Strong and radiative decays of $D\Xi$ molecular state and newly observed Ω_c states

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In this work, we study strong and radiative decays of S-wave $D\Xi$ molecular state, which is related to the Ω_c^* states newly observed at LHCb. The coupling between the $D\Xi$ molecular state and its constituents D and Ξ is calculated by using the compositeness condition. With the obtained coupling, the partial decay widths of the $D\Xi$ molecular state into the $\Xi_c^+ K^-$, $\Xi_c'^+ K^-$, and $\Omega_c^*(2695)\gamma$ final states through hadronic loop are calculated with the help of the effective Lagrangians. By comparison with the LHCb observation, the current results of total decay width support the $\Omega_c^*(3119)$ or $\Omega_c^*(3050)$ as $D\Xi$ molecule while the decay width of the $\Omega_c^*(3000)$, $\Omega_c^*(3066)$, and $\Omega_c^*(3090)$ can not be well reproduced in the molecular state picture. The partial decay widths are also presented and helpful to further understand the internal structures of $\Omega_c^*(3119)$ and $\Omega_c^*(3050)$.

I. INTRODUCTION

For a long time, little is known about the charmed baryon Ω_c with quantum numbers $C = 1$ and $S = -2$, which is composed of one charm quark and two strange quark in the conventional constituent quark model. Only the ground state $\Omega_c^*(2695)$ and $\Omega_c^*(2770)$ are listed in the newest version of the Review of Particle Physics (PDG) [1]. Recently, five new narrow Ω_c^* states named $\Omega_c^*(3000)$, $\Omega_c^*(3050)$, $\Omega_c^*(3066)$, $\Omega_c^*(3090)$, and $\Omega_c^*(3119)$ were reported by the LHCb Collaboration in the $\Xi_c^+ K^-$ mass spectrum [2]. Though the quantum numbers of these new Ω_c^* states are not confirmed, it is very helpful to understand the charmed baryon spectrum.

The LHCb observation stimulated a large amount of the theoretical studies about the new Ω_c^* states with different assumptions of their internal structures. Naturally, many authors try to assign these states into the conventional three-quark frames. In Refs. [3–6] the new Ω_c^* baryons were interpreted as $1P$ and $2S$ Ω_c^* baryons in the conventional quark models. The QCD sum rules were also applied to study these states in three-quark picture [7,8]. The lattice calculation was also performed and try to determine their quantum numbers [9]. In Refs. [10,11], the authors investigated the decay properties to reveal the nature of these states.

It is quite rare to observe five states in one observation simultaneously. So many states observed also make it difficult to put all states into the conventional quark model. Hence, after the observation at LHCb, the newly observed Ω_c^* was immediately interpreted as exotic state beyond three-quark picture, i.e., the pentaquark state. The largest mass gaps between the newly observed Ω_c^* baryons and the ground Ω_c^* baryon are about 400 MeV, which is large enough to excite a light quark-antiquark pair. Indeed, in Ref. [12], pentaquark-like Ω_c^* baryons were studied in the

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constituent quark model and associated to some of the LHCb Ω_c^* baryons. In Ref. [13], it was found that four $sscq\bar{q}$ states with $J^P = 1/2^-$ or $J^P = 3/2^-$ have masses close to the newly observed Ω_c^* states. In the chiral quark-soliton model, pentaquark-like structures were suggested for the $\Omega_c^*(3050)$ and $\Omega_c^*(3119)$ [14,15]. Since the $\Xi_c'\bar{K}$ and ΞD thresholds fall in the mass region of the LHCb observed Ω_c^* states, hadronic molecule interpretations cannot be excluded. In Ref. [16], the $\Omega_c^*(3050)$ and $\Omega_c^*(3090)$ were regarded as meson-baryon molecules and with a similar method, the $\Omega_c^*(3119)$ was also proposed to be a hadronic molecule [17]. Moreover, the $\Omega_c^*(3000)$, $\Omega^*(3050)$, and $\Omega^*(3090)$ or $\Omega^*(3119)$ can all be explained as meson-baryon molecular state in Ref. [18]. With the one-gluon-exchange and the Goldstone-boson-exchange in addition to the color confinement, the authors in Ref. [19] suggested that only $\Omega_c^*(3119)$ can be explained as an S-wave resonance state of ΞD with $J^P = 1/2^-$, which decays mainly through the S wave into $\Xi_c K$ and $\Xi_c' K$.

Until now, the nature of the observed Ω_c^* baryons remains unclear. In addition to their masses, the decay property also serves as an important way to unveil the nature of hadrons. In Ref. [10] the authors studied the decay patterns of the Ω_c^* baryons in a chiral quark model in three-quark picture and suggested that most of the low-lying Ω_c^* baryons have masses in the vicinity of the $\Xi_c^+ K^-$ and $\Xi_c'^+ K^-$ thresholds, to which the strong decay will almost saturate their total decay widths. However, the decays of the Ω_c^* baryons, which are helpful to understand their internal structures, have not been studied in the molecular state picture. Actually, lots of exotic hadrons have been observed and can be described as hadronic molecules [[20]].

In Refs. [21–25], the decays of hadronic molecular states have been studied by calculating the hadronic loop with the assumption that a molecular state prefers to decay into its two constituents. The technique for evaluating composite hadron systems has been widely used to study hadronic molecular state, where the compositeness condition, corresponding to $Z = 0$, has been employed to extract the coupling of a molecular state to its constituents [26–29]. In this work, we will calculate the radiative and strong decay pattern of S-wave $D\Xi$ molecular state within the effective Lagrangians approach, and find the relation between the $D\Xi$ molecular state and the Ω_c^* states by comparing with the LHCb observation.

This paper is organized as follows. The theoretical formalism is explained in Sec. II. The predicted partial decay widths are presented in Sec. III. Finally, we give discussion and summary in the last section.

