The $Z_{cs}$ states and the mixture of hadronic molecule and diquark-anti-diquark components within effective field theory

Ze-Hua Cao$^1$, Wei He$^{1,2}$, and Zhi-Feng Sun$^{1,2,3,4,*}$

$^1$School of Physical Science and Technology, Lanzhou University, Lanzhou 730000, China
$^2$Research Center for Hadron and CSR Physics, Lanzhou University and Institute of Modern Physics of CAS, Lanzhou 730000, China
$^3$Lanzhou Center for Theoretical Physics, Key Laboratory of Theoretical Physics of Gansu Province, Lanzhou University, Lanzhou, Gansu 730000, China
$^4$Frontiers Science Center for Rare Isotopes, Lanzhou University, Lanzhou, Gansu 730000, China

(Dated: June 28, 2022)

In this work, we construct the Lagrangian describing meson-diquark interaction, such that the diquark-anti-diquark component as well as the molecular component is introduced when studying the $Z_{cs}$ states. In this way, the problem is solved that if only considering the $D^0\bar{D}^{0*}$ components, the potentials are suppressed by OZI rule. Through solving the Bethe-Salpeter equation, we find that the $Z_{cs}(4000)^+$ can be explained as the mixture of $\bar{D}^0D^*_0$ and $A_{cs}S_{cs}$ components. Besides, for the $\bar{D}^0D^{*+}/A_{cs}A_{cs}$ system, the pole of 4208 ± 13i MeV on the second Riemann sheet is predicted, whose mass agrees with that of $Z_{cs}(4220)^+$ while the width is much smaller than $Z_{cs}(4220)^+$. Due to the large error of the $Z_{cs}(4220)^+$’s width, further measurements are expected. In addition, several other poles of different spins are predicted.

I. INTRODUCTION

A series of charmonium-like states have been discovered, since the observation of $X(3872)$ by Belle collaboration in 2003 [1]. Besides, searching for the $Z_{cs}$ states composed of $c, \bar{c}, s$ and $q$ is an important topic as well. In 2020, BESIII reports new results in the $e^+e^- \rightarrow K^+(D_s^+D^{0*0} + D_s^{-*}D^0)$ process. An excess over the known contributions of the conventional charmed mesons is observed near the $D_s^+D^{0*0}$ and $D_s^{-*}D^0$ mass thresholds in the $K^+$ recoil-mass spectrum for events collected at $\sqrt{s} = 4.681$ GeV [2]. The corresponding mass and width are determined as

$$m = 3982.5^{+1.8}_{-2.6} \pm 2.1 \text{ MeV}, \quad \Gamma = 12.8^{+5.3}_{-4.4} \pm 3.0 \text{ MeV}. \quad (1)$$

Soon after that, LHCb collaboration observed two exotic states decaying into $J/\psi K^*$ final state, which are named as $Z_{cs}(4000)^+$ and $Z_{cs}(4220)^+$ [3]. Their masses and the widths are

$$m_{Z_{cs}(4000)^+} = 4003 \pm 6_{-14}^{+14} \text{ MeV}, \quad (2)$$
$$\Gamma_{Z_{cs}(4000)^+} = 131 \pm 15 \pm 26 \text{ MeV}, \quad (3)$$

$$m_{Z_{cs}(4220)^+} = 4216 \pm 24_{-30}^{+43} \text{ MeV}, \quad (4)$$
$$\Gamma_{Z_{cs}(4220)^+} = 233 \pm 52_{-73}^{+97} \text{ MeV}. \quad (5)$$

Very recently, the evidence of $Z_{cs}(3985)^0$ was found by BESIII near the thresholds of $D_s^+D^{*+}$ and $D_s^{-*}D^0$ production in the $K^0_s$ recoil-mass spectrum [4]. Since its mass and width are close to those of $Z_{cs}(3985)^+$, they should be the isospin partners. However, $Z_{cs}(3985)$ and $Z_{cs}(4000)$ seem not to be the same states, due to the different masses and widths.

