Rapid Communications

$Z_{cs}(3985)^-$ as the U-spin partner of $Z_c(3900)^-$ and implication of other states in the $\mathrm{SU}(3)_F$ symmetry and heavy quark symmetry

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(Received 18 November 2020; accepted 2 December 2020; published 17 December 2020)

Recently, for the first time, the BESIII Collaboration reported the strange hidden charm tetraquark states $Z_{cs}(3985)^-$ in the K^+ recoil-mass spectrum near the $D_s^- D^{*0}/D_s^{*-} D^0$ mass thresholds in the processes of $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$ at $\sqrt{s} = 4.681$ GeV (M. Ablikim *et al.*, arXiv:2011.07855). The significance was estimated to be 5.3σ. We show that the newly observed $Z_{cs}(3985)^-$ state is the U-spin partner of $Z_c(3900)^-$ as a resonance within coupled-channel calculation in the $\mathrm{SU}(3)_F$ symmetry and heavy quark spin symmetry (HQSS). In the $\mathrm{SU}(3)_F$ symmetry, we introduce the $G_{U/V}$ parity to construct the flavor wave functions of the Z_{cs} states. In a unified framework, we consider the $J/\psi\pi(K)$, $\bar{D}_{(s)}D^*/\bar{D}^*_{(s)}D$ coupled-channel effect with the contact interaction. With the masses and widths of $Z_c(3900)$ and $Z_c(4020)$, we determine all the unknown coupling constants. We obtain mass and width of $Z_{cs}(3985)$ in good agreement with the experimental results, which strongly support the Z_{cs} states as the U/V-spin partner states of the charged $Z_c(3900)$. We also calculate the ratio of the partial decay widths of $Z_{cs}(3985)$, which implies that the $\bar{D}_s D^*/\bar{D}_s^* D$ decay modes are dominant. We also predict the Z'_{cs} states with a mass around 4130 MeV and width around 30 MeV, which are the U/V-spin partner states of the charged $Z_c(4020)$ and HQSS partner states of the $Z_{cs}(3985)$. In the hidden bottom sector, we predict the strange tetraquark states Z_{bs} and Z'_{bs} with a mass around 10700 and 10750 MeV, which are the U/V-spin partner states of $Z_b(10610)^\pm$ and $Z_b(10650)^\pm$, respectively.

DOI: 10.1103/PhysRevD.102.111502

I. INTRODUCTION

Very recently, the BESIII Collaboration reported a novel structure $Z_{cs}(3985)^-$ in the K^+ recoil-mass spectrum near the $D_s^- D^{*0}/D_s^{*-} D^0$ mass thresholds in the processes of $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$ at $\sqrt{s} = 4.681$ GeV [1]. The pole mass and width were determined with a mass-dependent-width Breit-Wigner line shape,

$$M^{\text{pole}}_{Z_{cs}} = (3982.5^{+1.8}_{-2.6} \pm 2.1)\ \text{MeV},$$
$$\Gamma^{\text{pole}}_{Z_{cs}} = (12.8^{+5.3}_{-4.4} \pm 3.0)\ \text{MeV}, \tag{1}$$

where the first and the second uncertainties are statistical and systematic, respectively. The significance of the resonance hypothesis is estimated to be 5.3σ over the pure contributions from the conventional charmed mesons.

The minimum quark constituents of $Z_{cs}(3985)$ are $(c\bar{c}s\bar{n})$, where n represents the u/d quark. While the number of exotic states is rapidly growing (see Refs. [2–7] for recent reviews), $Z_{cs}(3985)$ is still a very unusual state by current standards. Most XYZ states are isospin singlet, in which the numbers of constituent quark are not fixed. The unquenched quark dynamics [8,9] would mix the two quark components with four quark components. However, the charged Z_c/Z_b states [10–12], the P_c states [13,14], and the newly observed $Z_{cs}(3985)$ are multiquark states without much doubt. In addition, $Z_{cs}(3985)$ might be the rare hidden charm exotic candidate with strange number. Another candidate is the P_{cs} states reported recently by LHCb Collaboration [15].