II. FORMALISM AND INGREDIENTS

In the molecule scenario, the interaction between the state Ω_c^* and its components ΞD is mainly via S-wave and the simplest Feynman diagrams are shown in Fig. 1. For the $\Omega_c^* \Xi D$ coupling, following Refs. [26,27], we take the Lagrangian densities as
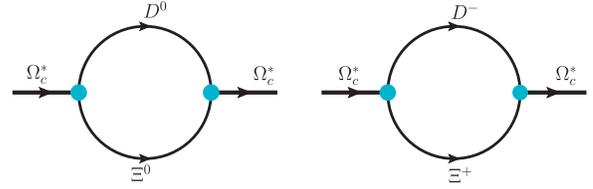
FIG. 1. Self-energy of the Ω_c^* states.

$$\mathcal{L}(x) = ig_{\Omega_c^* \Xi D} \Omega_c^*(x) \int d^4 y \Phi(y^2)$$
$$\times [\bar{\Xi}^0(x + \omega_{D^0} y) D^0(x - \omega_{\Xi^0} y)$$
$$+ \bar{\Xi}^+(x + \omega_{D^-} y) D^-(x - \omega_{\Xi^+} y)], \quad (1)$$

where $\omega_{D^{0,-}} = m_{D^{0,-}}/(m_{\Xi^{0,+}} + m_{D^{0,-}})$ and $\omega_{\Xi^{0,+}} = m_{\Xi^{0,+}}/(m_{\Xi^{0,+}} + m_{D^{0,-}})$. In the Lagrangian, an effective correlation function $\Phi(y^2)$ is introduced to reflect the distribution of two constituents, Ξ and D, in the hadronic molecule Ω_c^* state. It also play a role to avoid the Feynman diagrams ultraviolet divergence, which requires that its Fourier transform should vanish quickly in the ultraviolet region in the Euclidean space. Since only S wave is considered in current work, we adopt an exponential form $\Phi(-p_E^2) \doteq \exp(-p_E^2/\alpha^2)$ with p_E being the Euclidean Jacobi momentum as used in Refs. [26,27]. The α is a free size parameter characterizing the distribution of the two components in the molecule and we adopt the $\alpha = 1$ that is often used in Refs. [21–23,25–29].

The only undetermined parameter is the coupling between molecular state and two constituents, $g_{\Omega_c^* \Xi D}$, which strength is a key factor to the value of the decay width on which we focus in the current work. Following Refs. [30–32], we will adopt the compositeness condition to calculate the coupling of the hadronic molecule Ω_c^* and its constituents Ξ and D. This condition requires that the renormalization constant of the hadronic molecular wave function is equal to zero, $1 - \frac{d\Sigma_{\Omega_c^*}}{dk_0}|_{k_0 = m_{\Omega_c^*}} = 0$, with $\Sigma_{\Omega_c^*}$ being the self-energy of the hadronic molecule Ω_c^*. Such relation connects the binding energy and the coupling strength of bound state and its constituents. Now that the masses of Ω_c^* baryons have been observed in experiment, the couplings can be determined with such relation.

The Feynman diagram describing the self-energy of the Ω_c^* states is presented in Fig. 1. With the help of the effective Lagrangian in Eq. (1), we can obtain the self energy of the Ω_c^* as

$$\Sigma_{\Omega_c^*}(k_0) = g_{\Omega_c^* \Xi D}^2 \int \frac{d^4 k_1}{(2\pi)^4 i}$$

$$\times \left\{ \Phi^2[(k_1 - k_0 \omega_{\Xi^0})^2] \frac{\slashed{k}_1 + m_{\Xi^0}}{k_1^2 - m_{\Xi^0}^2} \frac{1}{(k_0 - k_1)^2 - m_{D^0}^2} \right.$$

$$\left. + \Phi^2[(k_1 - k_0 \omega_{\Xi^+})^2] \frac{\slashed{k}_1 + m_{\Xi^+}}{k_1^2 - m_{\Xi^+}^2} \frac{1}{(k_0 - k_1)^2 - m_{D^-}^2} \right\},$$

$$(2)$$

where $k_0^2 = m_{\Omega_c^*}^2$ with k_0, $m_{\Omega_c^*}$ denoting the four-momenta and mass of the Ω_c^*, respectively. Here, we set $m_{\Omega_c^*} = m_D + m_\Xi - E_b$ with E_b is the binding energy of Ω_c^*. While k_1, m_Ξ, and m_D are the four-momenta, mass of the Ξ and mass of D, respectively.

According to the normalization conditions, the coupling constants is given by

$$1/g_{\Omega_c^*\Xi D}^2 = \int_0^\infty \frac{d\eta d\beta}{16\pi z^2} \sum_{i=1}^2 H_i e^{-\frac{\omega_i}{\alpha^2}}, \qquad z = 2 + \eta + \beta \quad (3)$$

with

$$H_1 = \frac{2\omega_{\Xi^0} + \beta}{z} - \frac{2}{\alpha^2}\left[\frac{2\omega_{\Xi^0} + \beta}{z} m_{\Omega_c^*} + m_{\Xi^0}\right]$$
$$\times \left[\frac{(2\omega_{\Xi^0} + \beta)^2}{z} + (2\omega_{\Xi^0}^2 + \beta)\right]m_{\Omega_c^*} \quad (4)$$

$$\omega_1 = \left[\frac{(2\omega_{\Xi^0} + \beta)^2}{z} - 2\omega_{\Xi^0}^2 - \beta\right]m_{\Omega_c^*}^2 + \eta m_{\Xi^0}^2 + \beta m_{D^0}^2, \quad (5)$$

$$H_2 = \frac{2\omega_{\Xi^+} + \beta}{z} - \frac{2}{\alpha^2}\left[\frac{2\omega_{\Xi^+} + \beta}{z} m_{\Omega_c^*} + m_{\Xi^+}\right]$$
$$\times \left[\frac{(2\omega_{\Xi^+} + \beta)^2}{z} + (2\omega_{\Xi^+}^2 + \beta)\right]m_{\Omega_c^*} \quad (6)$$

$$\omega_2 = \left[\frac{(2\omega_{\Xi^+} + \beta)^2}{z} - 2\omega_{\Xi^+}^2 - \beta\right]m_{\Omega_c^*}^2 + \eta m_{\Xi^+}^2 + \beta m_{D^-}^2, \quad (7)$$

where the η and β will be integrated out, and the α is a free parameter, which will be discussed later.