These exciting discoveries enrich our understanding of the spectrum of hadronic states, and much attention is paid in this field. Before the observations, the authors in Ref. [5] predicted the decay width of a charged state near the $D_s^0\bar{D}^{*+}/D_s^{-*}\bar{D}$ threshold. Ref. [6] pointed out that it would be natural to expect the existence of $Z_{cs}$ states to decay into $\eta, K$ and $J/\psi K$. After the observations, in Refs. [7–29], the $Z_{cs}$ states are studied in the pictures of molecular, compact tetraquark or the mixture of them. For other theoretical works, see Refs. [30–36].

Since the masses of the heavy quarks are much larger than those of the light quarks, the heavy quarks can be seen as spectators in hadrons. From this point of view, the light-meson exchange is dominant in the charged and anti-charged mesons interactions. In this case, if only considering the $D^0\bar{D}^{0*}$ hadronic molecule component when studying the observed $Z_{cs}$ states, the scattering processes corresponding to the effective potentials are suppressed by the Okubo-Zweig-Iizuka (OZI) rule [37–39]. Such suppressed potentials may not be enough to form a particle. In order to solve this issue, in present work, we introduce the effective field theory for both mesons and diquarks, in which way, the diquark-anti-diquark component is introduced for the $Z_{cs}$ states. Next, we give a short review of the effective field theory.

As is well known, chiral perturbation theory (ChPT) is a powerful tool to study the phenomenon in the low energy region of quantum chromodynamics (QCD). It is based on the spontaneously broken approximate chiral symmetry of QCD. The pions, kaons and the eta can be identified with the Goldstone bosons of chiral symmetry breaking. However, in the higher energy region, ChPT may not be applicable. One simple way is to incorporate vector mesons in this energy region. In order to achieve this, there are various schemes [40–42], such as the hidden local symmetry (HLS) approach, the matter field method, the antisymmetric tensor field method and the massive Yang-Mills field method.

In this work, we focus on the first one, i.e., the HLS approach. In this approach [43], an artificial local symmetry is introduced into the nonlinear sigma model by the choice of field variables. The vector mesons are then introduced as gauge bosons for this symmetry. As stressed in Refs. [44, 45], the additional local symmetry has no physics associated with it, and it can be removed by fixing the gauge. In the unitary

*Corresponding Author: sunzf@lzu.edu.cn
of the diquarks contributes since there is a repulsion between the quarks in the color sextet and an attraction in the color anti-triplet.

At the meson-diquark level, the diquark fields are depicted as

\[
S^a = \begin{pmatrix}
0 & S_{ud} & S_{us} \\
-S_{ud} & 0 & S_{ds} \\
-S_{us} & -S_{ds} & 0
\end{pmatrix},
\]

\[
A^a_\mu = \begin{pmatrix}
A_{uu} & \frac{1}{\sqrt{2}}A_{ud} & \frac{1}{\sqrt{2}}A_{us} \\
\frac{1}{\sqrt{2}}A_{ud} & A_{dd} & \frac{1}{\sqrt{2}}A_{ds} \\
\frac{1}{\sqrt{2}}A_{us} & \frac{1}{\sqrt{2}}A_{ds} & A_{ss}
\end{pmatrix},
\]

\[
S^a_c = \begin{pmatrix}
S_{cu} & S_{cd} & S_{cs}
\end{pmatrix},
\]

\[
A^a_{\mu c} = \begin{pmatrix}
A_{cu} & A_{cd} & A_{cs}
\end{pmatrix},
\]

where \(S^a\) is the light scalar diquark, \(A^a_\mu\) the light axial vector diquark, \(S^c\) the charmed scalar diquark, and \(A^a_{\mu c}\) the charmed axial vector diquark. The superscript \(a = 1, 2, 3\) is the color index.

