Can $Z_{cs}(3985)$ be a molecular state of $\bar{D}_s^* D$ and $\bar{D}_s D^*$?

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We study the $Z_{cs}(3985)$ state recently observed by the BESIII Collaboration in the one-boson-exchange model, assuming that it is a $\bar{D}_s^*(c) D(c)$ molecule, which has the quark content $c\bar{c}s\bar{q}$ with $q = u, d$. It is shown that the one-boson-exchange potential is too weak to generate dynamically $\bar{D}_s D, \bar{D}_s^* D$ and $\bar{D}_s D^*$ states, while for the case of $\bar{D}_s^* D^*$, very loosely bound states are likely, with binding energies of the order of several MeV. We conclude that, the observed $Z_{cs}(3985)$ state, if confirmed by further experiments, cannot be a pure hadronic molecular state of $\bar{D}_s D^*$ and $\bar{D}_s^* D$ and could consist of large components of compact nature.

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I. INTRODUCTION

Many exotic states have been found experimentally ever since the discovery of $X(3872)$ and $D_{sJ}^*(2317)$ in 2003 [1,2]. Though many of them cannot easily fit into the conventional quark model, none of the well established ones are explicitly exotic, i.e., have minimum quark contents beyond those of $q\bar{q}$ or $qqq$, or cannot be explained in the molecular picture. As some, if not all, of these states are close to the threshold of some coupled channels, naively but quite reasonably, coupled channel dynamics are believed to play an important role, to the extent that some of the exotic states may just be bound states composed of two or more other conventional hadrons (see, e.g., Refs. [3,5]).

In a recent work, the BESIII Collaboration reported on the existence of an exotic state, $Z_{cs}(3985)$, which has the minimum quark content $c\bar{c}s\bar{q}$. The obtained mass and width are:

$$M_{Z_{cs}} = 3982.5^{+1.8}_{-2.6} \pm 2.1\text{MeV},$$
$$\Gamma_{Z_{cs}} = 12.8^{+5.3}_{-4.4} \pm 3.0\text{MeV},$$

with a significance of $5.3\sigma$. The $c\bar{c}s\bar{q}$ states have attracted some attention in the past, because one can rule out the possibility of conventional charmonium from the quark contents. Therefore, they can only be hadronic molecules, compact tetraquark states or kinetic effects. In Ref. [7], assuming a compact tetraquark picture, and considering the chromomagnetic interaction (CMI), the authors found that the lowest $c\bar{c}s\bar{q}$ tetraquark is about 100 MeV below the mass threshold of $DD_s$. In the relativistic quark model, the lowest $c\bar{c}s\bar{q}$ state is found to be 10 MeV below the $DD_s$ threshold [8].

In Ref. [9] no $D^{(*)}\bar{D}^{(*)}$ bound states were found in the one-boson-exchange (OBE) model, where only $\pi, \sigma, \omega$, and $\rho$ exchanges are considered. In the chiral unitary approach constrained by the hidden gauge symmetry and broken SU(4) symmetry [10], no resonance or bound state near the $DD_s$ mass threshold is found. Only in Ref. [11] an effective field theory study with constraints from heavy quark spin symmetry and SU(3) flavor symmetry predicted several hadronic molecules near the $D^{(*)}\bar{D}^{(*)}$ thresholds. These results should be taken with caution because $X(3915)$ and $Y(4140)$ are assumed to be $D^* D^*$ and $D_s^* D_s^*$ hadronic molecules with quantum numbers $J^{PC} = 0^{++}$. In addition, Chen et. al predicted in the initial single chiral particle emission mechanism enhancements near the mass thresholds of $DD^*_s/D^* D_s$ and $D^* D^*_s/D^* D^*_s$ in the $J/\Psi K$ invariant mass spectrum [13].

As the $Z_{cs}(3985)$ state lies close to the mass threshold of $D^{0}\bar{D}^{0}$ and $D^{0}\bar{D}^{0}$, in this work, we explore whether it can be understood as a hadronic molecule in the one-boson-exchange model by tweaking the model parameters and we conclude that the newly observed state cannot be a hadronic molecule or at least a state with large molecular components.

This paper is organized as follows. We briefly explain the pertinent ingredients of the OBE model in Sec. II. Results and discussions are given in Sec.III, followed by a short summary in the last section.