Considering the quantum numbers and phase space, the strong decay modes of Ω_c^* are $\Omega_c^* \to \Xi_c^{(\prime)+} K^-$ and $\Omega_c^* \to \Xi_c^{(\prime)0} \bar{K}^0$. In this work, we only compute the partial decay width of $\Omega_c^* \to \Xi_c^{(\prime)+} K^-$, and that of $\Omega_c^* \to \Xi_c^{(\prime)0} \bar{K}^0$ can be obtained by isospin symmetry $\Gamma(\Omega_c^* \to \Xi_c^{(\prime)+} K^-) = \Gamma(\Omega_c^* \to \Xi_c^{(\prime)0} \bar{K}^0)$. The sum of the two parts is the total decay width of the $\Omega_c^* \to \bar{K}\Xi_c^{(\prime)+}$.

In the hadronic molecule picture, Ω_c^* can decay into $\Xi_c^+ K^-$, $\Xi_c^{\prime+} K^-$, and $\gamma\Omega_c^*(2695)$ by rearranging the quarks in its components. At the hadron level, Ω_c^* is treated as a bound state of ΞD and the decay $\Omega_c^* \to \Xi_c^+ K^-$, $\Xi_c^{\prime+} K^-$, and $\gamma\Omega_c^*(2695)$ occurs by exchanging a proper strange meson and hyperon as shown in Fig. 2. In the present work, we estimate these triangle diagrams in an effective Lagrangian approach. Besides the Lagrangian in Eq. (1), the effective Lagrangians of relevant interaction vertices are also needed [33–37].

$$\mathcal{L}_{KDD_s^*} = ig_{KDD_s^*}D_s^{*\mu}(\bar{D}\partial_\mu\bar{K} - \bar{K}\partial_\mu\bar{D}) + \text{H.c.}, \quad (8)$$

$$\mathcal{L}_{\Xi^0 D_s^{*-}\Xi_c^+} = \frac{\sqrt{6}g}{4}\bar{\Xi}^0\gamma_\mu D_s^{*-\mu}\Xi_c^+ + \text{H.c.}, \quad (9)$$

$$\mathcal{L}_{\Xi^0 D_s^{*-}\Xi_c^{\prime+}} = \frac{\sqrt{2}g}{4}\bar{\Xi}^0\gamma_\mu D_s^{*-\mu}\Xi_c^{\prime+} + \text{H.c.}, \quad (10)$$

$$\mathcal{L}_{\Xi D^*\Omega_c^0} = \frac{g}{\sqrt{2}}\bar{\Omega}_c^0\gamma^\mu D_\mu^{*+}\Xi^- + \frac{g}{\sqrt{2}}\bar{\Omega}_c^0\gamma^\mu D_\mu^{*0}\Xi^0, \quad (11)$$

$$\mathcal{L}_{\Xi_c^{(\prime)}\Lambda D} = \frac{ig_{\Xi_c^{(\prime)}\Lambda D}}{m_{\Xi_c^{(\prime)}} + m_D}\bar{\Xi}_c\gamma^\mu\gamma^5\Lambda\partial^\mu\bar{D}, \quad (12)$$

$$\mathcal{L}_{\Xi_c^{(\prime)}\Sigma D} = \frac{ig_{\Xi_c^{(\prime)}\Sigma D}}{m_{\Xi_c^{(\prime)}} + m_D}\bar{\Xi}_c\gamma_\mu\gamma^5\vec{\tau}\cdot\vec{\Sigma}\partial^\mu\bar{D}, \quad (13)$$

$$\mathcal{L}_{\Xi\Lambda K} = \frac{ig_{\Xi\Lambda K}}{m_\Lambda + m_\Xi}\partial^\mu\bar{K}\,\bar{\Lambda}\,\gamma_\mu\gamma_5\Xi + \text{H.c.}, \quad (14)$$

$$\mathcal{L}_{\Xi\Sigma K} = \frac{ig_{\Xi\Sigma K}}{m_\Sigma + m_\Xi}\partial^\mu\bar{K}\,\bar{\Sigma}\cdot\tau\gamma_\mu\gamma_5\Xi + \text{H.c.}, \quad (15)$$

where the m_Λ, m_Σ, and $m_{\Xi_c^{(\prime)}}$ are the masses of the particle Λ, Σ, and $\Xi_c^{(\prime)}$, respectively. The coupling constant $g_{KD_s^*D} = 1.84$ is estimated in the framework of light-cone QCD sum rules [38] and $g = 6.6$ is taken from [33,36]. The $\vec{\tau}$ is the Pauli matrix, $\vec{\Sigma}$ represents the Σ triplets, and $\bar{D}$ and $\bar{K}$ are the doublets of charmed and K mesons.

$$\bar{D} = \begin{pmatrix} D^- \\ \bar{D}^0 \end{pmatrix}, \qquad \bar{K} = \begin{pmatrix} K^- \\ \bar{K}^0 \end{pmatrix}. \quad (16)$$

