Hidden charm decays of $X(4014)$ in a $D^*\bar{D}^*$ molecule scenario

Zi-Li Yue,[1] Man-Yu Duan,[1] Chun-Hua Liu,[1,*] Dian-Yong Chen,[1,2,†] and Yu-Bing Dong[3,4,‡]

[1]*School of Physics, Southeast University, Nanjing 210094, China*
[2]*Lanzhou Center for Theoretical Physics, Lanzhou University, Lanzhou 730000, China*
[3]*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China*
[4]*School of Physical Sciences, University of Chinese Academy of Sciences, Beijing 101408, China*

(Received 13 July 2022; accepted 24 August 2022; published 12 September 2022)

Inspired by the recent observation of a new structure, $X(4014)$, in the process $\gamma\gamma \to \gamma\psi(2S)$, we evaluate the possibility of assigning $X(4014)$ as a $D^*\bar{D}^*$ molecular state with $I(J^{PC}) = 0(0^{++})$ by investigating the hidden charm decays of $X(4014)$. The partial widths of $J/\psi\omega$, $\eta_c\eta$ and $\eta_c\eta'$ channels are evaluated to be about (0.41–5.00), (2.05–7.49) and (0.11–0.51) MeV, respectively. Considering the experimental observation and the present estimations, we proposed to search $X(4014)$ in the $\gamma\gamma \to J/\psi\omega$ process in Belle II.

DOI: 10.1103/PhysRevD.106.054008

I. INTRODUCTION

Similar to the deuteron composed of a proton and a neutron, the deuteronlike molecule states [1] composed of other hadrons are expected to exist [2–7]. Searching for these kinds of molecule states experimentally is an intriguing topic in hadron physics. The first promising candidate is the long standing and well-established $X(3872)$, which was observed by the Belle Collaboration in the year of 2003 [8], and the observed mass is very close to the threshold of $D^*\bar{D}$ [6,9–14]. The $I(J^{PC})$ quantum numbers have been determined to be $0(1^{++})$. Besides the $X(3872)$, there exist another two states near the threshold of $D^*\bar{D}/D^*D$, which are $Z_c(3900)$ [15–18] and $T_{cc}(3875)$ [19–30], respectively. The former state $Z_c(3900)$ was first observed in 2013 by the BESIII [31] and Belle [32] Collaborations in the $\pi^\pm J/\psi$ invariant mass spectrum of the process $e^+e^- \to \pi^+\pi^- J/\psi$ at $\sqrt{s} = 4260$ MeV, and later, the authors in Ref. [33] confirmed the existence of $Z_c(3900)$ by using the data sample collected by the CLEO-c Collaboration at $\sqrt{s} = 4170$ MeV. The $I(J^P)$ quantum numbers of $Z_c^0(3900)$ are determined to be $1(1^{+-})$. As for the later state $T_{cc}(3875)$, it was observed by the LHCb Collaboration in the $D^0D^0\pi^+$ invariant mass spectrum in 2021 [34,35]. Since the measured masses of $X(3872)$, $Z_c(3900)$, and $T_{cc}(3875)$ are all close to the threshold of $D^*\bar{D}/D^*D$, these states have been extensively investigated in the molecular scenario [2–7]. If $X(3872)$, $Z_c(3900)$, and $T_{cc}(3875)$ are all molecular, it seems that the interactions between S-wave charmed mesons are attractive and strong enough in various channels.

Besides the states near the threshold of $D^*\bar{D}$, there is another state named $Z_c(4020)$ [36,37] near the threshold of $D^*\bar{D}^*$, which could be considered as a deuteronlike molecular state composed of $D^*\bar{D}^*$. The state $Z_c(4020)$ was first observed in the $\pi^\pm h_c$ invariant mass spectrum of the process $e^+e^- \to \pi^+\pi^- h_c$ by the BESIII Collaboration at $\sqrt{s} = 4260$ MeV in 2013 [38]. Extensive investigations from different aspects, such as mass spectrum [39–41], decay [39,40,42,43], and production properties [15] from various groups indicated that $Z_c(4020)$ could be assigned as a $D^*\bar{D}^*$ molecular state. Similar to the case of the prosperous states near the $D^*\bar{D}$ threshold, it is expected that there also exist abundant molecular candidates near the threshold of $D^*\bar{D}^*$.

Recently, the Belle Collaboration reported their measurements of the cross section for the two-photon process $\gamma\gamma \to \gamma\psi(2S)$ from the threshold to 4.2 GeV [44]. Two structures were observed in the cross sections, and the one with a mass of $3922.4 \pm 6.5 \pm 2.0$ MeV and a width of $22 \pm 17 \pm 4$ MeV could be considered $X(3915)$, $\chi_{c2}(3930)$, or an admixture of them. Besides, there exists a new state at 4014 MeV, hereinafter, we named this new state as $X(4014)$. The mass and width of $X(4014)$ were reported to be

$$M = (4014.3 \pm 4.0 \pm 1.5)\ \text{MeV},$$
$$\Gamma = (4 \pm 11 \pm 6)\ \text{MeV}, \tag{1}$$

respectively.