III. THE LAGRANGIAN

In this work, we extend the HLS to the meson-diquark interaction sector, considering as well the chiral symmetry, parity, and charge conjugation. The constructed Lagrangian is shown below

\[
\mathcal{L} = e_1 (iPD_\mu S^a A^{\mu \nu} - iA^{\mu \nu}_c D_\mu S^a P^{\mu \nu}) \\
+ e_2 (iPA_\mu D_\mu S^a - iD^{\mu \nu}_c S^a A_{\mu \nu} P^{\mu \nu}) \\
+ e_3 (e^{\mu \nu \rho} P A_{\rho c} A^{\mu \nu} + e^{\mu \nu \rho} A_{\rho c} A^{\mu \nu} P^{\mu \nu}) \\
+ e_4 (iP_\mu D^\mu S^a S^a_c - iS^c D^\mu S^a P^{\mu a}) \\
+ e_5 (e^{\mu \nu \rho} P_\mu A_{\rho c} D_\mu S^a_c + e^{\mu \nu \rho} A_{\rho c} D_\mu S^a_c P^{\mu a}) \\
+ e_6 (iP_\mu A^{\mu \nu} A_c^{\nu} - iA^a_c A^{\mu \nu} P^{\mu a} P^{\mu a}) \\
+ e_7 (iP_{\mu \nu c} A^{\mu \nu} A_c^{\nu} - iA^{\mu \nu}_c A^{\mu \nu} P^{\mu a} P^{\mu a}) \\
+ e_8 (iP_{\mu \nu c} A^{\mu \nu} A_c^{\nu} - iA^{\mu \nu}_c A^{\mu \nu} P^{\mu a} P^{\mu a}),
\]
where

\[ P = (D^0, D^+, D^0_π), \quad P_τ = (D^{τ0}, D^{τ+}, D^{τ0}_π), \] (11)

\[ D_μP = \partial_μP + iP_μA_μ, \] (12)

\[ D_μP_τ = \partial_μP_τ + iP_μA_μ, \] (13)

\[ \alpha_{\text{p}μ} = (\partial_μ\xi R_π - \partial_μ\xi L_π)/(2i), \] (14)

\[ \alpha_{\text{p}μ} = (\partial_μ\xi R_π + \partial_μ\xi L_π)/(2i), \] (15)

\[ \xi_{\text{p}μ} = (\partial_μ\xi R_π - \partial_μ\xi L_π)/(2i), \] (16)

\[ \xi_{\text{p}μ} = (\partial_μ\xi R_π + \partial_μ\xi L_π)/(2i), \] (17)

\[ \xi_{\text{p}} = e^{i\mu F_\text{p}} e^{-im/(2F_\text{p})}, \] (18)

\[ A_{\text{p}μ}^a = D_μA_μ^a - D_μA_μ^a, \] (19)

\[ D_μA_μ^a = \partial_μA_μ^a - iV_μA_μ^a - iA_μ^aV_μ, \] (20)

\[ D_μS^a = \partial_μS^a - iV_μS^a - iS^aV_μ, \] (21)

\[ D_μA_μ^a = \partial_μA_μ^a - iA_μ^a\alpha_{\text{p}μ}^T, \] (22)

with the pseudoscalar meson fields

\[
\Phi = \begin{pmatrix}
\sqrt{\sqrt{2}m_π^2 + \sqrt{2}m_π} & \sqrt{\sqrt{2}K^+} \\
\sqrt{2}m_π & \sqrt{\sqrt{2}K^+} & \sqrt{\sqrt{2}K^+} \\
\sqrt{2}K^- & \sqrt{\sqrt{2}K^0} & \sqrt{2}m_π^2 + \sqrt{2}m_π \\
\sqrt{2}K & \sqrt{2}m_π^2 & \sqrt{2}m_π^2 + \sqrt{2}m_π
\end{pmatrix},
\] (23)

and the gauge boson fields

\[
V_μ = \frac{g_μ}{\sqrt{2}} \begin{pmatrix}
\frac{1}{\sqrt{2}}(ρ^0 + \omega) & ρ^+ & K^{++} \\
ρ^- & \frac{1}{\sqrt{2}}(ρ^0 - \omega) & K^{0+} \\
K^{-} & \bar{K}^{0} & φ_μ
\end{pmatrix}.
\] (24)

The pion decay constant \( F_π \) = 93 MeV. In the unitary gauge, i.e., \( σ = 0 \), we have \( ξ_L = ξ_R = e^{-i\Phi/(2F_π)} \). The \( e_i \) (i = 1, 2, ..., 9) are the coupling constants.