The $Z_c(3900)$ and $Z_c(4020)$ states are above the threshold of $\bar{D}^*D/\bar{D}D^*$ and $\bar{D}^*D^*$ by several MeV, respectively. $Z_c(4020)$ states are likely the heavy quark spin symmetry (HQSS) partners of the $Z_c(3900)$ states. The theoretical interpretations of $Z_c(3900)$ and $Z_c(4020)$ range from the threshold effect [16], to compact tetraquark states [17,18], to hadronic molecules [19,20]. The threshold effect picture

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of Z_c states was challenged by Guo *et al.* [21] and JPAC Collaboration [22]. In the tetraquark scheme, it is hard to understand their proximity to the dimeson thresholds. In molecular scenarios, the one-pion-exchange interaction for $I = 1$ $\bar{D}^{(*)}D^{(*)}$ systems is mainly repulsive. Therefore, theorists resorted to the coupled-channel calculation to interpret Z_c states as the molecular-type resonances, virtual states, or bound states [23–35].

In the history, the successful prediction of Ω^- taught us the importance of $\mathrm{SU}(3)_F$ symmetry [36] in hadron spectroscopy. In the exotic hadron sector, within a dominant short-range interaction from $\mathrm{SU}(3)_F$ symmetry, we predicted the strange hidden charm pentaquark state as the $\Xi_c\bar{D}^*$ bound state with a mass of 4456.9 MeV [37]. Recently, our prediction was supported by the observation of $P_{cs}(4459)^0$ by LHCb Collaboration [15]. The hidden charm and bottom tetra- and pentaquarks with strangeness were also investigated in Ref. [38]. The $Z_c(3900)$ and $Z_{cs}(3985)$ states are in the proximity of the threshold of $\bar{D}D^*/\bar{D}^*D$ and $\bar{D}_sD^*/\bar{D}_s^*D$, respectively. It is natural to conjecture that they belong to the same $\mathrm{SU}(3)_F$ multiplet. Therefore, it is crucial to investigate $Z_c(3900)/Z_c(4020)$ and the newly observed $Z_{cs}(3985)$ state in a unified framework with $\mathrm{SU}(3)_F$ symmetry and HQSS. In this paper, we first make use of the HQSS to interpret the $Z_c(3900)$ and $Z_c(4020)$ as resonances in the $J/\psi\pi$, $\bar{D}D^*/\bar{D}^*D$, and $\bar{D}^*D^*$ coupled-channel calculation. Then, within the $\mathrm{SU}(3)_F$ symmetry, we extend the calculation to the strange channels without unknown parameters. We aim to obtain the mass and width of Z_{cs} state and its HQSS partner state. Meanwhile, the Z_{cs} was first observed in the $\bar{D}_sD^*/\bar{D}^*D_s$ channel rather than in the hidden channels like $J/\psi K$. Another question addressed in this paper is to determine the dominant decay channels of $Z_{cs}(3985)$ and its possible HQSS partners.

II. U/V-SPIN PARTNERS OF $Z_c(3900)^\pm$ AND $Z_c(4020)^\pm$

The quantum numbers of $Z_c(3900)$ are $I^G(J^{PC}) = 1^+(1^{+-})$ (C parity only for the neutral states here and below) [39]. For the S-wave $\bar{D}^*D/\bar{D}D^*$ channel, we could construct two orthogonal basis vectors,

$$\frac{1}{\sqrt{2}}(|\bar{D}D^*\rangle + \eta|\bar{D}^*D\rangle), \tag{2}$$

where $J^{PC} = 1^{+\pm}$ for $\eta = \mp 1$. We omit the isospin information in Eq. (2). For the $I = 1$ channels, the G parity (eigenvalue of $\hat{G} = \hat{C}e^{i\hat{I}_2\pi}$) is η. Thus, the $Z_c(3900)$ states correspond to the isovector channel with $\eta = +1$ in Eq. (2). The quantum numbers of $Z_c(4020)$ are $I^G(J^{PC}) = 1^+(?^{?-})$ [39]. As the HQSS partner states of the $Z_c(3900)$, $Z_c(4020)$ states will couple with the S-wave $\bar{D}^*D^*$ isovector channel, which implies that it is possible J^P could be

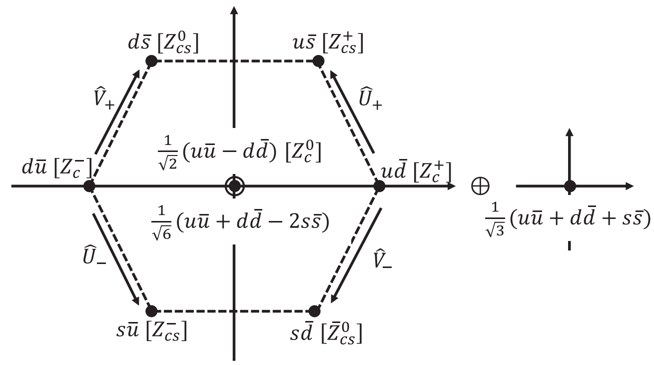

FIG. 1. The multiplet structure of the $\bar{D}_{(s)}^{(*)}D_{(s)}^{(*)}$ dimeson systems in the $\mathrm{SU}(3)_F$ symmetry. We omit the heavy quarks in flavor wave functions for conciseness.