It is interesting to notice that the newly observed $X(4014)$ matches none of the known charmonium or charmoniumlike states, and, moreover, its mass is just several MeV below the threshold of $D^*\bar{D}^*$, which is similar to the case of $Z_c(4020)$. Thus, one can consider $X(4014)$ as a candidate of the $D^*\bar{D}^*$

*liuch@seu.edu.cn
†chendy@seu.edu.cn
‡dongyb@ihep.ac.cn

molecular state with positive C parity. In Ref. [45], we investigated the molecular possibilities of $X(4014)$ in the framework of the local hidden gauge approach [46], and we found the most possible $I(J^{PC})$ numbers of $X(4014)$ are $0(0^{++})$. In the present work, we further test the molecular possibility of $X(4014)$ by investigating the hidden charm decay properties of $X(4014)$ in such a $D^*\bar{D}^*$ molecular scenario with effective Lagrangian approaches [47–49]. The predicted decay channels can be experimentally accessible by Belle II, which could be a crucial test of the $D^*\bar{D}^*$ molecular assignment of $X(4014)$.

This work is organized as follows. The hadronic molecular structures of $X(4014)$ are discussed in the following section and the hidden charm decays processes, including $X(4014) \to J/\psi\omega$, $\eta_c\eta$, and $\eta_c\eta'$ are estimated in Sec. III. The numerical results and the relevant discussions are presented in Sec. IV, and the last section is dedicated to a short summary.

II. HADRONIC MOLECULAR STRUCTURE

In the present work, the newly observed $X(4014)$ is assigned as a molecular state composed of $D^*\bar{D}^*$ with $I(J^{PC}) = 0(0^{++})$. The interaction between $X(4014)$ and its components can be described by an effective Lagrangian in the form,

$$\mathcal{L}_X = \frac{g_X}{\sqrt{2}} X \int dy \Phi_X(y^2) \left[D^{*+}_\mu \left(x - \frac{y}{2} \right) D^{*-\mu} \left(x + \frac{y}{2} \right) + D^{*0}_\mu \left(x - \frac{y}{2} \right) \bar{D}^{*0\mu} \left(x + \frac{y}{2} \right) \right], \tag{2}$$

where $\Phi_X(y^2)$ is the correlation function, which is introduced to describe the distribution of the D^* and $\bar{D}^*$ mesons in the molecular state.

The Fourier transformation of the correlation function is

$$\Phi_X(y^2) = \int \frac{d^4p}{(2\pi)^4} e^{-ipy} \tilde{\Phi}_X(-p^2). \tag{3}$$

An appropriate $\tilde{\Phi}_X(-p^2)$ should not only describe the interior structure of the molecular state, but also fall fast enough in the ultraviolet region. Here, we employ the form factor in the Gaussian form [4,5],

$$\tilde{\Phi}_X(p_E^2) = \exp(-p_E^2/\Lambda^2) \tag{4}$$

where Λ is a model parameter for parametrizing the distribution of the components inside the molecular state.

As a composite particle, the renormalization constant of the $X(4014)$ should be zero [50–52], which can be used to determine the coupling constant between the molecular and its components, i.e.,

$$Z = 1 - \Pi'(m_X^2) = 0, \tag{5}$$

where $\Pi'(m_X^2)$ is the derivative of the mass operator of the $X(4014)$, and the concrete form of the mass operator of the $X(4014)$ corresponding to Fig. 1 is

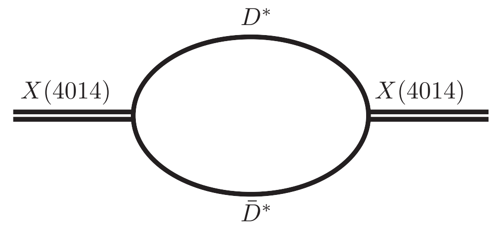

FIG. 1. The mass operator of the $X(4014)$. Here D^* and $\bar{D}^*$ refer to (D^{*+}, D^{*0}) and $(D^{*-}, \bar{D}^{*0})$, respectively.

$$\Pi(m_X{}^2) = \int \frac{d^4q}{(2\pi)^4} \tilde{\Phi}^2 \left[-(q - \frac{1}{2}p)^2, \Lambda^2 \right] \times \frac{-g^{\mu\nu} + q^\mu q^\nu / m_{D^*}^2}{q^2 - m_{D^*}^2} \times \frac{-g^{\mu\nu} + (p-q)^\mu (p-q)^\nu / m_{\bar{D}^*}^2}{(p-q)^2 - m_{\bar{D}^*}^2}. \tag{6}$$

III. HIDDEN CHARM DECAY

In the present work, we estimate the hidden charm decays of $X(4014)$ in the $D^*\bar{D}^*$ molecular scenario, where the $I(J^{PC})$ quantum numbers of the $X(4014)$ are considered as $0(0^{++})$. The possible decay channels include $X(4014) \to J/\psi\omega, \eta_c\eta, \eta_c\eta'$. These decay processes are estimated in the