IV. THE EFFECTIVE POTENTIALS

With the constructed Lagrangian in Eq. (10), we calculate the potentials of two mesons into diquark-anti-diquark, which are shown in the following

\[ V^{DσDσ'→\hat{e}_i\hat{e}_j} = e_\sigma \sqrt{m_{Sσ}m_{Sσ'}} \frac{m_{Sσ'}-m_{Sσ}^2}{2m_{A_A}} \frac{e_8}{2} \frac{2m_{A_A}}{m_{A_A}} \left( e_8^2 - \frac{s - m_{A_A}^2 - m_{Sσ}^2}{2} \right) \] (25)

\[ V^{DσDσ'→SσAσ'} = e_\sigma \sqrt{m_{Dσ}m_{Dσ'}} \frac{m_{Dσ'}-m_{Dσ}^2}{2m_{A_A}} \frac{e_8}{2} \frac{2m_{A_A}}{m_{A_A}} \left( e_8^2 - \frac{s - m_{A_A}^2 - m_{Dσ}^2}{2} \right) \] (26)

\[ V^{DσDσ'→\hat{e}_iS_σ} = e_\sigma \sqrt{m_{Dσ}m_{Dσ'}} \frac{m_{Dσ'}-m_{Dσ}^2}{2m_{A_A}} \frac{e_8}{2} \frac{2m_{A_A}}{m_{A_A}} \left( e_8^2 - \frac{s - m_{A_A}^2 - m_{Dσ}^2}{2} \right) \] (27)

with \( s = (p_1 + p_2)^2 \) and \( u = (p_1 - p_3)^2 \). Here, other amplitudes are negligible due to the OZI suppressed processes and the very small momentums of the initial and final particles.

Then we project the polarization vector products into different spin states

\[ \mathcal{P}(1) = \hat{e}_i \cdot \hat{e}_j = \hat{e}_i \cdot \hat{e}_j, \] (28)

\[ \mathcal{P}'(0) = \frac{1}{3} \hat{e}_i \cdot \hat{e}_j \hat{e}_3 \cdot \hat{e}_4, \] (29)

\[ \mathcal{P}'(1) = \frac{1}{2} (\hat{e}_i \cdot \hat{e}_j \hat{e}_3 \cdot \hat{e}_4 - \hat{e}_i \cdot \hat{e}_j \hat{e}_3 \cdot \hat{e}_4), \] (30)

\[ \mathcal{P}'(2) = \frac{1}{2} (\hat{e}_i \cdot \hat{e}_j \hat{e}_3 \cdot \hat{e}_4 + \hat{e}_i \cdot \hat{e}_j \hat{e}_3 \cdot \hat{e}_4), \] (31)

V. THE BETHE-SALPETER EQUATION IN THE ON-SHELL FACTORIZED FORM

With the effective potentials obtained above, we utilize the Bethe-Salpeter equation of the on-shell factorized form to calculate the T-matrix considering the coupled-channel effect, i.e.,

\[ T = (I - VG)^{-1}V. \] (32)