The couplings for the different charge states are related by isospin symmetry:

$$\sqrt{2}g_{\Xi_c^{(\prime)+}D^0\Sigma^+} = g_{\Xi_c^{(\prime)+}D^-\Sigma^0} = \sqrt{2}g_{\Xi_c^{(\prime)0}D^-\Sigma^-} = -g_{\Xi_c^{(\prime)0}D^0\Sigma^0}, \quad (17)$$

$$\sqrt{2}g_{\Xi^+K^0\Sigma^-} = g_{\Xi^+K^-\Sigma^0} = \sqrt{2}g_{\Xi^0K^-\Sigma^+} = -g_{\Xi^0K^0\Sigma^0}. \quad (18)$$

One can estimate the couplings constants from SU(4) symmetry and phenomenological constraints [39]

$$g_{\Xi_c\Sigma D} = \frac{3 - 2\alpha_{NN\pi}}{\sqrt{6}}g_{NN\pi}, \qquad g_{\Xi_c'\Sigma D} = (2\alpha_{NN\pi} - 1)g_{NN\pi},$$

$$g_{\Xi_c\Lambda D} = \frac{-3 + 2\alpha_{NN\pi}}{3\sqrt{2}}g_{NN\pi}, \qquad g_{\Xi_c'\Lambda D} = \sqrt{3}(2\alpha_{NN\pi} - 1)g_{NN\pi},$$

$$g_{\Xi\Sigma K} = -g_{NN\pi}, \qquad g_{\Xi\Lambda K} = \frac{-4\alpha_{NN\pi} + 3}{\sqrt{3}}g_{NN\pi}, \quad (19)$$

where $g_{NN\pi} = 13.26$ [37], and $\alpha_{NN\pi} = 0.64$ [39]. The numerical values of the couplings constant are listed in Table I.

The involved interaction related to the photon field and the charmed mesons is [40].

TABLE I. Values of the effective meson-baryon couplings constants.

$g_{\Xi_c \Sigma D}$	$g_{\Xi'_c \Sigma D}$	$g_{\Xi_c \Lambda D}$	$g_{\Xi'_c \Lambda D}$	$g_{\Xi \Sigma K}$	$g_{\Xi \Lambda K}$
9.31	3.71	−5.38	6.43	−13.26	3.37

$$\mathcal{L}_{D^* D \gamma} = \frac{g_{D^{*+} D^+ \gamma}}{4} e \epsilon^{\mu\nu\alpha\beta} F_{\mu\nu} D^{*+}_{\alpha\beta} D^-$$
$$+ \frac{g_{D^{*0} D^0 \gamma}}{4} e \epsilon^{\mu\nu\alpha\beta} F_{\mu\nu} D^{*0}_{\alpha\beta} \bar{D}^0 + \text{H.c.}, \quad (20)$$

where the field-strength tensors are defined as $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$, $D^*_{\alpha\beta} = \partial_\alpha D^*_\beta - \partial_\beta D^*_\alpha$, and $e = \sqrt{4\pi/137}$. According to the Lagrangian and the radiative decay width of $\Gamma_{D^{*0} \to D^0 \gamma} = 26$ KeV that was deduced from the data on strong and radiative decays of D^* meson by theoretical predictions [26,41], the coupling constant $g_{D^{*0} D^0 \gamma}$ can be determined as

$$g_{D^{*0} D^0 \gamma} = \left[\frac{96 \pi m^3_{D^{*0}}}{e^2 (m^2_{D^{*0}} - m^2_{D^0})^3} \Gamma_{D^{*0} \to D^0 \gamma} \right]^{1/2}$$
$$= 2.0 \text{ GeV}^{-1} \quad (21)$$

where $m_{D^{*0}} = 2.007$ GeV, $m_{D^0} = 1.865$ GeV. Similar, the coupling constant $g_{D^{*+} D^+ \gamma} = -0.5$ GeV^{-1} is estimated from the partial decay width of $\Gamma_{D^{*+} \to D^+ \gamma} = 1.334$ KeV [1] with $m_{D^{*\pm}} = 2.010$ GeV. The minus sign is adopted according to the lattice QCD and QCD sum rule calculations [42,43].

In evaluating the amplitudes which are shown in Fig. 2, we need to include the form factors because hadrons are not pointlike particles. We adopt here the monopole-type form factor $\mathcal{F}_B(q^2)$ that was used in many previous works [27,44],

$$\mathcal{F}(q^2) = \frac{\Lambda^2 - M^2}{\Lambda - q^2}, \quad (22)$$

with M being the mass of the exchanged meson and baryon. The cutoff $\Lambda = M + \lambda \Lambda_{\text{QCD}}$ with $\Lambda_{\text{QCD}} = 220$ MeV is taken from Refs. [45,46]. The parameter λ reflects the nonperturbative property of QCD at the low-energy scale, which will be taken as a parameter and discussed later.

Putting all pieces together, we obtain the amplitudes for $\Omega^*_c(k_0) \to [D\Xi] \to K^- \Xi^{(\prime)+}_c$, and $\Omega^*_c(2695)\gamma$ which correspond to the diagrams in Fig. 2, which reads