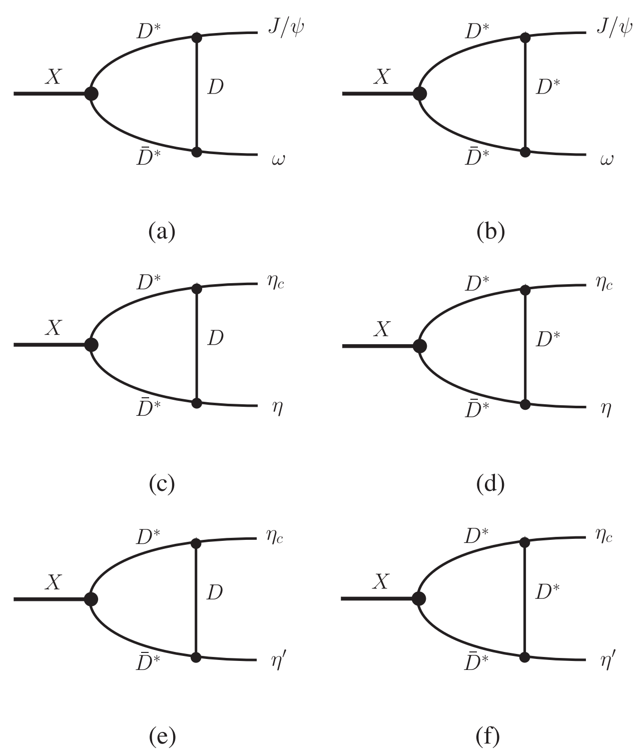

FIG. 2. The typical diagrams contributing to $X(4014) \to J/\psi\omega$ [diagrams (a) and (b)], $X(4014) \to \eta_c\eta$ [diagrams (c) and (d)] and $X(4014) \to \eta_c\eta'$ [diagrams (e) and (f)].

hadronic level, and the possible diagrams contributing to these processes are collected in Fig. 2.

A. Effective Lagrangians

To estimate the diagrams in Fig. 2, we employ an effective Lagrangian approach. The coupling between the molecular state and its components has been given in Eq. (2). Considering the heavy quark limit, one can construct the coupling between charmonia and the charmed meson pair, and the relevant effective Lagrangians are [53–56]

$$\begin{aligned}\mathcal{L}_{\psi\mathcal{D}^{(*)}\mathcal{D}^{(*)}} &= -ig_{\psi\mathcal{D}\mathcal{D}}\psi_\mu\mathcal{D}^\dagger\overset{\leftrightarrow}{\partial^\mu}\mathcal{D}\\ &\quad + g_{\psi D^*D}\epsilon^{\mu\nu\alpha\beta}\partial_\mu\psi_\nu(\mathcal{D}^*_\alpha\overset{\leftrightarrow}{\partial_\beta}\mathcal{D}^\dagger - \mathcal{D}\overset{\leftrightarrow}{\partial_\beta}\mathcal{D}^{*\dagger}_\alpha)\\ &\quad + ig_{\psi\mathcal{D}^*\mathcal{D}^*}\psi^\mu(\mathcal{D}^*_\nu\overset{\leftrightarrow}{\partial^\nu}\mathcal{D}^{*\dagger}_\mu + \mathcal{D}^*_\mu\overset{\leftrightarrow}{\partial^\nu}\mathcal{D}^{*\dagger}_\nu\\ &\quad - \mathcal{D}^*_\nu\overset{\leftrightarrow}{\partial_\mu}\mathcal{D}^{*\nu\dagger}),\\ \mathcal{L}_{\eta_c\mathcal{D}^*\mathcal{D}^{(*)}} &= -ig_{\eta_c\mathcal{D}^*\mathcal{D}}\eta_c(\mathcal{D}\overset{\leftrightarrow}{\partial_\mu}\mathcal{D}^{*\dagger\mu} + D^{*\mu}\overset{\leftrightarrow}{\partial_\mu}\mathcal{D}^\dagger)\\ &\quad + -g_{\eta_c\mathcal{D}^*\mathcal{D}^*}\epsilon^{\mu\nu\alpha\beta}\partial_\mu\eta_c\mathcal{D}^*_\nu\overset{\leftrightarrow}{\partial_\alpha}\mathcal{D}^{*\dagger}_\beta,\end{aligned} \tag{7}$$

where $\mathcal{D}^{(*)\dagger} = (\bar{D}^{(*)0}, D^{(*)-}, D_s^{(*)-})$ and $A\overset{\leftrightarrow}{\partial_\mu}B = A\partial_\mu B - B\partial_\mu A$.

Considering the heavy quark limit and chiral symmetry, one can construct the effective coupling between light mesons and the charmed meson pair, which is [53–55,57,58]

$$\begin{aligned}\mathcal{L}_{\mathcal{D}^{(*)}\mathcal{D}^{(*)}\mathcal{P}} &= -ig_{\mathcal{D}^*\mathcal{D}\mathcal{P}}(\mathcal{D}^i\partial^\mu\mathcal{P}_{ij}\mathcal{D}^{*j\dagger}_\mu - \mathcal{D}^{*i}_\mu\partial_\mu\mathcal{P}_{ij}\mathcal{D}^{j\dagger})\\ &\quad + \frac{1}{2}g_{\mathcal{D}^*\mathcal{D}^*\mathcal{P}}\epsilon_{\mu\nu\alpha\beta}\mathcal{D}^{*\mu}_i\partial^\nu\mathcal{P}^{ij}\overset{\leftrightarrow}{\partial^\alpha}\mathcal{D}^{*\beta\dagger}_j,\\ \mathcal{L}_{\mathcal{D}^{(*)}\mathcal{D}^{(*)}\mathcal{V}} &= -ig_{\mathcal{D}\mathcal{D}\mathcal{V}}\mathcal{D}^\dagger_i\overset{\leftrightarrow}{\partial_\mu}\mathcal{D}^j(\mathcal{V}^\mu)^i_j\\ &\quad - 2f_{\mathcal{D}^*\mathcal{D}\mathcal{V}}\epsilon_{\mu\nu\alpha\beta}(\partial^\mu\mathcal{V}^\nu)^i_j(\mathcal{D}^\dagger_i\overset{\leftrightarrow}{\partial^\alpha}\mathcal{D}^{*\beta\dagger} - \mathcal{D}^{*\beta\dagger}_i\overset{\leftrightarrow}{\partial^\alpha}\mathcal{D}^j)\\ &\quad + ig_{\mathcal{D}^*\mathcal{D}^*\mathcal{V}}\mathcal{D}^{*\nu\dagger}_i\overset{\leftrightarrow}{\partial_\mu}\mathcal{D}^{*j}_\nu(\mathcal{V}^\mu)^i_j\\ &\quad + 4if_{\mathcal{D}^*\mathcal{D}^*\mathcal{V}}\mathcal{D}^{*\dagger}_{i\mu}(\partial^\mu\mathcal{V}^\nu - \partial^\nu\mathcal{V}^\mu)^i_j\mathcal{D}^{*j}_\nu,\end{aligned} \tag{8}$$