Here, \( V \) is the matrix of the effective potential, and \( G \) is the matrix of the two-particle loop function whose non-zero element has the form of

\[ G_{ij} = i \int \frac{d^4q}{(2\pi)^4} \frac{1}{q^2 - m_{i1}^2 + ie} \frac{1}{(P - q)^2 - m_{i2}^2 + ie}, \] (33)

where \( P_μ \) is the four momentum of the two particles, \( q_μ \) is the four momentum of one of the particles, \( m_{i1} \) and \( m_{i2} \) are
the masses of the particles in the loop, $i$ is the label of the channel. The above loop integral is logarithmically divergent, which can be regularized by the three-momentum-cutoff. The expression of the cutoff-regularized loop function has been calculated in Ref. [54], i.e.,

$$
G_{ii} = \frac{1}{32\pi^2} \left\{ \log \frac{s - \Delta + \sqrt{1 + \frac{m_i^2}{q_{\text{max}}}}}{s - \Delta + \sqrt{1 + \frac{m_i^2}{q_{\text{max}}}}} + \log \frac{s + \Delta + \sqrt{1 + \frac{m_i^2}{q_{\text{max}}}}}{s + \Delta + \sqrt{1 + \frac{m_i^2}{q_{\text{max}}}}} \right\}$$

with $q_{\text{max}}$ the cutoff, $\Delta = m_i^2 - m_{11}^2$, and $\nu = \sqrt{(s - (m_1 + m_2)^2)(s - (m_1 - m_2)^2)}$.

Eq. (34) justifies on the first Riemann sheet, on which the bound state can be found. In order to look for the pole of resonance or virtual state, we need to extrapolate the loop function to the second Riemann sheet by a continuation via

$$
G^{	ext{II}}_{ii} = G^I_{ii} + i\frac{\nu}{8\pi s}.
$$

Since the amplitudes close to a pole behave like

$$
T_{ij} = \frac{g_i g_j}{s - s_R},
$$

we can calculate the couplings to each channel from the residue of the amplitudes.

### VI. NUMERICAL RESULTS

In the Lagrangian shown above, there are 9 unknown constants. To determine them, we approximately use the quark-pair-creation model. Their values are given in Tab. I. The masses of diquarks are taken from Ref. [55]. Because the relative phase between the amplitudes obtained from the Lagrangian and the quark-pair-creation model can not be completely fixed, the values of $(e_1, e_2, e_3)$ are possibly chosen as $(2.840 \text{ GeV}^{-1}, -11.098 \text{ GeV}^{-1}, 16.778 \text{ GeV}^{-1})$ and $(-16.778 \text{ GeV}^{-1}, -2.840 \text{ GeV}^{-1}, -2.840 \text{ GeV}^{-1})$, respectively, where we omit the unphysical ones. Next we use the values in Tab. I, and discuss the other cases finally.

By solving the Bethe-Salpeter equation, we find the pole positions. In Tab. II, we show the dependence of the pole positions on the cutoff. The spins of $D^{0}D_s^{*+}/\bar{A}_sS_{cs}$ and $D^{0}D_s^{*+}/\bar{A}_sS_{cs}$ systems are 1. In the case of $D^{0}D_s^{*+}/\bar{A}_sS_{cs}$, the spin of the states can be 0, 1 and 2, since the pole positions are the same for all these spins.

For the $D^{0}D_s^{*+}/\bar{A}_sS_{cs}$ system, if the cutoff is chosen as $q_{\text{max}} = 1385$ MeV, we get a resonance with the pole position at $(4013 \pm 42)$ MeV on the second Riemann sheet. The mass of this resonance is consistent with that of $Z_{c_7}(4000)^+$, and the width about 84 MeV is close to the lower limit of the $Z_{c_7}(4000)^+$ width. That is to say, $Z_{c_7}(4000)^+$ is identified as the mixture of $D^{0}D_s^{*+}$ and $\bar{A}_sS_{cs}$ components. The module of the coupling to $D^{0}D_s^{*+} (\bar{A}_sS_{cs})$ channel is calculated as 9.80 GeV (18.60 GeV), which means that the $\bar{A}_sS_{cs}$ component is dominant.