$$\mathcal{M}_a = -i g_{\Xi^0 \Xi^{(\prime)+}_c D^{*-}_s} g_{\Omega^*_c \Xi D} g_{K^- D^0 D^{*-}_s} \int \frac{d^4 q}{(2\pi)^4 i} \mathcal{F}^2(q^2)$$
$$\times \Phi((k_1 \omega_{D^0} - k_2 \omega_{\Xi^0})^2) \bar{u}(p_2) \gamma_\mu \frac{1}{\not{k_1} - m_{\Xi^0}} u(k_0)$$
$$\times (p^\nu_1 + k^\nu_2) \frac{-g_{\mu\nu} + q_\mu q_\nu / m^2_{D^{*-}_s}}{q^2 - m^2_{D^{*-}_s}} \frac{1}{k^2_2 - m^2_{D^0}}, \quad (23)$$
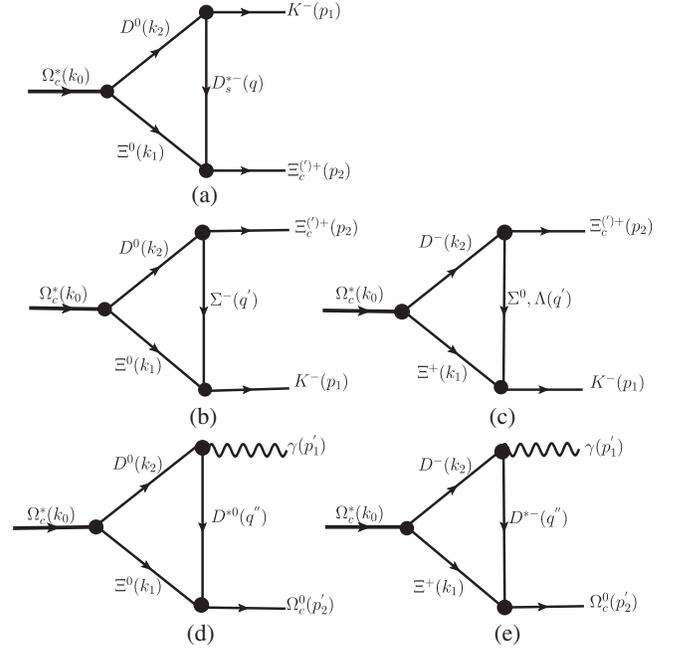
FIG. 2. Feynman diagrams for the $\Omega^{0*}_c \to K^- \Xi^{(\prime)+}_c$ and $\Omega^*_c \gamma$ decay processes.

$$\mathcal{M}_b = \frac{-i g_{\Xi^{(\prime)+}_c \Sigma^- D^0} g_{\Xi^0 \Sigma^- K^-} g_{\Omega^{*0}_c \Xi D}}{(m_{\Xi^{(\prime)+}_c} + m_{D^0})(m_{\Sigma^-} + m_{\Xi^0})} \int \frac{d^4 q'}{(2\pi)^4 i} \mathcal{F}^2(q'^2)$$
$$\times \Phi((k_1 \omega_{D^0} - k_2 \omega_{\Xi^0})^2) \bar{u}(p_2) \gamma^\mu \gamma_5 \frac{1}{\not{q'} - m_{\Sigma^-}} \gamma^\nu \gamma_5$$
$$\times \frac{1}{\not{k_1} - m_{\Xi^0}} u(k_0) \frac{1}{k^2_2 - m^2_{D^0}} k_{2\mu} p_{1\nu}, \quad (24)$$

$$\mathcal{M}^\Lambda_c = \frac{-i g_{\Xi^{(\prime)+}_c \Lambda D^-} g_{\Xi^+ \Lambda K^-} g_{\Omega^{*0}_c \Xi D}}{(m_{\Xi^{(\prime)+}_c} + m_{D^-})(m_\Lambda + m_{\Xi^+})} \int \frac{d^4 q'}{(2\pi)^4 i} \mathcal{F}^2(q'^2)$$
$$\times \Phi((k_1 \omega_{D^-} - k_2 \omega_{\Xi^+})^2) \bar{u}(p_2) \gamma^\mu \gamma_5 \frac{1}{\not{q'} - m_\Lambda} \gamma^\mu \gamma_5$$
$$\times \frac{1}{\not{k_2} - m_{\Xi^+}} u(k_0) \frac{1}{k^2_1 - m^2_{D^-}} k_{2\mu} p_{1\nu}, \quad (25)$$

$$\mathcal{M}^{\Sigma^0}_c = \mathcal{M}^\Lambda_c |_{\Lambda \to \Sigma^0}$$

$$\mathcal{M}_d = \frac{e g g_{\Omega^{*0}_c \Xi D} g_{D^{*0} D^0 \gamma}}{4\sqrt{2}} \int \frac{d^4 q''}{(2\pi)^4 i} \mathcal{F}^2(q''^2)$$
$$\times \Phi((k_1 \omega_{D^0} - k_2 \omega_{\Xi^0})^2) \bar{u}(p_2) \gamma_\rho \frac{1}{\not{k_1} - m_{\Xi^0}} u(k_0)$$
$$\times \epsilon^{\mu\nu\alpha\beta} (g_{\nu\eta} p'_{1\mu} - g_{\mu\eta} p'_{1\nu})(g_{\beta\sigma} q''_\alpha - g_{\alpha\sigma} q''_\beta) \varepsilon^{*\eta}$$
$$\times \frac{-g_{\rho\sigma} + q''_\rho q''_\sigma / m^2_{D^{*0}}}{q''^2 - m^2_{D^{*0}}} \frac{1}{k^2_2 - m^2_{D^0}}. \quad (26)$$

$$\mathcal{M}_e = \frac{egg_{\Omega_c^{0*}\Xi D}g_{D^{*+}D^-\gamma}}{4\sqrt{2}} \int \frac{d^4q''}{(2\pi)^4 i}\mathcal{F}^2(q''^2)$$

$$\times \Phi((k_1\omega_{D^-} - k_2\omega_{\Xi^+})^2)\bar{u}(p_2)\gamma_\rho \frac{1}{\not{k}_1 - m_{\Xi^+}}u(k_0)$$

$$\times \epsilon^{\mu\nu\alpha\beta}(g_{\nu\eta}p'_{1\mu} - g_{\mu\eta}p'_{1\nu})(g_{\beta\sigma}q''_\alpha - g_{\alpha\sigma}q''_\beta)\epsilon^{*\eta}$$

$$\times \frac{-g_{\rho\sigma} + q''_\rho q''_\sigma/m^2_{D^{*-}}}{q''^2 - m^2_{D^{*-}}} \frac{1}{k^2_2 - m^2_{D^-}}. \tag{27}$$

