The newly observed $Z_{cs}(3985)^-$ state: in vacuum and a dense medium

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We report on some properties of the newly observed charged hidden-charmed open strange $Z_{cs}(3985)^-$ state by BESIII Collaboration. Assigning the quantum numbers $J^{PC}=1^{+-}$ and the quark composition $car{c}sar{u}$ and considering it as the strange partner of the famous $Z_c(3900)$ state, we estimate the mass of the $Z_{cs}(3985)^-$ resonance in vacuum and compare it with the experimental data. We also investigate its mass, current coupling and vector-self energy in a medium with finite density. Our result on the mass in vacuum agrees well with the experimental data. We estimate the mass and current coupling of the $b$-partner of this state, $Z_{bs}$, in the vacuum as well. For its mass we get $m_{Z_{bs}} = 10732_{-96}^{+97}$ MeV, which may be checked via other nonperturbative approaches as well as future experiments. We present the dependence of the spectroscopic parameters of $Z_{cs}(3985)^-$ state on density and observe that these parameters are linearly changed with increasing in the density.

I. INTRODUCTION

The recently discovered charged resonances are good candidates of tetraquark systems as they can not be put in the spectrum of the usual $car{c}$ mesons by any means. The observation of the ground state $Z_c(3900)$ was reported by the BESIII [1] and Belle [2] Collaborations in 2013, simultaneously. After these observations many theoretical studies were performed on different properties of these states (as examples see Refs. [3–7] and references therein). The next state in this group is the $Z(4430)$ which discovered by the Belle and LHCb Collaborations [8–12] and fully studied in Refs. [4, 13–18] and references therein. The mass difference between $Z(4430)$ and $Z_c(3900)$ is roughly equal to the mass difference between $\psi(2S)$ and $J/\psi$, that respectively appear in their decay products, was the reason for consideration of $Z(4430)$ to be the first radial excitation of the $Z_c(3900)$ state [4, 18].

Very recently, as the first candidate, the BESIII Collaboration reported the observation of a charged hidden-charm tetraquark with strangeness, decaying into $D_s^+D_s^0$ and $D_s^-D^0$ in the process $e^+e^- \rightarrow K^+(D_s^+D_s^0 + D_s^-D^0)$ [19]. This new member is called $Z_{cs}(3985)^-$ and its quark composition is most likely $car{c}sar{u}$. The measured mass is just above the thresholds of $D_s^+D_s^*$ and $D_s^-D_s^*$. This value together with the value of the width reported by the experiment are:

$$m = 3982.5_{-2.6}^{+1.8} \pm 2.1 \text{ MeV,} \quad (1)$$

$$\Gamma = 12.8_{-4.4}^{+5.3} \pm 3.0 \text{ MeV.}$$

The charmonium-like open strange four quark systems were already in agenda of different theoretical studies [20–23]. However, there appeared various studies after the BESIII Collaboration observation report. Different assumptions and assignments have been made to clarify the nature and structure of the observed state [24–32].

In the present study, we investigate the $Z_{cs}(3985)^-$ (hereafter $Z_{cs}$) state both in the vacuum and a medium with finite density. Based on the provided information by the experiment, we treat it as a compact tetraquark and assign the quantum numbers $J^{PC}=1^{+-}$ and quark composition $car{c}sar{u}$ to this state and consider it as the strange partner of the famous $Z_c(3900)$ state. We calculate its mass and current coupling in vacuum. We also investigate this particle in a dense medium to estimate its vector self-energy, mass and current coupling at nuclear matter saturation density and study the changes of its parameters with respect to the density of the medium in order to more clarify its nature and structure. We use the technique of the QCD sum rules [33, 34] to calculate the spectroscopic parameters of this state. Our calculations let us also estimate some parameters of the $b$-partner of $Z_{cs}$ state, namely $Z_{bs}$, which may be in agenda of future experiments.

In in-medium sum rules, the medium effects are included via various operators in the nonperturbative parts of the operator product expansion (OPE) (see for example [35, 36]). The new progresses recorded in the heavy ion collision experiments like the Relativistic Heavy Ion Collider (RHIC) at the Brookhaven National Laboratory (BNL) and the Large Hadron Collider (LHC) and some in-medium experiments like $P\!A\!N\!A\!D\!A$ at Facility for Antiproton and Ion Research (FAIR) at GSI and the Nuclotron-based Ion Collider Facility at JINR (NICA) at Dubna, it will be possible to study not only the ground state particles but also the excited exotic states [37–39]. Hence, these experiments may provide good opportunities to investigate $Z_c(3900)$, $Z(4430)$ and $Z_{cs}$ in order to clarify their nature and substructure and fix their quantum numbers.

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In next section we provide some details of the calculations to obtain sum rules for the physical quantities under study. Section III, encompasses the numerical analyses of the obtained expressions. The last section is devoted to the summary of the results and conclusions.