II. THEORETICAL FORMALISM

We will explore whether the $D^{(*)}\bar{D}^{(*)}$ interactions are strong enough to form bound states. The relevant Lagrangians are the same as those of the $\bar{D}^{(*)} D^{(*)}$ interactions, which can

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³ The $J^{PC}$ of $Y(4140)$ has now been determined to be $1^{++}$ [12].
be found in Ref. [14]. The Lagrangian describing the interaction between the charm and the light mesons are

\[
\mathcal{L}_{HH,K} = -\frac{g_K}{f_K} \text{Tr} \left[ H^I \sigma \cdot \vec{r} K H \right],
\]

\[
\mathcal{L}_{HH, K^*} = \sqrt{2g_{K^*}} \text{Tr} \left[ H^I K^* H_s \right] - \sqrt{\frac{2f_{K^*}}{4M}} \epsilon_{ijk} \times \text{Tr} \left[ H^I \sigma_k (\partial_i K^*_j - \partial_j K^*_i) H_s \right],
\]

where \( H = \frac{1}{\sqrt{2}}(D + \bar{D}^*) \) and \( H_s = \frac{1}{\sqrt{2}}(D_s + \bar{D}^*_s) \), satisfying the constraint of heavy quark spin symmetry. The coupling of \( K \) to \( D_s^* \) \((g_{K^*})\) can be derived from that of \( \pi \) to \( D_s^* \) assuming SU(3) flavor symmetry, which yields \( g_{K^*} = g = 0.6 \). In the same way the coupling \( f_K \) can also be taken the same as \( f_\pi \), arriving at \( f_K = f_\pi = 0.132 \text{ GeV} \). SU(3) symmetry also relates the \( K \) meson to \( \rho \) and \( \omega \) mesons. The couplings of \( K^* \) to \( D \) are of two types, electric \((f_{K^*})\) and magnetic \((f_{K^*})\). We obtain \( g_{K^*} = g_{\rho} = 2.6 \) and \( f_{K^*} = f_\omega = 4.5 \) using a common mass \( M = 1.867 \text{ GeV} \) for the normalization [14].

For the \( D D_s \) system the exchanged light meson can only be \( K^* \), where both \( K \) and \( K^* \) are allowed for the \( D^* D_s \), \( D D^*_s \), and \( D^* D^*_s \) systems. From the Lagrangians of Eq. (3) we can derive the OBE potentials for the \( D^{(*)} D_s^{(*)} \) systems as

\[
V_{K^*}(\bar{r}) = \frac{-g_{K^*}^2}{3f_{K^*}^2} \left[ -\sigma \cdot \hat{r} \delta(\bar{r}) + \sigma \cdot \vec{r} \delta(\bar{r}) m_{K^*}^2 W_Y(m_{K^*} r) \right. \\
+ \left. S_{12}(\bar{r}) m_{K^*} W_T(m_{K^*} r) \right],
\]

\[
V_{K^*}(\bar{r}) = -\frac{2g_{K^*}^2}{M_{K^*}^2} \left[ -\frac{2}{3} \sigma \cdot \hat{r} \delta(\bar{r}) + \frac{2}{3} \sigma \cdot \vec{r} m_{K^*}^2 W_Y(m_{K^*} r) \right.
\\
- \left. \frac{1}{3} \frac{S_{12}(\bar{r}) m_{K^*}^2 W_T(m_{K^*} r)}{S_{12}(\bar{r}) m_{K^*}^2 W_T(m_{K^*} r)} \right],
\]

where the functions \( W_Y \) and \( W_T \) are defined as

\[
W_Y(x) = \frac{e^{-x}}{4\pi x},
\]

\[
W_T(x) = \left( 1 + \frac{3}{x} + \frac{3}{x^2} \right) \frac{e^{-x}}{4\pi x}.
\]

To simulate the finite sizes of the charmed mesons, as usual, we introduce a monopolar form factor (for more details we refer to Refs. [14][15])

\[
F(q, m, \Lambda) = \frac{\Lambda^2 - m^2}{\Lambda^2 - q^2},
\]

with the above form factor, the functions \( \delta, W_Y \), and \( W_T \) in Eq. (4) should be replaced with

\[
\delta(r) \rightarrow m^3 d(x, \lambda),
\]

\[
W_Y(x) \rightarrow W_Y(x, \lambda),
\]

\[
W_T(x) \rightarrow W_T(x, \lambda),
\]

where \( \lambda = \Lambda/m \). The corresponding functions \( d, W_Y \), and \( W_T \) read

\[
d(x, \lambda) = \frac{(\lambda^2 - 1)^2}{2\Lambda^2} \frac{e^{-\lambda x}}{4\pi x},
\]

\[
W_Y(x, \lambda) = W_Y(x) - \lambda W_Y(\lambda x) - \frac{(\lambda^2 - 1)}{2\Lambda^2} \frac{e^{-\lambda x}}{4\pi x},
\]

\[
W_T(x, \lambda) = W_T(x) - \lambda^2 W_T(\lambda x) - \frac{(\lambda^2 - 1)}{2\Lambda^2} \frac{1}{\lambda x} \frac{e^{-\lambda x}}{4\pi x}.
\]

In addition, since \( D \)-wave interactions may play an important role in forming hadronic molecules, we also consider them in the \( D^* D_s^* \) systems, which produce two kinds of spin operators, spin-spin \( \sigma \cdot \sigma \) and tensor \( \delta \). The explicit matrix elements of spin-spin and tensor operators for the \( D^* D_s^* \) systems are displayed in Table I.