where $\mathcal{V}$ and $\mathcal{P}$ are the matrices forms of vector nonet and pseudoscalar nonet, and their concrete forms are

$$\mathcal{V} = \begin{pmatrix} \frac{1}{\sqrt{2}}(\rho^0+\omega) & \rho^+ & K^{*+}\\ \rho^- & \frac{1}{\sqrt{2}}(-\rho^0+\omega) & K^{*0}\\ K^{*-} & \bar{K}^{*0} & \phi\end{pmatrix}$$

$$\mathcal{P} = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}}+\alpha\eta+\beta\eta' & \pi^+ & K^+\\ \pi^- & -\frac{\pi^0}{\sqrt{2}}+\alpha\eta+\beta\eta' & K^0\\ K^- & \bar{K}^0 & \gamma\eta+\delta\eta'\end{pmatrix}, \tag{9}$$

where α, β, and δ are the parameters related to the mixing angle by

$$\alpha = \frac{\cos\theta - \sqrt{2}\sin\theta}{\sqrt{2}}, \qquad \beta = \frac{\sin\theta + \sqrt{2}\cos\theta}{\sqrt{6}},$$
$$\gamma = \frac{-2\cos\theta - \sqrt{2}\sin\theta}{\sqrt{6}}, \qquad \delta = \frac{-2\sin\theta + \sqrt{2}\cos\theta}{\sqrt{6}}, \tag{10}$$

where the mixing angle θ is determined to be 19.1° [59,60].

B. Decay amplitude

With the effective Lagrangians listed above, we can get the amplitudes for $X(4014)(p_0) \to [D^*(p_1)\bar{D}^*(p_2)]D^{(*)}(q) \to J/\psi(p_3)\omega(p_4)$ corresponding to Figs. 2(a) and 2(b), which are

$$\begin{aligned}i\mathcal{M}_a &= i^3\int\frac{d^4q}{2\pi^4}[g_X\tilde{\Phi}_X(-p_{12}^2,\Lambda^2)g^{\phi\tau}][g_{D^*D\psi}\epsilon_{\mu\nu\alpha\beta}(ip_3)^\mu(iq+ip_1)^\beta\epsilon_\theta(p_3)g^{\nu\theta}g^{\alpha\zeta}]\\ &\quad\times[-2f\epsilon_{\sigma\omega\delta\lambda}(ip_4)^\sigma\epsilon_\rho(p_4)(-ip_2+q)^\delta g^{\omega\rho}g^{\lambda\iota}]\frac{-g^{\phi x}+p_1^\phi p_1^x/m_1^2}{p_1^2-m_1^2}\frac{-g^{\tau a}+p_2^\tau p_2^a/m_2^2}{p_2^2-m_2^2}\frac{1}{q^2-m_q^2},\\ i\mathcal{M}_b &= i^3\int\frac{d^4q}{2\pi^4}[g_X\tilde{\Phi}_X(-p_{12}^2,\Lambda^2)g^{\phi\tau}][ig_{D^*D^*\psi}g^{\mu\theta}(g^{\mu\sigma}g^{\nu\iota}(-ip_1-iq)^\nu + g^{\nu\zeta}g^{\mu\iota}(-ip_1-iq)^\nu\\ &\quad - g^{\nu\zeta}g^{\nu\iota}(-ip_1-iq)^\mu)\epsilon_\theta(p_3)][ig_{D^*D^*V}(-ip_2+q)^\rho g^{\omega\iota}g^{\omega\kappa}\epsilon_\rho(p_4) + 4if_{D^*D^*V}\\ &\quad\times(ip_4^\sigma g^{\omega\rho} - ip_4^\omega g^{\sigma\rho})g^{\sigma o}g^{\omega\iota}\epsilon_\rho(p_4)]\frac{-g^{\phi x}+p_1^\phi p_1^x/m_1^2}{p_1^2-m_1^2}\frac{-g^{\tau a}+p_2^\tau p_2^a/m_2^2}{p_2^2-m_2^2}\frac{-g^{yb}+q^y q^b/m_q^2}{q^2-m_q^2},\end{aligned} \tag{11}$$

where $p_{12} = (p_1 - p_2)/2$. $\epsilon(p_3)$ and $\epsilon(p_4)$ are the polarization vectors of J/ψ and ω mesons, respectively.