For the $D^{0}D_s^{*+}/\bar{A}_sA_{cs}$ system of spin 1, if choosing the cutoff as 1385 MeV, a resonance at $(4208 \pm 13)$ MeV on the second Riemann sheet is obtained with the modules of the couplings $|g_{\bar{D}^{0}D_s^{*+}}| = 4.88$ GeV and $|g_{\bar{A}_sA_{cs}}| = 7.62$ GeV. The mass is in agreement with the one of $Z_{c_5}(4220)^+$, however, the width is much smaller than that of $Z_{c_5}(4220)^+$. We suggest the experiments make further measurements, since the error of the width by LHCb is very large. Meanwhile, we predict a virtual state on the second Riemann sheet of 4106 MeV, and a bound state on the first Riemann sheet of 4091 MeV. The modules of the couplings of the virtual state and the bound state to $D^{0}D_s^{*+} (\bar{A}_sA_{cs})$ channel are 4.39 GeV (8.02 GeV) and 7.79 GeV (11.27 GeV), respectively. For spin 0 and 2, the obtained pole positions are the same as those of spin 1.

For the $D^{0}D_s^{*+}/\bar{S}_{cs}A_{cs}$ system, with the cutoff $q_{\text{max}} = 1385$ MeV, there is a pole at $(4112 \pm 66)$ MeV. The modules of the couplings to $D^{0}D_s^{*+}$ and $\bar{S}_{cs}A_{cs}$ are 9.12 GeV and 16.27 GeV, respectively.

As discussed above, there are two other choices of the cou-
pling constants $e_7$, $e_8$ and $e_9$. However, if choosing these values, we can neither explain the $Z_{cs} (4000)^+$ and $Z_{cs} (4220)^+$ nor explain the $Z_{cs} (3985)$ observed by BESIII.

For the further experiments, as well as the $J/ψ K$ channel as measured by LHCb, the $J/ψ K^*$ channel may also be of importance, since the resonances of spin 0 and spin 2 would be observed in this channel.

VII. SUMMARY

In this work, applying the HLS approach to the meson-diquark sector, we construct the Lagrangian to describe the corresponding interactions. And we study the $Z_{cs}$ states as the mixture of the hadronic molecule and the diquark-anti-diquark components. It is in this way the problem is solved that if considering only the pure molecular component, the interaction is OZI suppressed.

With the potentials obtained by using the Lagrangian, we solve the Bethe-Salpeter equation. We find three resonances of spin 1 with the pole positions on the second Riemann sheet of $(4013 \pm 42i)$ MeV, $(4208 \pm 13i)$ MeV, $(4112 \pm 66i)$ MeV for $D_{s}^{0}D_{s}^{+}/A_{4}A_{cu}$, $D_{s}^{0}D_{s}^{+}/A_{c}A_{cu}$ and $D_{s}^{0}D_{s}^{+}/\bar{S}_{c}A_{cu}$ systems, respectively. The first resonance is identified as the $Z_{cs} (4000)^+$, since the calculated mass agrees with the value by LHCb, and the obtained width is close to the lower limit of the LHCb data. The mass of the second resonance agrees with that of $Z_{cs} (4220)^+$, however, the width is much smaller than that of $Z_{cs} (4220)^+$. Due to the large error of the experimental data of $Z_{cs} (4220)^+$ width, further experiments are expected. There are as well a bound state and a virtual state with the masses around 4100 MeV and spins $J = 1$ for $D_{s}^{0}D_{s}^{+}/\bar{A}_{4}A_{cu}$ system. For spins 0 and 2 of $D_{s}^{0}D_{s}^{+}/\bar{A}_{c}A_{cu}$ system, the obtained pole positions are the same as those of the spin 1 case. For all these states, the dominant channels are the diquark-anti-diquark channels. Further experiments are expected to explore all these states. Besides the $J/ψ K$ channel, the $J/ψ K^*$ channel may also be important.

Acknowledgments

This project is supported by the National Natural Science Foundation of China (NSFC) under Grants No. 11965016 and 11705069. We would like to thank Lanzhou Center for Theoretical Physics for the support to this project under the Grant No. 12047501 (NSFC). In this work, Ze-Hua Cao and Wei He contribute equally.

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