Where the $\Lambda \to \Sigma^0$ mean the baryon Λ is replaced by baryon Σ^0. The corresponding partial decay widths then read

$$\Gamma[\Omega_c^* \to K^-\Xi_c^{(\prime)+}, \gamma\Omega_c^*(2695)] = \frac{1}{2J+1}\frac{1}{8\pi}\frac{|\vec{p}_1^{K/\gamma}|}{m^2_{\Omega_c^*}}\overline{|\mathcal{M}|^2}, \tag{28}$$

where J is the total angular momentum of the initial Ω_c^* state, the overline indicates the sum over the polarization vectors of final hadrons. Here $|\vec{p}_1^{K/\gamma}|$ is the 3-momenta of the decay products in the center of mass frame.

III. RESULTS

Regarding the five new Ω_c^* as ΞD hadronic molecules, the coupling constants $g_{\Omega_c^*\Xi D}$ can be estimated from the compositeness condition. As shown in Eq. (3), the coupling constant is dependent on the parameter α. In Fig. 3, we show the dependence of the coupling constants $g_{\Omega_c^*\Xi D}$ on the cutoff parameter α. The coupling constant $g_{\Omega_c^*\Xi D}$ decreases with the increase of α. Taking the $\Omega_c^*(3119)$ as an example, the value of the coupling constant $g_{\Omega_c^*(3119)\Xi D}$ is not very sensitive to the model parameter α when varying cutoff parameter α from 0.7 to 1.3 GeV (not sensitive to α also). Fixing the α at certain value, such as 1.00 GeV, the coupling constants decrease with increase of the mass $m_{\Omega_c^*}$. According to the studies of the XYZ
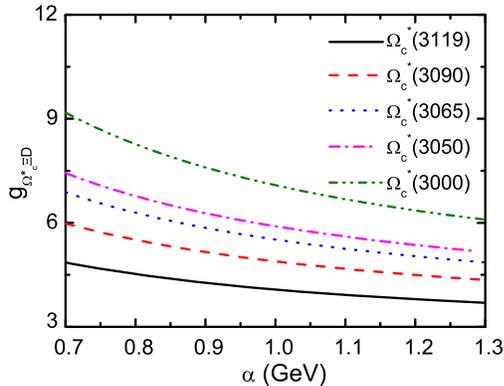
FIG. 3. Coupling constants, $g_{\Omega_c^*\Xi D}$ (GeV^{-1}), for different Ω_c^* states as a function of the parameter α.

TABLE II. Coupling constants, $g_{\Omega_c^*\Xi D}$, for different Ω_c^* states with $\alpha = 1$ GeV.

	$\Omega_c^*(3000)$	$\Omega_c^*(3050)$	$\Omega_c^*(3065)$	$\Omega_c^*(3090)$	$\Omega_c^*(3119)$
$g_{\Omega_c^*\Xi D}$	7.08	5.90	5.52	4.89	4.08

resonances and the deuteron [41,47], a typical value of $\alpha \sim 1$ GeV is often employed. Thus, in this work we take $\alpha = 1.0$ and the corresponding coupling constants are listed in Table II, which are used to calculate the decay processes of Fig. 2.

Once the coupling constants of the molecular Ω_c^* baryons and ΞD are determined, the partial decay widths of the $\Omega_c^* \to \Xi_c^+K^-$, $\Omega_c^* \to \Xi_c'^+K^-$, $\Omega_c^* \to \Omega_c^*(2695)\gamma$, and the total decay width are only dependent on the parameter λ in the cutoff. Though the value of λ could not be determined in first principles, it is usually chosen as about 1 in the literature. In Ref. [27], by comparing the sum of the partial decay modes of the $\eta(2225)$ and $\phi(2170)$ with the total width, the parameter λ was constrained as $\lambda = 0.91$–1.00. In addition, the experimental branching ratios of $\psi(4040) \to J/\psi\eta$ and $\psi(4160) \to J/\psi\eta$ can be well explained with $\lambda = 0.53$–1.20 [46]. Larger range of 0.5 to 5 can be found in Refs. [48–51]. Considering the values adopted in above literatures, we adopt a parameter λ in the a range of $0.91 \le \lambda \le 1.0$ because this range is determined from the experimental data of branching ratios within the
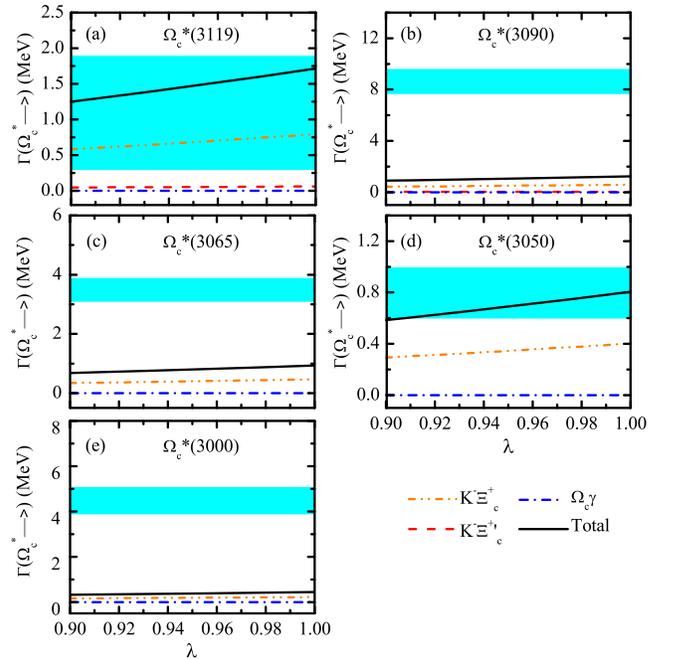
FIG. 4. Partial decay widths of the $\Omega_c^* \to K^-\Xi_c^+$ (Orange dash dot dot line), $\Omega_c^* \to K^-\Xi_c'^+$ (red dash line), $\Omega_c^* \to \gamma\Omega_c(2695)$ (blue dash dot), and the total decay width (black solid line) with different Ω_c^* states depending on the parameter λ. The oycn error bands correspond to the total width observed in experiment.[2].
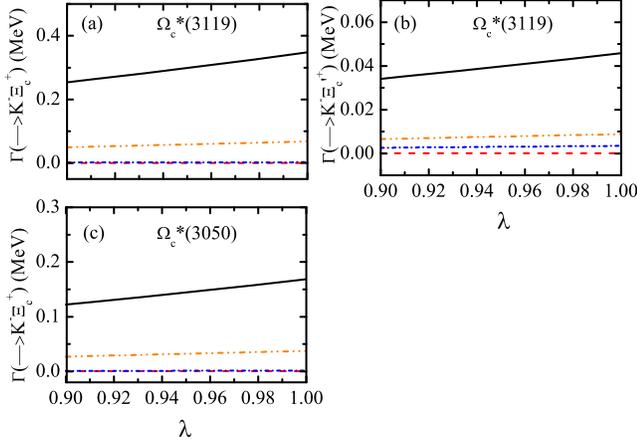
FIG. 5. Individual contributions of the D_s^{*-}, Λ, Σ^-, and Σ^0 exchange for the $\Omega_c^* \to K^- \Xi_c^+$ and $\Omega_c^* \to K^- \Xi_c'^+$ for $\Omega_c^*(3119)$ and $\Omega_c^*(3050)$ depending on the parameter λ. The red dash, blue dash dot, black solid, and orange dash dot dot lines stand for the D_s^{*-}, Λ, Σ^-, and Σ^0 contributions, respectively.