As for the decay process $X(4014) \to \eta_c\eta$, the amplitudes corresponding to Figs. 2(c) and 2(d) are

$$\begin{aligned} i\mathcal{M}_c &= i^3 \int \frac{d^4q}{2\pi^4} [g_X \tilde{\Phi}_X(-p_{12}^2, \Lambda^2) g^{\phi\tau}][-ig_{D^*D\eta_c}(ip_1 - q)^\mu g^{\mu\alpha}] \\ &\quad \times [-ig_{D^*D}p(ip_4)^\sigma g^{\sigma\iota}] \frac{-g^{\phi x} + p_1^\phi p_1^x/m_1^2}{p_1^2 - m_1^2} \frac{-g^{\tau a} + p_2^\tau p_2^a/m_2^2}{p_2^2 - m_2^2} \frac{1}{q^2 - m_q^2}, \\ i\mathcal{M}_d &= i^3 \int \frac{d^4q}{2\pi^4} [g_X \tilde{\Phi}_X(-p_{12}^2, \Lambda^2) g^{\phi\tau}][-g_{D^*D^*\eta_c} \epsilon_{\mu\nu\alpha\beta}(ip_3)^\mu (-ip_1 - q)^\alpha] \\ &\quad \times \left[\frac{1}{2} g_{D^*D^*V} \epsilon_{\sigma\omega\delta\lambda}(ip_4)^\omega (-iq + ip_2)^\delta g^{\lambda\kappa} g^{\sigma\kappa}\right] \frac{-g^{\phi x} + p_1^\phi p_1^x/m_1^2}{p_1^2 - m_1^2} \frac{-g^{\tau a} + p_2^\tau p_2^a/m_2^2}{p_2^2 - m_2^2} \frac{-g^{yb} + q^y q^b/m_q^2}{q^2 - m_q^2}. \end{aligned} \tag{12}$$

The amplitudes of the decay progress $X(4014) \to \eta_c\eta'$ can be obtained by replacing the mass and relevant coupling constants of the η meson with those of η', i.e.,

$$\mathcal{M}_e = \mathcal{M}_c|_{\eta\to\eta'}, \quad \mathcal{M}_f = \mathcal{M}_d|_{\eta\to\eta'}. \tag{13}$$

The total amplitudes of $X(4014) \to J/\psi\omega, \eta_c\eta, \eta_c\eta'$ are

$$\begin{aligned} \mathcal{M}_{X\to J/\psi\omega} &= \mathcal{M}_a + \mathcal{M}_b, \\ \mathcal{M}_{X\to J/\psi\eta} &= \mathcal{M}_c + \mathcal{M}_d, \\ \mathcal{M}_{X\to J/\psi\eta_c} &= \mathcal{M}_e + \mathcal{M}_f, \end{aligned} \tag{14}$$

respectively.

With the total amplitudes defined in Eq. (14), one can estimate the partial width of the above three decay processes by

$$\Gamma_{X\to\ldots} = \frac{1}{8\pi} \frac{|\vec{p}|}{m_X^2} |\overline{\mathcal{M}_{X\to\ldots}}|^2, \tag{15}$$

where the overline above indicates the sum over the spin of the final states, and $|\vec{p}| = \sqrt{(m_X^2 - (m_3 + m_4)^2)(m_X^2 - (m_3 - m_4)^2)}/(2m_X)$ is the momentum of the daughter particles in the mother particle rest frame.

IV. NUMERICAL RESULTS AND DISCUSSIONS

Before we discuss the hidden charm decay widths of $X(4014)$, we have to clarify the values of the relevant coupling constants. In the heavy quark effective theory, the coupling constants between S-wave charmonia and the charmed meson pair can be related to a gauge coupling g_1 by [53–55]

$$\begin{aligned} g_{\psi D^*D} &= 2g_1\sqrt{m_{D^*}m_D/m_\psi}, \\ g_{\psi D^*D^*} &= 2g_1\sqrt{m_\psi}m_{D^*}, \\ g_{\eta_c D^*D} &= 2g_1\sqrt{m_D m_{D^*} m_{\eta_c}}, \\ g_{\eta_c D^*D^*} &= 2g_1 m_{D^*}/\sqrt{m_{\eta_c}}, \end{aligned} \tag{16}$$

where $g_1 = \sqrt{m_\psi}/(2m_D f_\psi)$ and $f_\psi = 426$ MeV is the decay constant of the J/ψ meson [55]. Considering the heavy quark limit and chiral symmetry, the coupling constants between the light meson and charmed meson pair have the following relationship [61–64]:

$$\begin{aligned} g_{DD\mathcal{V}} &= g_{D^*D^*\mathcal{V}} = \frac{\beta g_V}{\sqrt{2}}, \\ f_{D^*D\mathcal{V}} &= \frac{f_{D^*D^*\mathcal{V}}}{m_{D^*}} = \frac{\lambda g_V}{\sqrt{2}}, \\ g_{D^*D\mathcal{P}} &= \frac{2g}{f_\pi}\sqrt{m_D m_{D^*}}, \\ g_{D^*D^*\mathcal{P}} &= \frac{g_{D^*D\mathcal{P}}}{\sqrt{m_D m_{D^*}}}, \end{aligned} \tag{17}$$

where the parameter $g_V = m_\rho/f_\pi$ with $f_\pi = 132$ MeV being the pion decay constant and $\beta = 0.9$ [53]. By matching the form factor obtained from the light cone sum rule with that calculated from lattice QCD, one obtained the parameters $\lambda = 0.56\ \mathrm{GeV}^{-1}$ and $g = 0.59$ [63].