$0^+, 1^+, 2^+$. We will assume the J^P of $Z_c(4020)$ is 1^+ and the reason will be given later.

We assume the $Z_{cs}(3985)$ state is the strange partner of $Z_c(3900)$ in the $\mathrm{SU}(3)_F$ symmetry. To be specific, the Z_{cs} states are related to the Z_c states with the rotation in U/V-spin space as shown in Fig. 1,

$$Z_c^- \overset{U}{\leftrightarrow} Z_{cs}^-, \qquad Z_c^+ \overset{V}{\leftrightarrow} \bar{Z}_{cs}^0. \tag{3}$$

U spin and V spin are the SU(2) subgroups of the SU(3) group just like the isospin subgroup. The SU(2) doublets for these subgroups are

$$u, d(I); \qquad d, s(U); \qquad u, s(V). \tag{4}$$

The thresholds of $D_s^-D^{*0}$ (3975 MeV) and $D_s^{*-}D^0$ (3977 MeV) are very close. In the heavy quark limit, $\bar{D}_sD^*$ and $\bar{D}_s^*D$ are degenerate. We construct the basis of the dimeson channel $\bar{D}_sD^*/\bar{D}_s^*D$ like Eq. (2),

$$|G_V = \eta\rangle = \frac{1}{\sqrt{2}}(|D_s^-D^{*0}\rangle + \eta|D_s^{*-}D^0\rangle),$$
$$|G_U = \eta\rangle = \frac{1}{\sqrt{2}}(|D_s^-D^{*+}\rangle + \eta|D_s^{*-}D^+\rangle), \tag{5}$$

where $\hat{G}_U$ and $\hat{G}_V$ transformations are defined like $\hat{G}$,

$$\hat{G}_U = \hat{C}e^{i\hat{U}_2\pi}, \qquad \hat{G}_V = \hat{C}e^{i\hat{V}_2\pi}. \tag{6}$$

The dimeson channels with $\eta = +1$ correspond to Z_{cs}^- and $\bar{Z}_{cs}^0$ with $G_{U/V} = +1$. Similarly, we construct the $\bar{D}_s^*D^*$ dimeson channels with $J^P = 1^+$ and $G_{U/V} = +1$, which are the HQSS partner channels of Eq. (5) with $\eta = +1$. These channels correspond to the HQSS partner states of Z_{cs} and U/V-spin partner states of $Z_c(4020)$, which are named as Z'_{cs} here and below.

The dynamics of the $\bar{D}_{(s)}^{(*)}D_{(s)}^{(*)}$ dimeson systems are constrained by both $\mathrm{SU}(3)_F$ symmetry and HQSS. In the heavy quark limit, the c and $\bar{c}$ are the spectators in the dimeson systems. For the S-wave channel, $\mathbb{I}_s$ and $\boldsymbol{l}_1 \cdot \boldsymbol{l}_2$ are the only interaction operators in spin space, where $\mathbb{I}_s$ is the unit operator in spin space and $\boldsymbol{l}_i$ is the light spin operator of the heavy meson. In the $\mathrm{SU}(3)_F$ symmetry, the interaction operators in flavor space between light degrees of freedom are $\mathbb{I}_F$ and $\mathbb{C}_2$, where $\mathbb{I}_F$ is the unit operator and $\mathbb{C}_2 = -\sum_{i=1}^{8} \lambda_F^i \lambda_F^{*i}$ is the Casimir operator. Therefore, the general interaction for $\bar{D}_{(s)}^{(*)} D_{(s)}^{(*)}$ could be parametrized as

$$V_{q\bar{q}} = c_1 + c_2 \boldsymbol{l}_1 \cdot \boldsymbol{l}_2 + c_3 \mathbb{C}_2 + c_4 (\boldsymbol{l}_1 \cdot \boldsymbol{l}_2) \mathbb{C}_2. \tag{7}$$

