{c3}(1D,5/2^+)$. When presenting these decay behaviors, the masses of these six $1D$ states of Ω_c are from the experimental mass of $\Omega_c(3327)$.

Decay channels	$\Omega_{c1}(1D,1/2^+)$	$\Omega_{c1}(1D,3/2^+)$	$\Omega_{c2}(1D,3/2^+)$	$\Omega_{c2}(1D,5/2^+)$	$\Omega_{c3}(1D,5/2^+)$	$\Omega_{c3}(1D,7/2^+)$
$\Xi_c(2470)\bar{K}$	2.7	2.7	×	×	13.4	13.4
$\Xi_c(2790)\bar{K}$	125.0	0.5	1.1	0.4	3.6	0.0
$\Xi_c(2815)\bar{K}$	0.0	114.1	0.0	0.1	0.0	0.3
$\Xi_c'(2580)\bar{K}$	3.9	0.9	8.7	2.6	3.0	1.7
$\Xi_c^*(2645)\bar{K}$	2.7	6.7	5.2	15.8	2.2	3.0
$\Omega_c(2695)\eta$	0.4	0.1	1.0	0.0	0.0	0.0
$\Omega_c(2765)\eta$	0.0	0.0	0.0	0.1	0.0	0.0
ΞD	244.9	15.3	137.8	31.3	2.2	80.6
ΞD^*	5.6	16.3	3.8	10.2	0.0	0.0
Total	385.2	156.6	157.6	60.5	24.4	99.0
Exp.					$20\pm5^{+13}_{-1}$ [1]	

Here, $\Omega_c(1D,3/2^+)_a$ and $\Omega_c(1D,3/2^+)_b$ are two physical states, where the subscripts a and b are applied to distinguish the physical states with lower and higher masses, respectively. θ_1 is the mixing angle, which can be estimated to be zero in the limit of the heavy quark mass $m_Q\to\infty$ [9,45]. Note, however, that the charm quark mass is not heavy enough. Thus, the mixing angle θ_1 is not zero in a realistic situation. We take a range of mixing angle $-90°\leq\theta_1\leq 90°$ to discuss the dependence of their total and partial decay widths on the mixing angle, which is shown in Fig. 2.

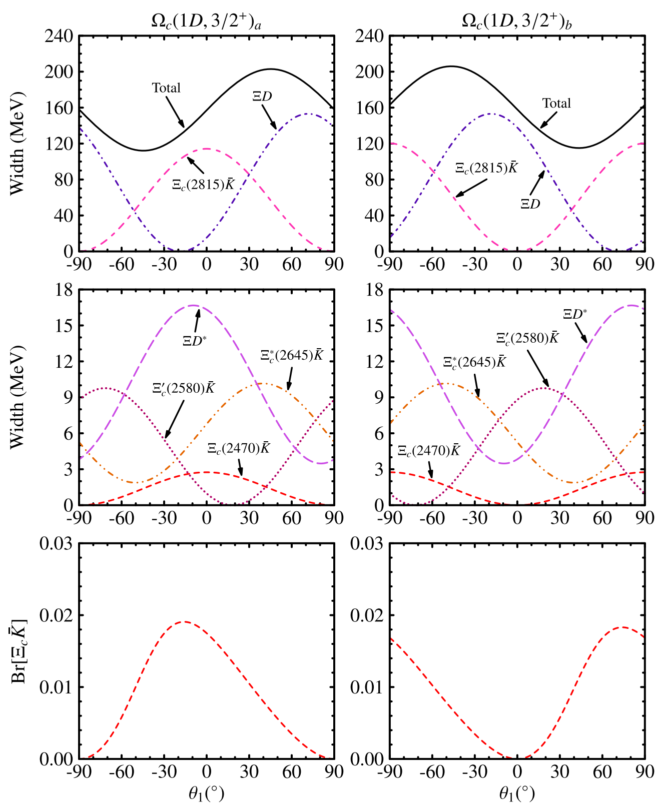

FIG. 2. The decay widths' and branch ratios' dependence on the mixing angles for $\Omega_c(1D,3/2^+)_a$ and $\Omega_c(1D,3/2^+)_b$. The masses are taken from the measured mass of $\Omega_c(3327)$ [1]. Some small widths are not shown here but are still counted in the total widths.