As for the coupling constants g_X, it can be estimated by the compositeness condition as given in Eq. (5). In the present work, a model parameter Λ is introduced in the correlation function. Empirically, Λ should be of the order of 1 GeV [4,5,65,66]. It should be clarified that the parameter Λ cannot be determined by the first principle. Its value, in an alternative way, is usually fixed by comparing the theoretical estimations with the corresponding experimental measurements. Unfortunately, the present experimental data for $X(4014)$ is not abundant to determine the accurate value of Λ. Thus in the present work, we vary

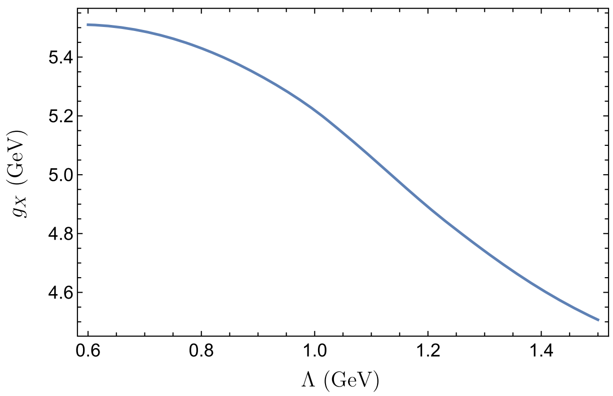

FIG. 3. The coupling constant g_X depending on model parameter Λ.

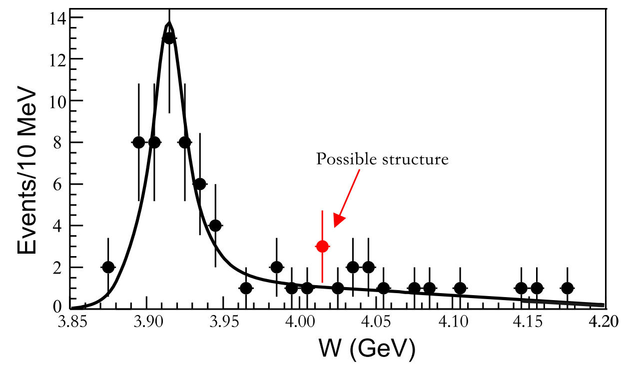

FIG. 5. The measured cross sections (points with error) and fit result (solid curve) for $\gamma\gamma \to J/\psi\omega$ reported by the Belle Collaboration [67].

Λ in a sizable range around 1 GeV, which is from 0.6 to 1.5 GeV. The coupling constant g_X, depending on model parameter Λ, is present in Fig. 3. From the figure one can find that the coupling constant g_X decreases with the increasing of Λ. In particular, when Λ increases from 0.6 to 1.5 GeV, the coupling constants g_X decrease from 5.51 to 4.50 GeV.

The estimated partial widths of the $X(4014) \to J/\psi\omega$, $\eta_c\eta$ and $\eta_c\eta'$ are presented in Fig. 4. Our estimations indicate that the partial widths of all these hidden charm decay processes increase with the increasing of Λ. Particularly, in the considered parameter range, the partial widths of the hidden charm decays are

$$\begin{aligned} \Gamma(X \to J/\psi\omega) &= (0.41\text{–}5.00)\ \text{MeV}, \\ \Gamma(X \to \eta_c\eta) &= (2.05\text{–}7.49)\ \text{MeV}, \\ \Gamma(X \to \eta_c\eta') &= (0.11\text{–}0.51)\ \text{MeV}, \end{aligned} \tag{18}$$

respectively. As for $X(4014)$, the measured upper limit of the width is about 16.5 MeV. Our estimations in the present work indicate that the total widths of these three channels can reach up to 13 MeV, which is still safely below the upper limit of the width of $X(4014)$. Moreover, the Λ dependence of the partial widths are very similar; thus, one can check the ratios of these widths. Here we define the ratios as $R_{12} = \Gamma_{X\to J/\psi\omega}/\Gamma_{X\to\eta_c\eta}$, $R_{31} = \Gamma_{X\to\eta_c\eta'}/\Gamma_{X\to J/\psi\omega}$ and $R_{32} = \Gamma_{X\to\eta_c\eta'}/\Gamma_{X\to\eta_c\eta}$. In the right panel of Fig. 4, we present the Λ dependence of these ratios. Our estimations indicate that in the considered Λ range, one has $0.20 < R_{12} < 0.67$, $0.10 < R_{31} < 0.27$, and $0.05 < R_{32} < 0.07$, respectively.

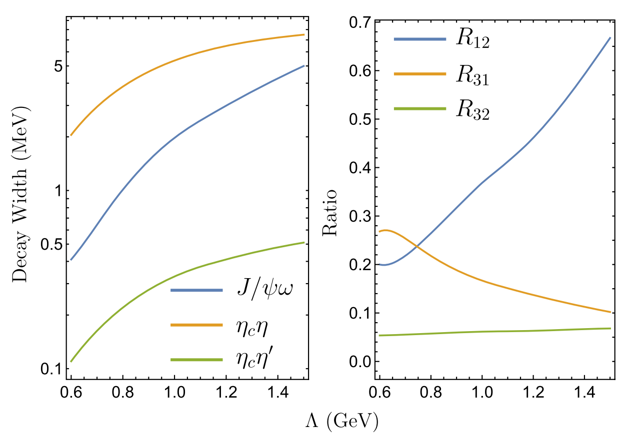

FIG. 4. The Λ dependences of the hidden charm decay widths (left panel) and their ratios (right panel).