same theoretical framework adopted in current work in Ref. [27]. The numerical results are presented in Fig. 4 with the variation of λ from 0.90 to 1.0. In the discussed range, the partial decay widths increase with λ, and the Ω_c^* states mainly decay into $\Xi_c \bar{K}$ and the partial width into $\Xi_c \bar{K}$ is much larger than those into $\Xi_c' \bar{K}$ and, of course, $\gamma \Omega^*(2695)$. The total width of $\Omega_c^*(3119)$ and $\Omega_c^*(3050)$ can be well reproduced in the λ range considered here. If we increase λ to higher values, the total widths of all five Ω_c^* baryons cannot be reproduced until a much larger λ value of about 2 adopted. Hence, it is reasonable to adopt a λ of about 1 in the current work.

The individual contributions of the D_s^{*-}, Λ, Σ^-, and Σ^0 exchanges for the decays $\Omega_c^* \to K^- \Xi_c^+$ and $\Omega_c^* \to K^- \Xi_c'^+$ are calculated and presented in Fig. 5. Since the relative signs of the three Feynman diagrams [(a),(b),(c) in Fig. 2] are well defined, the total decay widths obtained are the square of their coherent sum. It is found that the Σ^- exchange plays a dominant role, while the D_s^{*-}, Λ, and Σ^0 exchanges give minor contributions. However, the interferences among them are still sizable. Even for

the $\Omega_c^*(3119)$ case, the $|\mathcal{M}_{D^{*-}} + \mathcal{M}_\Lambda + \mathcal{M}_{\Sigma^0}|$ is about $1/8 \sim 1/3$ of the $\mathcal{M}_{\Sigma^-}$, which contributes to the decay constructively.

The five new Ω_c^* particles were observed as resonances in the $\Xi_c^+ K^-$ invariant mass distribution and are in the vicinity of the $\Xi_c \bar{K}$ and $\Xi_c' \bar{K}$ thresholds. The transition $\Omega_c^* \to \Xi_c \bar{K}$ and $\Omega_c^* \to \Xi_c' \bar{K}$ may be considered as main decay channels, the sum of which almost saturates the total width of each Ω_c^*. For the $\Omega_c^*(3090)$, $\Omega_c^*(3000)$, and $\Omega_c^*(3065)$, their total decay widths are much smaller than the experimental total width. Such results disfavor the assignment of these three states as $D\Xi$ molecular state. Hence, only the $\Omega_c^*(3119)$ or $\Omega_c^*(3050)$ states can be considered as S-wave ΞD molecules. Hence, we only list the decay widths of $\Omega_c^*(3119)$ and $\Omega_c^*(3050)$ with $\lambda = 0.91$–1.00 in Table III. For comparisons, we show the results in the constituent quark model as well [10]. The decay width $\Gamma_{\Xi_c \bar{K}}$ is close to that in the constituent quark model if we assign the S-wave ΞD bound state as $\Omega_c^*(3050)$. Assuming this channel is dominant decay channel, the total decay width under such assignment is also consistent with that in constituent quark model and the experimental value. Under assignment as $\Omega_c^*(3119)$, the total widths decay width $\Gamma_{\Xi_c \bar{K}}$ is larger than that in the constituent quark model while $\Gamma_{\Xi_c' \bar{K}}$ is smaller, which leads to a comparable total decay width to those in the constituent quark model and in experiment.