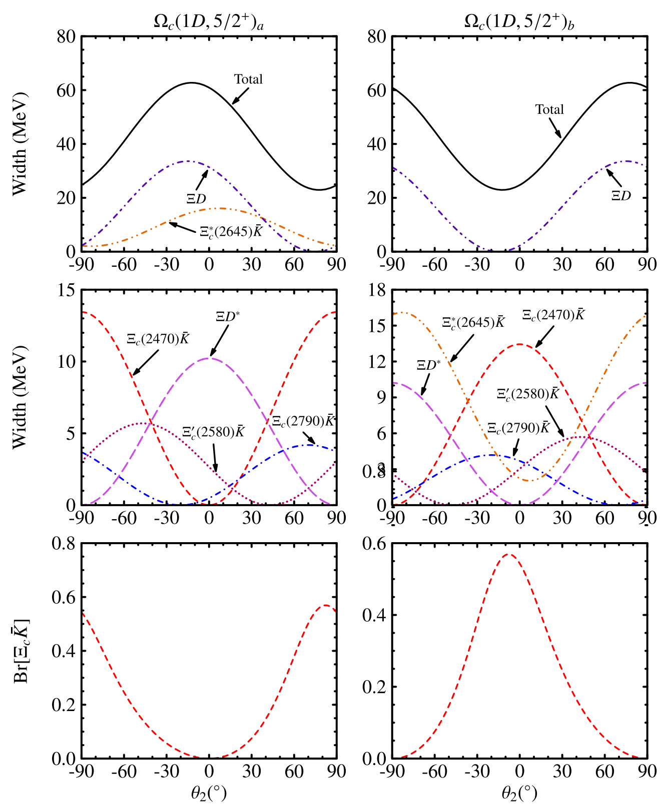

FIG. 3. The decay widths' and branch ratios' dependence on the mixing angles for $\Omega_c(1D,5/2^+)_a$ and $\Omega_c(1D,5/2^+)_b$. The conventions are consistent with those in Fig. 2.

There is also a mixture between $\Omega_{c2}(1D, 5/2^+)$ and $\Omega_{c3}(1D, 5/2^+)$, which is written as

$$\begin{pmatrix} |\Omega_c(1D, 5/2^+)_a\rangle \\ |\Omega_c(1D, 5/2^+)_b\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta_2 & \sin\theta_2 \\ -\sin\theta_2 & \cos\theta_2 \end{pmatrix} \begin{pmatrix} |\Omega_{c2}(1D, 5/2^+)\rangle \\ |\Omega_{c3}(1D, 5/2^+)\rangle \end{pmatrix}. \quad (19)$$

In this paper, we also show the dependence of their decay behavior on the mixing angle θ_2 as given in Fig. 3. Since this mixing angle cannot be fixed by experimental data or theoretical input, we have to stop the discussion on the strong decay behaviors of these four mixing states.

In summary, stimulated by the observation of the $\Omega_c(3327)$ from LHCb [1], in this work we decipher its nature by carrying out the analysis of the mass spectrum analysis and the calculation of the two-body OZI-allowed strong decay. Our result shows the possibility of assigning the $\Omega_c(3327)$ as a $1D$ state of Ω_c, which has the spin parity quantum number $J^P = 5/2^+$. We also notice a detail of its partial decay widths under this assignment, where $\Xi_c(2470)\bar{K}$ is its main decay channel in our calculation, which can naturally explain why the $\Omega_c(3327)$ was first observed in this decay channel. As a byproduct, we also predict the decay behavior of the other five $1D$ states of Ω_c, which are still missing in the experiment. Obviously, the present study can provide some clues for their future exploration.

The study of this work opens a window for the construction of the $1D$ states of charmed baryons. With the accumulation of experimental data in LHCb and Belle II, we have a reason to believe that further experimental progress will be made. For the discussed $\Omega_c(3327)$, the measurement of its spin parity quantum number and the observation of its other decay modes are a crucial step to establish the $\Omega_c(3327)$ as the $1D$ states of the charmed baryon, which will be a new task for experimentalists.

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Note added.—In a recent paper on the $\Omega_c(3327)$ in arXiv [62], the authors tried to explain the $\Omega_c(3327)$ as a $1D$ state of the Ω_c with $J^P = 3/2^+$, which is different from our assignment to the $\Omega_c(3327)$.

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