Considering the fact that the $X(4014)$ is observed in the $\gamma\gamma \to \psi(2S)\gamma$ process, and the present estimations indicate that the width of $X(4014) \to J/\psi\omega$ is sizable, one can expect to observe $X(4014)$ in the $\gamma\gamma \to J/\psi\omega$ process. In the year of 2009, the Belle Collaboration reported the cross sections for $\gamma\gamma \to J/\psi\omega$, where a new charmoniumlike state named $X(3915)$ was observed [67]. From the experimental data as shown in Fig. 5, one can find there are a number of events at $\sqrt{s} = 4.015$ GeV, and it seems that there is structure corresponding to $X(4014)$, which may be checked by further analysis with a larger data sample.

V. SUMMARY

Stimulated by the recent observation of the new structure, named $X(4014)$, in the process $\gamma\gamma \to \gamma\psi(2S)$ by the Belle Collaboration, we evaluate the possibility of interpreting $X(4014)$ as a $D^*\bar{D}^*$ molecular state. In Ref. [45], we find the most possible $I(J^{PC})$ quantum numbers of $X(4014)$ are $0(0^{++})$. In the present work, we further checked such a possibility by investigating the hidden charm decay properties of $X(4014)$ in the $D^*\bar{D}^*$ molecular scenario. Here, three hidden charm channels are considered, which are $J/\psi\omega$, $\eta_c\eta$, and $\eta_c\eta'$, respectively. Our estimations indicates that the partial width of $\eta_c\eta$ is much larger than the other two channels and the one of $\eta_c\eta$ is also sizable in the consider parameter range.

Considering that $X(4014)$ is observed in the $\gamma\gamma$ collision process, and the present estimations indicate the width of $X(4014) \to J/\psi\omega$ is sizable, we suggest to search $X(4014)$ in the $\gamma\gamma \to J/\psi\omega$ process, which should be accessible in Belle II.

ACKNOWLEDGMENTS

This work is supported by the National Natural Science Foundation of China (NSFC) under the Grants No. 11775050, No. 12175037, and No. 11475192, the NSFC and the Deutsche Forschungsgemeinschaft (DFG) through the funds provided to the Sino-German Collaborative Research Center TRR110 "Symmetries and the Emergence of Structure in QCD" project by NSFC under the Grant No. 12070131001, the Key Research Program of Frontier Sciences, Chinese Academy of Sciences, under the Grant No. Y7292610K1, and the National Key Research and Development Program of China under Contracts No. 2020YFA0406300. Supports from Institute of High Energy Physics (IHEP) Innovation Fund under the Grant No. Y4545190Y2 is also appreciated.

[1] S. Weinberg, Phys. Rev. **137**, B672 (1965).
[2] C. J. Xiao, D. Y. Chen, and Y. L. Ma, Phys. Rev. D **93**, 094011 (2016).
[3] Y. Dong, A. Faessler, and V. E. Lyubovitskij, Prog. Part. Nucl. Phys. **94**, 282 (2017).
[4] A. Faessler, T. Gutsche, V. E. Lyubovitskij, and Y. L. Ma, Phys. Rev. D **76**, 014005 (2007).
[5] A. Faessler, T. Gutsche, V. E. Lyubovitskij, and Y. L. Ma, Phys. Rev. D **76**, 114008 (2007).
[6] Z. G. Wang, Int. J. Mod. Phys. A **36**, 2150107 (2021).
[7] R. F. Lebed and S. R. Martinez, arXiv:2207.01101.
[8] S. K. Choi *et al.* (Belle Collaboration), Phys. Rev. Lett. **91**, 262001 (2003).
[9] Y. R. Liu, X. Liu, W. Z. Deng, and S. L. Zhu, Eur. Phys. J. C **56**, 63 (2008).
[10] Q. Wu, D. Y. Chen, and T. Matsuki, Eur. Phys. J. C **81**, 193 (2021).
[11] M. B. Voloshin and L. B. Okun, JETP Lett. **23**, 333 (1976), http://jetpletters.ru/ps/1801/article_27526.shtml.
[12] A. De Rujula, H. Georgi, and S. L. Glashow, Phys. Rev. Lett. **38**, 317 (1977).
[13] N. A. Tornqvist, Z. Phys. C **61**, 525 (1994).
[14] N. A. Tornqvist, Phys. Lett. B **590**, 209 (2004).
[15] Q. Wu, D. Y. Chen, X. J. Fan, and G. Li, Eur. Phys. J. C **79**, 265 (2019).
[16] Y. Dong, A. Faessler, T. Gutsche, and V. E. Lyubovitskij, Phys. Rev. D **88**, 014030 (2013).
[17] X. Liu, Z. G. Luo, Y. R. Liu, and S. L. Zhu, Eur. Phys. J. C **61**, 411 (2009).
[18] Z. F. Sun, Z. G. Luo, J. He, X. Liu, and S. L. Zhu, Chin. Phys. C **36**, 194 (2012).
[19] N. Li, Z. F. Sun, X. Liu, and S. L. Zhu, Phys. Rev. D **88**, 114008 (2013).
[20] H. Xu, B. Wang, Z. W. Liu, and X. Liu, Phys. Rev. D **99**, 014027 (2019); **104**, 119903(E) (2021).
[21] M. Z. Liu, T. W. Wu, M. Pavon Valderrama, J. J. Xie, and L. S. Geng, Phys. Rev. D **99**, 094018 (2019).
[22] Z. M. Ding, H. Y. Jiang, and J. He, Eur. Phys. J. C **80**, 1179 (2020).
[23] N. Li, Z. F. Sun, X. Liu, and S. L. Zhu, Chin. Phys. Lett. **38**, 092001 (2021).
[24] R. Chen, Q. Huang, X. Liu, and S. L. Zhu, Phys. Rev. D **104**, 114042 (2021).
[25] S. S. Agaev, K. Azizi, and H. Sundu, Nucl. Phys. **B975**, 115650 (2022).
[26] H. Ren, F. Wu, and R. Zhu, Adv. High Energy Phys. **2022**, 9103031 (2022).
[27] M. Albaladejo, Phys. Lett. B **829**, 137052 (2022).
[28] X. K. Dong, F. K. Guo, and B. S. Zou, Commun. Theor. Phys. **73**, 125201 (2021).
[29] V. Baru, X. K. Dong, M. L. Du, A. Filin, F. K. Guo, C. Hanhart, A. Nefediev, J. Nieves, and Q. Wang, Phys. Lett. B **833**, 137290 (2022).
[30] M. L. Du, V. Baru, X. K. Dong, A. Filin, F. K. Guo, C. Hanhart, A. Nefediev, J. Nieves, and Q. Wang, Phys. Rev. D **105**, 014024 (2022).
[31] M. Ablikim *et al.* (BESIII Collaboration), Phys. Rev. Lett. **110**, 252001 (2013).
[32] Z. Q. Liu *et al.* (Belle Collaboration), Phys. Rev. Lett. **110**, 252002 (2013); **111**, 019901(E) (2013).
[33] T. Xiao, S. Dobbs, A. Tomaradze, and K. K. Seth, Phys. Lett. B **727**, 366 (2013).
[34] R. Aaij *et al.* (LHCb Collaboration), Nat. Commun. **13**, 3351 (2022).
[35] R. Aaij *et al.* (LHCb Collaboration), Nat. Phys. **18**, 751 (2022).
[36] J. He, X. Liu, Z. F. Sun, and S. L. Zhu, Eur. Phys. J. C **73**, 2635 (2013).
[37] W. Chen, T. G. Steele, M. L. Du, and S. L. Zhu, Eur. Phys. J. C **74**, 2773 (2014).
[38] M. Ablikim *et al.* (BESIII Collaboration), Phys. Rev. Lett. **111**, 242001 (2013).
[39] Z. G. Wang, arXiv:2207.00947.
[40] S. Sakai, arXiv:2107.11026.
[41] P. G. Ortega, J. Segovia, D. R. Entem, and F. Fernández, Eur. Phys. J. C **79**, 78 (2019).
[42] L. Y. Xiao, G. J. Wang, and S. L. Zhu, Phys. Rev. D **101**, 054001 (2020).
[43] H. W. Ke and X. Q. Li, Eur. Phys. J. C **76**, 334 (2016).
[44] X. L. Wang *et al.* (Belle Collaboration), Phys. Rev. D **105**, 112011 (2022).
[45] M. Y. Duan, D. Y. Chen, and E. Wang, arXiv:2207.03930.