Now we turn to the radiative decay $\Omega_c^* \to \Omega_c^*(2695)\gamma$. The individual contributions of the D^{*0} and D^{*-} exchange and total decay width with varying λ from 0.90 to 1.00 for the $\Omega_c^* \to \Omega_c^*(2695)\gamma$ are presented in Figs. 6 and 4, respectively. Our study shows that the partial width of the $\Omega_c^* \to \Omega_c^*(2695)\gamma$ is rather small and the D^{*0} exchange plays a dominant role, weakly increasing with the λ increasing. In the considered parameter region, the partial widths for the $\Omega_c^* \to \Omega_c^*(2695)\gamma$ are predicted and listed in Table III, compared with the results in conventional charmed baryons scheme [10]. The partial widths of $\Omega_c^*(3119) \to \Omega_c^*(2695)\gamma$ and $\Omega_c^*(3050) \to \Omega_c^*(2695)\gamma$ in Ref. [10] were 1.2 and $2.9/1.0 \times 10^{-3}$ MeV, respectively, which are totally different with the results in the present work.

TABLE III. Partial decay widths of $\Omega_c^* \to \Xi_c \bar{K}, \Xi_c' \bar{K}, \Omega_c^*(2695)\gamma$, and the total decay width Γ_{total} with $\lambda = 0.91$–1.00 that is introduced by the form factor, in comparison with the results in the constituent quark model [10]. The total width obtained from the LHCb experiments [2]. All masses and widths are in units of MeV. The two values of decay width for the $\Omega_c^*(3119)$ in Ref [10] are for the assignments $|2^2S_{\Lambda\Lambda}1/2^+\rangle$ or $|2^4S_{\Lambda\Lambda}3/2^+\rangle$, respectively.

State	$\Gamma_{\Xi_c \bar{K}}$		$\Gamma_{\Xi_c' \bar{K}}$		$\Gamma_{\Omega_c^*(2695)\gamma}$		Γ_{total}		
	This work	Reference [10]	This work	Reference [10]	This work ($\times 10^{-7}$)	Reference [10] ($\times 10^{-3}$)	This work	Reference [10]	Exp.[2]
$\Omega_c^*(3050)$	0.61–0.81	0.61	...	...	1.06–1.42	1.12	0.61–0.81	0.94	0.8 ± 0.2
$\Omega_c^*(3119)$	1.20–1.59	0.6/0.6	0.094–0.122	0.45/0.11	1.85–2.48	2.9/1.0	1.29–1.71	1.15/0.73	1.1 ± 0.8
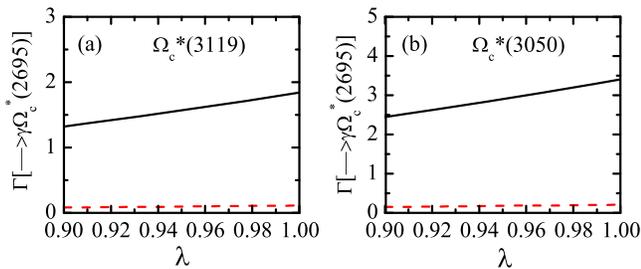
FIG. 6.   Individual contributions of the D^{*0} and D^{*-} exchange for the $\Omega_c^* \to \Omega_c(2695)\gamma$ for different Ω_c^* states as a function of the parameter λ. The black solid and red dash lines stand for the D^{*0} and D^{*-} contributions, respectively. The numerical results are in units of 10^{-7} MeV.

IV. DISCUSSION AND SUMMARY

In this work, the S-wave $D\Xi_c$ molecular states were studied by calculating their strong and radiative decays to investigate whether the five new narrow Ω_c^* baryons, $\Omega_c(3000)$, $\Omega_c^*(3050)$, $\Omega_c^*(3066)$, $\Omega_c^*(3090)$, and $\Omega_c^*(3119)$, can be understood as ΞD molecules. With the coupling constants obtained by the composition condition, the decays through hadronic loops are calculated in a phenomenological effective Lagrangian approach. The total decay widths can be well reproduced with the assumption that the $\Omega_c^*(3119)$ or $\Omega_c^*(3050)$ as S-wave ΞD bound state with $J^p = 1/2^-$, which decay channels are S-wave $\Xi_c K$, $\Xi_c' K$ and $\Omega_c^*(2659)\gamma$. The other newly reported Ω_c^* states cannot be accommodated in the current molecular picture. If the $\Omega_c^*(3119)$ or $\Omega_c^*(3050)$ is pure $D\Xi$ molecule, the radiative transition strength is quite small and the decay width is of the order of about 0.1 eV.

It is interesting to compare our results with those in Refs. [10,14–19]. According to Ref. [10], the Ω_c^* baryons at LHCb may be conventional charmed baryons with P-wave or even higher partial waves. In Refs. [16,17] the $J^p = 1/2^-$ state is identified as a meson-baryon molecule that can be associated to the $\Omega_c^*(3050)$, in agreement with our conclusion. However they claim that the $\Omega_c^*(3050)$ only has a small $D\Xi$ component. In Ref. [17] a $J^p = 3/2^-$ state can be associated to the experimental $\Omega_c^*(3119)$. This is quite different from the our results and those by Huang *et al.* [19] that the $\Omega_c^*(3119)$ can be explained as S-wave ΞD state with $J^p = 1/2^-$. Furthermore, in the chiral quark-soliton model, pentaquark-like structures were suggested for the $\Omega_c(3050)$ and $\Omega_c(3119)$ [14,15]. It is very interesting to find that authors in the Ref. [18] regarded $\Omega_c(3050)$ and $\Omega_c^*(3090)$ or $\Omega_c^*(3119)$ as meson-baryons. However, a completely different conclusion was drawn from Refs. [10] that the $\Omega_c^*(3119)$ and $\Omega_c^*(3050)$ can be understood as conventional css states. The radiative decay $\Omega_c^* \to \Omega_c^*(2695)\gamma$ may be helpful to distinguish these results. If the $\Omega_c^*(3119)$ or $\Omega_c^*(3050)$ is pure $D\Xi$ molecule, the radiative transition strength is quite small and the decay width is of the order of about 0.1 eV. Future experimental measurements of such a process can be quite useful to test the different interpretations of the $\Omega_c^*(3119)$ and $\Omega_c^*(3050)$.

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