In the $\mathrm{SU}(3)_F$ symmetry, the $\bar{D}_{(s)}^{(*)} D_{(s)}^{(*)}$ systems could be classified by $3_F \otimes \bar{3}_F \to 8_F \oplus 1_F$ as shown in Fig. 1. The matrix elements of the Casimir operator $\mathbb{C}_2$ read

$$\langle \mathbb{C}_2 \rangle_{8_F} = \frac{2}{3}, \qquad \langle \mathbb{C}_2 \rangle_{1_F} = -\frac{16}{3}. \tag{8}$$

Thus, in the $\mathrm{SU}(3)_F$ symmetry, the $\bar{D}^{(*)} D^{(*)}$ interactions for the $Z_c(3900)$ and $Z_c(4020)$ are the same as those of $\bar{D}_s^{(*)} D^{(*)}$ concerned with the Z_{cs} states.

In the spin space, we write the spin wave function of $\bar{D}_{(s)}^{(*)} D_{(s)}^{(*)}$ as $|l_1 h_1 (j_1) l_2 h_2 (j_2) JM\rangle$, where l_i, h_i, and j_i are the light spin, heavy spin, and total spin of the heavy meson with label i. J and M are the total spin and its third component of the dimeson system. One can use the $9j$ symbols to relate the above spin wave function to state $|l_1 l_2 (L) h_1 h_2 (H) JM\rangle$, where L and H are the total light spin and total heavy spin, respectively. The matrix elements of $\boldsymbol{l}_1 \cdot \boldsymbol{l}_2$ can be calculated,

$$\langle \boldsymbol{l}_1 \cdot \boldsymbol{l}_2 \rangle^{0^+}_{\{\mathtt{PP},\mathtt{VV}\}} = \begin{bmatrix} 0 & \frac{\sqrt{3}}{4} \\ \frac{\sqrt{3}}{4} & -\frac{1}{2} \end{bmatrix}, \tag{9}$$

$$\langle \boldsymbol{l}_1 \cdot \boldsymbol{l}_2 \rangle^{1^+}_{\{\mathtt{PV}\eta=+1,\mathtt{VV}\}} = \begin{bmatrix} -\frac{1}{4} & -\frac{1}{2} \\ -\frac{1}{2} & -\frac{1}{4} \end{bmatrix}, \tag{10}$$

$$\langle \boldsymbol{l}_1 \cdot \boldsymbol{l}_2 \rangle^{1^+}_{\{\mathtt{PV}\eta=-1\}} = \frac{1}{4}, \qquad \langle \boldsymbol{l}_1 \cdot \boldsymbol{l}_2 \rangle^{2^+}_{\{\mathtt{VV}\}} = \frac{1}{4}, \tag{11}$$

where $\mathtt{P}$ and $\mathtt{V}$ denote the pseudoscalar and vector heavy mesons, respectively. We use the superscript to denote the J^P of the dimeson channel. For the $\mathtt{PV}$ channels, we write the η of Eqs. (2) and (5) explicitly. Equations (9)–(11) are the results in the heavy quark limit. We can see that among the $\mathtt{VV}$ channels, the $J^P = 1^+$ channel has the same matrix elements with the $\mathtt{PV}\eta = +1$ channel, which couples with the $Z_c(3900)$. Thus, it is reasonable to assume the $J^P = 1^+$ for $Z_c(4020)$. The matrix elements in spin space of channels corresponding to $Z_c(3900)/Z_{cs}(3985)$ and $Z_c(4020)/Z'_{cs}$ are equal.

The dimeson channels corresponding to $Z_c(3900)$, $Z_c(4020)$, $Z_{cs}(3985)$, and Z'_{cs} have the same interaction, which is the result of the $\mathrm{SU}(3)_F$ symmetry and HQSS. We embed these symmetries in Eq. (7). One could adopt other equivalent approaches like the superfield method in Ref. [40].