[46] W. Liu, C. M. Ko, and L. W. Chen, Nucl. Phys. **A765**, 401 (2006).
[47] Q. Wu and D. Y. Chen, Phys. Rev. D **104**, 074011 (2021).
[48] Q. Wu, D. Y. Chen, W. H. Qin, and G. Li, Eur. Phys. J. C **82**, 520 (2022).
[49] D. Y. Chen and C. J. Xiao, Nucl. Phys. **A947**, 26 (2016).
[50] K. Hayashi, M. Hirayama, T. Muta, N. Seto, and T. Shirafuji, Fortschr. Phys. **15**, 625 (1967).
[51] S. Weinberg, Phys. Rev. **130**, 776 (1963).
[52] A. Salam, Nuovo Cimento **25**, 224 (1962).
[53] R. Casalbuoni, A. Deandrea, N. Di Bartolomeo, R. Gatto, F. Feruglio, and G. Nardulli, Phys. Rep. **281**, 145 (1997).
[54] Y. s. Oh, T. Song, and S. H. Lee, Phys. Rev. C **63**, 034901 (2001).
[55] P. Colangelo, F. De Fazio, and T. N. Pham, Phys. Lett. B **542**, 71 (2002).
[56] M. Neubert, arXiv:hep-ph/0512222.
[57] D. B. Kaplan, arXiv:nucl-th/0510023.
[58] O. Kaymakcalan, S. Rajeev, and J. Schechter, Phys. Rev. D **30**, 594 (1984).
[59] D. Coffman *et al.* (MARK-III Collaboration), Phys. Rev. D **38**, 2695 (1988); **40**, 3788(E) (1989).
[60] J. Jousset *et al.* (DM2 Collaboration), Phys. Rev. D **41**, 1389 (1990).
[61] R. Chen, Z. F. Sun, X. Liu, and S. L. Zhu, Phys. Rev. D **100**, 011502 (2019).
[62] Y. R. Liu and M. Oka, Phys. Rev. D **85**, 014015 (2012).
[63] C. Isola, M. Ladisa, G. Nardulli, and P. Santorelli, Phys. Rev. D **68**, 114001 (2003).
[64] A. F. Falk and M. E. Luke, Phys. Lett. B **292**, 119 (1992).
[65] D. Y. Chen and Y. B. Dong, Phys. Rev. D **93**, 014003 (2016).
[66] C. J. Xiao, D. Y. Chen, Y. B. Dong, and G. W. Meng, Phys. Rev. D **103**, 034004 (2021).
[67] S. Uehara *et al.* (Belle Collaboration), Phys. Rev. Lett. **104**, 092001 (2010).