III. NUMERICAL RESULTS AND DISCUSSION

The \( D D_s \) interaction can only be mediated by exchanging the \( K^* \) meson, which provides the short range interaction in the OBE model. We plot the OBE potential of the \( D D_s \) system as a function of the space coordinate \( r \) with three different cutoffs in Fig. 1. The strength of the potential is quite weak for a typical cutoff of 1 GeV. With a larger cutoff, the strength increases, but is still very weak. The strength of the potential in the range less than 1 fm becomes larger with increasing cutoff and quickly approaches to 0 when \( r \) is larger than 1 fm, which shows the particular behavior of the OBE potential for heavy meson exchanges. We should stress that in the one-boson-exchange model, a cutoff of about 1 GeV is often adopted based on various arguments, either of naturalness or of typical hadron sizes. In Ref. [14] a cutoff \( \Lambda = 1.04 \text{ GeV} \) is adopted to study the \( D^{(*)} D_s^{(*)} \) system determined by fitting to the binding energy of \( X(3872) \). Recently we reproduced the mass of \( P_c(4312) \) with a cutoff of \( \Lambda = 1.2 \text{ GeV} \), by assuming that it is a \( D^{(*)} \Xi_c^{(*)} \) bound state [15]. In Ref. [16], a cutoff of \( \Lambda = 1.16 \text{ GeV} \) is adopted to study the \( D^{(*)} \Xi_c \) system, which is determined by reproducing the binding energy and charge radius of the deuteron. From these studies of hadronic molecules in the one-boson-exchange model, we conclude that a cutoff of \( \Lambda \) about 1 GeV seems to be a reasonable choice.

In Figs. 2 and 3 we show the binding energies of the \( D^{(*)} D_s^{(*)} \) systems as a function of the cutoff. Note that in our present studies, these systems are related to each other by heavy quark spin symmetry. To get a bound \( D D_s \) state
with $J^P = 0^+$, a cutoff larger than 3.7 GeV is needed, far away from the preferred value of about 1 GeV. Hence the OBE model does not support the existence of a bound state near the $D\bar{D}_s$ mass threshold.

For the $D^*\bar{D}_s + D\bar{D}_s^*$ system with $J^P = 1^+$ and $D^*\bar{D}_s^*$ system with $J^P = 2^+$ to bind, a cutoff about 2 GeV is needed, which is somehow much smaller than the one needed for the $D\bar{D}_s$ system, but still much larger than the natural value of 1 GeV. While for the cases of $D^*\bar{D}_s - D\bar{D}_s^*$ with $J^P = 1^+$ and $D^*\bar{D}_s^*$ with $J^P = 0^+$ and $J^P = 1^+$, a cutoff $\Lambda > 3$ GeV is needed to generate bound states, and we can conclude that there are no bound states in these systems within the OBE model at least in the present setting. As a result, the BESIII near-threshold structure [6] cannot be easily explained as a $D_s D^* / D_s^* D$ bound state.

Finally, it is worth mentioning that we have checked that in the unitary model of Ref. [10], to dynamically generate a $D\bar{D}_s$ state with quantum numbers $I(J^P) = \frac{1}{2}(0^+)$, a cutoff larger than 3.7 GeV is needed, far away from the preferred value of about 1 GeV. Hence the OBE model does not support the existence of a bound state near the $D\bar{D}_s$ mass threshold.

![FIG. 1: OBE potentials as a function of the distance between $D$ and $\bar{D}_s$ for quantum numbers $I(J^P) = \frac{1}{2}(0^+)$.](image1.png)

![FIG. 2: Binding energies of $D\bar{D}_s$ and $D^*\bar{D}_s \pm D\bar{D}_s^*$ system as a function of the cutoff.](image2.png)

![FIG. 3: Binding energies of $D^*\bar{D}_s^*$ as a function of the cutoff.](image3.png)
state, one needs a subtraction constant of about $-8,3$ which could be lowered a bit in the $D_s\bar{D} - \eta_c K$ coupled channel case, while a reasonable subtraction constant has a value about $-2$. It will be interesting to check whether the BESIII state can be dynamically generated in the hidden-gauge approach. We note by passing that to generate the $X(5568)$ state as a $B\bar{K}$ state one also needs a larger than expected subtraction constant [17].

IV. SUMMARY

We showed that from the perspective of the one-boson-exchange model, the newly observed state by the BESIII Collaboration cannot be a meson-meson molecule, because it requires an unnaturally large cutoff regulator. It is necessary to stress that the above conclusion was reached in the single-channel scenario studied in the present work. Inclusions of other relevant coupled channels, see, e.g., Ref. [18] for the case of $P_{cs}(4559)$, might change the above conclusion and shed more light on the nature of the $Z_{cs}(3985)$ state. Therefore such studies are urgently needed.

Another caveat of the present study is that we only searched for bound states of $D_s^{(*)}D(*)$ while the experimental $Z_{cs}(3985)$ state is above the threshold of $D_s^{(*)}D_s^{(*)}$. A study similar to that of Ref. [19] is needed to search for $D_s^{(*)}D_s^{(*)}$ resonances.

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