III. COUPLED-CHANNEL CALCULATION

We list the channels considered in Table I. Apart from the $\bar{D}_{(s)}^{(*)} D_{(s)}^{(*)}$ channels, we also include the $J/\psi\pi$ channel for the $Z_c(3900)/Z_c(4020)$ systems and the $J/\psi K$ channel for the $Z_{cs}(3985)/Z'_{cs}$ systems. The coupled-channel T matrix can be obtained by solving the Lippmann-Schwinger equations (LSEs):

$$T_{ij} = V_{ij} + \sum_k V_{ik} G_k T_{kj}. \tag{12}$$

The loop function G_i reads [41]

$$G_i(E) = \int_0^{\Lambda_i} \frac{l^2 dl}{(2\pi)^2} \frac{w_{i1} + w_{i2}}{w_1 w_2 [E^2 - (w_{i1} + w_{i2})^2 + i\epsilon]}, \tag{13}$$

where $w_{ia} = (\boldsymbol{l}^2 + m_{ia}^2)^{1/2}$ and m_{ia} is the mass of the ath particle in the channel i. We take a hard cutoff Λ_i to regulate the integral. We vary the cutoff parameters $\Lambda_2 = \Lambda_3 =$ 0.5–1.0 GeV but keep the same Λ_2 and Λ_3 to avoid the unintentional HQSS breaking effect. For definiteness, we fix $\Lambda_1 = 1.5$ GeV. For the Z_{cs} and Z_c systems, we choose the same cutoff parameters to keep the $\mathrm{SU}(3)_F$ symmetry.

Following the pionless effective field theory [42,43], we only introduce the contact interaction. For the off-diagonal potential $V_{23} = V_{32}$, we take the leading order contact interaction as a constant v_{23}. For the diagonal potential, we have $V_{22} = V_{33}$ from Eq. (10). In order to obtain the resonances above thresholds, we introduce the next-to-leading-order contact interaction for the elastic potential [31]

$$V_{22} = V_{33} = C_d + \frac{C'_d}{2} (\boldsymbol{p}^2 + \boldsymbol{p}'^2), \tag{14}$$

where $\boldsymbol{p}$ and $\boldsymbol{p}'$ are the initial and final momenta in the center-of-mass system (c.m. system). The general terms at the next-to-leading order are $(\boldsymbol{p} + \boldsymbol{p}')^2$ and $(\boldsymbol{p} - \boldsymbol{p}')^2$, while the $\boldsymbol{p} \cdot \boldsymbol{p}'$ term vanishes after partial wave expansion for the S wave. When the particles are on shell, the magnitude $p_i = |\boldsymbol{p}_i|$ of channel i in the c.m. system is

$$p_i(E) = \frac{\sqrt{[E^2 - (m_{i1} + m_{i2})^2][E^2 - (m_{i1} - m_{i2})^2]}}{2E}. \tag{15}$$

TABLE I. Channels considered in the coupled-channel calculation.

Channel	1	2	3
Z_c/Z'_c	$J/\psi\pi$	$\frac{1}{\sqrt{2}}(\lvert\bar{D}D^*\rangle + \lvert\bar{D}^*D\rangle)$	$\bar{D}^*D^*$
Z_{cs}/Z'_{cs}	$J/\psi K$	$\frac{1}{\sqrt{2}}(\lvert\bar{D}_sD^*\rangle + \lvert\bar{D}_s^*D\rangle)$	$\bar{D}_s^*D^*$

The elastic interaction for $J/\psi\pi$ or $J/\psi K$ is purely gluonic van der Waals force, which is known to be tiny [44–46]. We neglect the diagonal interaction in the first channel, $V_{11} = 0$. The processes $\bar{D}^{(*)}D^{(*)} \to J/\psi\pi$ and $\bar{D}_s^{(*)}D^{(*)} \to J/\psi K$ are related by the U/V-spin transformation. Thus, the V_{1i} for strange systems and nonstrange systems is the same. In the heavy quark limit, channel 2 and channel 3 have the same spatial wave function and flavor wave function; thus, we focus on the spin wave function. The ratio V_{12}/V_{13} could be estimated by the ratio of spin wave function overlaps,

$$\frac{V_{12}}{V_{13}} = \frac{\langle J/\psi\pi|\mathbb{PP}\eta = +1, 1^+\rangle_{\text{spin}}}{\langle J/\psi\pi|\mathbb{VV}, 1^+\rangle_{\text{spin}}} = 1. \tag{16}$$

With Eq. (16), we can parametrize the V_{12} and V_{13} with one single coupling constant v_{12}.

With the HQSS and $SU(3)_F$ symmetries, the V_{ij} reads

$$V_{ij} = \begin{bmatrix} 0 & v_{12} & v_{12} \\ v_{12} & C_d + \frac{C_d'}{2}(\boldsymbol{p}^2 + \boldsymbol{p}'^2) & v_{23} \\ v_{12} & v_{23} & C_d + \frac{C_d'}{2}(\boldsymbol{p}^2 + \boldsymbol{p}'^2) \end{bmatrix}. \tag{17}$$

We have four unknown coupling constants, v_{12}, v_{23}, C_d, and C_d'. We shall solve the LSEs and fit the masses and widths of $Z_c(3900)$ and $Z_c(4020)$ to determine the four coupling constants. The resonances are located in the unphysical Riemann sheet which is accessed by analytical continuation [41,47]. We replace $G_i(E)$ with

$$G_i^{\text{II}}(E) = G_i^{\text{I}}(E) + i\frac{p_i(E)}{4\pi E}, \tag{18}$$

where G_i^{I} is the loop function in Eq. (13).

Since the widths of these resonances are narrow, $\Gamma \ll M$, we could estimate the partial decay widths with the Breit-Wigner parametrization [41]. The $T_{ij}(E)$ matrix reads

$$T_{ij}(E) = \frac{1}{2M_R}\frac{g_i(E)g_j(E)}{E - M_R + i\frac{\Gamma_R}{2}}, \tag{19}$$

where M_R and Γ_R are the mass and width of the resonance, respectively. g_i is the coupling vertex of the resonance and particles in channel i. The partial decay width Γ_i reads

$$\Gamma_i = \int \frac{1}{2M_R}|\mathcal{M}_{R\to i}|^2 2\pi\delta(M_R - E_{i1} - E_{i2})\frac{d^3\boldsymbol{p}_{i1}}{(2\pi)^3 2E_{i1}2E_{i2}}, \tag{20}$$

where $\mathcal{M}_{R\to i} = g_i$. We make the substitution in the narrow-width approximation,

$$2\pi\delta(M_R - E_{i1} - E_{i2}) \to 2\text{Im}\frac{1}{M_R - E_{i1} - E_{iR} - i\frac{\Gamma_R}{2}}. \tag{21}$$

We change the integral variable to E and the partial wave decay width becomes

$$\Gamma_i = -\frac{1}{16\pi^2}\int_{m_{i1}+m_{i2}}^{\infty} dE\frac{p_{i1}(E)}{E^2}4M_R\text{Im}T_{ii}(E). \tag{22}$$

In practical calculation, we integrate in E around two widths up and down the pole mass (if allowed by the lower limit) to obtain Γ_i, since we find $\sum_i \Gamma_i \approx \Gamma_R$ in this integration range.

IV. NUMERICAL RESULTS AND DISCUSSION

We choose the recent results of the charged $Z_c(3900)$ and $Z_c(4020)$ in Refs. [48,49] as input. We could either choose the averaged results in Ref. [39], which would give the similar final results. We determine the coupling constants in either $\Lambda_{2/3} = 1.0$ or 0.5 GeV and then calculate the masses and widths of Z_{cs} and Z_{cs}'. We present the T_{11} matrix in the unphysical sheet with $\Lambda_{2/3} = 1.0$ GeV in Fig. 2. We can see two poles corresponding to $Z_c(3900)$ and $Z_c(4020)$, which are barely above the thresholds of $\bar{D}D^*$ and $\bar{D}^*D^*$ by several MeV, respectively. The positions of poles are $M - i\Gamma/2$, where M and Γ are the mass and width of the resonances.

We give the numerical results in Table II. One can see that we could reproduce the mass and width of the newly observed $Z_{cs}(3985)$ state with $Z_c(3900)$ and $Z_c(4020)$ as

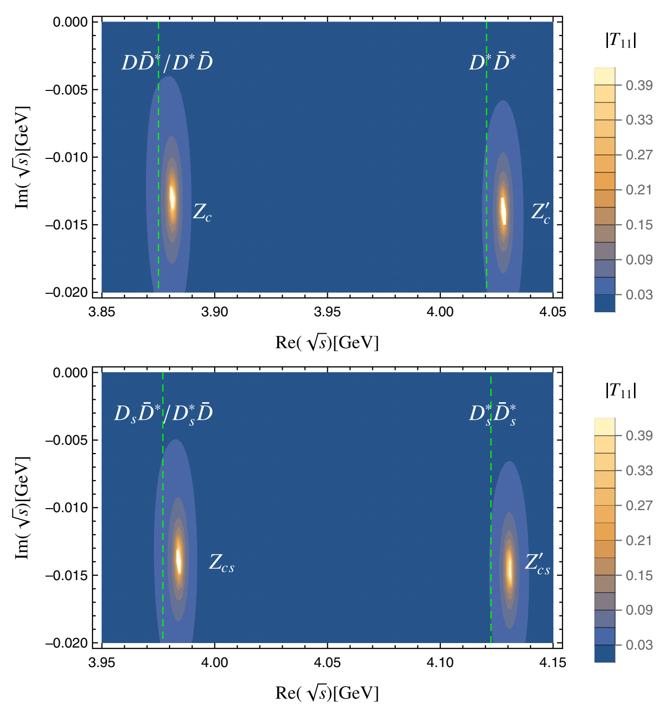

FIG. 2. T_{11} matrix in the unphysical sheet with $\Lambda_{2/3} = 1.0$ GeV and pole positions. The upper plot and the lower plot are for the nonstrange and strange states, respectively. In each plot, the dashed lines represent the thresholds of $\bar{D}_{(s)}D^*/\bar{D}_{(s)}^*D$ and $\bar{D}_{(s)}^*D^*$.

TABLE II. Numerical results for masses, widths, and partial widths. We use "†" to label input. The ratios Γ_3/Γ_2 are estimated with central values of coupling constants. The lower limit of ratios Γ_i/Γ_1 are estimated with upper limits of v_{12}. M and Γ are in units of MeV and Λ_i are in units of GeV.

(M,Γ)	$Z_c(3900)$	$Z_c(4020)$	$Z_{cs}(3985)$	Z'_{cs}
Exp. [1,48,49]	$(3881.7\pm2.3, 26.6\pm2.9)^\dagger$	$(4026.3\pm4.5, 24.8\pm9.5)^\dagger$	$(3982.5^{+1.8}_{-2.6}\pm2.1, 12.8^{+5.3}_{-4.4}\pm3.0)$	
$\Lambda_{2/3}=1.0$	$(3881.3\pm3.3, 26.3\pm6.1)$	$(4028.0\pm2.6, 28.0\pm6.5)$	$(3984.2\pm3.3, 27.6\pm7.3)$	$(4130.7\pm2.5, 29.1\pm6.4)$
	$\frac{\Gamma_2}{\Gamma_1}\gtrsim13.7$	$\frac{\Gamma_3}{\Gamma_2}\approx0.51$, $\frac{\Gamma_3}{\Gamma_1}\gtrsim12.1$	$\frac{\Gamma_2}{\Gamma_1}\gtrsim16.1$	$\frac{\Gamma_3}{\Gamma_2}\approx0.48$, $\frac{\Gamma_3}{\Gamma_1}\gtrsim13.7$
$\Lambda_{2/3}=0.5$	$(3881.5\pm3.5, 26.4\pm5.8)$	$(4027.3\pm3.3, 27.0\pm6.7)$	$(3983.7\pm4.1, 26.7\pm5.8)$	$(4129.4\pm3.3, 27.3\pm9.2)$
	$\frac{\Gamma_2}{\Gamma_1}\gtrsim11.2$	$\frac{\Gamma_3}{\Gamma_2}\approx2.5$, $\frac{\Gamma_3}{\Gamma_1}\gtrsim11.0$	$\frac{\Gamma_2}{\Gamma_1}\gtrsim12.8$	$\frac{\Gamma_3}{\Gamma_2}\approx2.3$, $\frac{\Gamma_3}{\Gamma_1}\gtrsim11.6$

input. Our results are in good agreement with the experimental results, which strongly support that isospin doublet $Z_{cs}(3985)$ states are the U/V-spin partner of the charged $Z_c(3900)$ as resonances. Meanwhile, we predict a new resonance above the threshold of the $\bar{D}_s^*D^*$ by 8 MeV with a width about 30 MeV, which is the HQSS partner of the $Z_{cs}(3985)$ and U/V-spin partner of $Z_c(4020)$.

In this calculation, we use the decay modes $J/\psi\pi(K)$, $\bar{D}_{(s)}D^*/\bar{D}^*_{(s)}D$, $\bar{D}^*_{(s)}D^*$ to saturate the total widths, which would bring some uncertainties. These uncertainties would be compensated in ratios of partial decays widths. The coupling constants v_{12} are very small and thus the resonances are dominated by the $\bar{D}_{(s)}D^*/\bar{D}^*_{(s)}D$ and $\bar{D}^*_{(s)}D^*$ components. With the central value of v_{12}, the partial wave decay widths of Γ_1 are very small; thus, we take the upper limit of v_{12} to give the lower limit of Γ_i/Γ_1. From Table II, we can see that the decay process to $J/\psi\pi(K)$ is suppressed by at least one order compared with the open charmed final state decays. The dominant $\bar{D}_{(s)}D^*/\bar{D}^*_{(s)}D$ decay modes lead to the observation in these channels in experiment [1]. Meanwhile, as shown in Eq. (5), the $Z_{cs}(3985)$ states with $G_{V/U}=1$ have the same components of $\bar{D}_sD^*$ and $\bar{D}_s^*D$, which are constrained by the $\mathrm{SU}(3)_F$ symmetry.

We have assigned seven states $Z_c^{0/\pm}$, $Z_{cs}^{0/+}$, $\bar{Z}_{cs}^{0/-}$ into the SU(3) octet in Fig. 1. The left isospin singlet in 8_F representation might mix with the isospin singlet in 1_F like the ϕ and ω mesons. The $\mathbb{C}_2$ matrix elements read

$$\langle\mathbb{C}_2\rangle_{s\bar{s}}=-\frac{4}{3},\qquad \langle\mathbb{C}_2\rangle_{(u\bar{u}+d\bar{d})/\sqrt{2}}=-\frac{10}{3}.$$

Both matrix elements have different signs from those of the octet in ideal SU(3) symmetry. Therefore, the mixture would make the eighth state disappear. In the compact tetraquark scheme, the existence of the tetraquark states do not depend on the flavor. Searching for the eighth state would help to distinguish the compact tetraquark states from the dimeson states.

We further extend the calculation to the hidden bottom sector with heavy quark flavor symmetry (HQFS). We use the coupling constants determined with $\Lambda_{2/3}=0.5$ GeV and obtain two poles (M,Γ) in the nonstrange channel,

$$(10612.0, 32.2)\ \mathrm{MeV},\qquad (10656.9, 32.3)\ \mathrm{MeV},\qquad (23)$$

which correspond to the $Z_c(10610)$ and $Z_c(10650)$. We also predict two strange hidden bottom states Z_{bs} and Z'_{bs} near the $B_s\bar{B}^*/B_s^*\bar{B}$ and $B_s^*\bar{B}^*$ threshold, respectively,

$$(10699.9, 32.3)\ \mathrm{MeV},\qquad (10747.9, 32.2)\ \mathrm{MeV}.\qquad (24)$$

The resonance Z_{bs} could be searched for in the $B_s\bar{B}^*$, $B_s^*\bar{B}$, and ΥK final states and Z'_{bs} in the $B_s^*\bar{B}^*$, $B_s\bar{B}^*$, $B_s^*\bar{B}$, and ΥK final states.

V. SUMMARY AND OUTLOOK

In summary, we perform the $J/\psi\pi(K)$, $\bar{D}_{(s)}D^*/\bar{D}^*_{(s)}D$, and $\bar{D}^*_{(s)}D^*$ coupled-channel calculations in the contact interaction with the $\mathrm{SU}(3)_F$ symmetry and HQSS. We fit the masses and widths of $Z_c(3900)$ and $Z_c(4020)$ to determine the coupling constants. We reproduce the mass and width of $Z_{cs}(3985)$ very well as the U/V-spin partner of $Z_c(3900)$. We also obtain the ratios of the partial decay widths of $Z_{cs}(3985)$ and obtain its dominant $\bar{D}_sD^*/\bar{D}_s^*D$ decay modes. We introduce the $G_{U/V}$ parity to label Z_{cs} states. In the $\mathrm{SU}(3)_F$ limit, the partial decay widths to $\bar{D}_sD^*$ and $\bar{D}_s^*D$ are equal. We also predict the Z'_{cs} with the mass around 4130 MeV, which are the HQSS partner states of the $Z_{cs}(3985)$ and U/V-spin partner states of the $Z_c(4020)$. With the HQFS, we reproduce the masses and widths of $Z_b(10610)$ and $Z_b(10650)$ and predict their $G_{U/V}$ partner states Z_{bs} and Z'_{bs} with mass around 10700 and 10750 MeV.

ACKNOWLEDGMENTS

We are grateful to Rui Chen for helpful discussions. This project is supported by the National Natural Science Foundation of China under Grants No. 11975033 and No. 12070131001. This project is also funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation), Project ID 196253076-TRR 110.

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