II. SUM RULES FOR IN-MEDIUM PARAMETERS OF Z_{cs}

The information provided by the BESIII collaboration lead us to assign the quantum numbers \( J^{PC} = 1^+ \) to \( Z_{cs} \) state and consider it as the strange partner of the famous \( Z_c(3900) \) particle with quark composition \( c\bar{c}s\bar{u} \). By separating the hadronic states from the long-distance (nonperturbative) effects. By matching the obtained results in two different parameters and the in-medium quark and gluon condensates and the second in terms of QCD fundamental parameters and the in-medium quark and gluon condensates. By matching the obtained results in two different pictures we will able to calculate the in-medium hadronic parameters in terms of the QCD degrees of freedom.

The hadronic representation of CF is obtained by saturating it with a full set of hadronic state. By separating the ground state contribution, we get the following expression after performing the four-integral over \( x \):

\[
\Pi_{\mu\nu}^{Had}(p) = -\frac{\langle \psi_0 | J_{\mu} | Z_{cs}(p) \rangle \langle Z_{cs}(p) | J^\dagger_{\nu} | \psi_0 \rangle}{p^2 - m^2_{Z_{cs}}} + ..., \tag{4}
\]

where \( p^* \) is the in-medium momentum, \( m^2_{Z_{cs}} \) is the in-medium mass and dots stand for the contributions of the higher states and continuum. The above expression can be further simplified by introducing the in-medium decay constant or current coupling \( f^2_{Z_{cs}} \) defined by

\[
\langle \psi_0 | J_{\mu} | Z_{cs}(p) \rangle = f^2_{Z_{cs}} m^2_{Z_{cs}} \epsilon_{\mu}, \tag{5}
\]

where \( \epsilon_{\mu} \) is the polarization four-vector of \( Z_{cs} \). Using this definition leads to the summation over the polarization vector. Hence,

\[
\Pi_{\mu\nu}^{Had}(p) = -\frac{m^2_{Z_{cs}}^2 f^2_{Z_{cs}}^2}{p^2 - m^2_{Z_{cs}}} \left[ -g_{\mu\nu} + \frac{p^2_{\mu} p^2_{\nu}}{m^2_{Z_{cs}}} \right] + ..., \tag{6}
\]

is obtained for the hadronic side. To proceed, we need to define two kinds of self-energies. First one is the scalar self-energy defined by \( \Sigma = m^2_{Z_{cs}} - m_{Z_{cs}} \) and the second one is the vector self-energy \( \Sigma_{\nu} \), entering the expression \( \Sigma^\nu = p^\nu - \Sigma_{\nu} u_{\mu} \). Here, \( u_{\mu} \) is the velocity four-vector of the nuclear matter. We perform the calculations in the rest frame of the medium, where \( u_{\mu} = (1, 0) \). We should remark that we also choose to work at zero momentum limit of the particle’s three momentum, for which the longitudinal and transverse polarizations become degenerate, and there is no way to distinguish these two polarizations from each other. For the finite and non-zero three momentum in a dense medium, the longitudinal and transverse polarizations are distinguishable and they should be calculated, separately. In terms of the new quantities, the hadronic part takes the form

\[
\Pi_{\mu\nu}^{Had}(p) = -\frac{f^2_{Z_{cs}}^2}{p^2 - m^2_{Z_{cs}}} \left[ -g_{\mu\nu} + p^2_{\mu} p^2_{\nu} \right.
\]

\[
- \Sigma_{\nu} p^\nu u_{\mu} - \Sigma_{\nu} p^\nu u_{\mu} + \Sigma^2_{\nu} u_{\mu} u_{\nu} \bigg] + ..., \tag{7}
\]

where \( m^2 = m^2_{Z_{cs}} - \Sigma^2_{\nu} + 2 p_0 \Sigma_{\nu} \), with \( p_0 = p \cdot u \) being the energy of the quasi-particle in the dense medium. We apply the Borel transformation to suppress the contributions of the higher states and continuum based on the standard prescriptions of the method. As a result, we get

\[
\Pi_{\mu\nu}^{Phe}(M^2) = f^2_{Z_{cs}} e^{-M^2/M^2} \left[ -g_{\mu\nu} m^2_{Z_{cs}} \right.
\]

\[
+ p^2_{\mu} p^2_{\nu} - \Sigma_{\nu} p^\nu u_{\mu} - \Sigma_{\nu} p^\nu u_{\mu} + \Sigma^2_{\nu} u_{\mu} u_{\nu} \bigg] + ..., \tag{8}
\]

where \( M^2 \) is the Borel mass parameter.

The QCD side of the CF is calculated in deep Euclidean region by the help of OPE. In this representation, the short-distance (perturbative) effects are separated from the long-distance (nonperturbative) effects. To this end, we insert the explicit expression of the interpolating current \( J_{\mu}(x) \) into the CF and perform all the possible contractions among the quark fields using the Wick’s theorem. As a result, we get an expression in terms of the in-medium light and heavy quark propaga-


\[ \Pi_{\mu\nu}^{QCD}(p) = -\frac{i}{2} \tilde{\varepsilon}_{abc} \tilde{e}^a \gamma^\mu \gamma^\nu e^b \gamma^c \varepsilon_{de} \varepsilon^d \varepsilon^e \]

\[ \times \int d^4x e^{ipx} \left\{ T \left[ \gamma_5 \tilde{S}_{a}^{\mu}(x) \gamma_5 \tilde{S}_{b}^{\nu}(x) \right] - \frac{1}{2} \int d^4x \left[ \gamma_5 \tilde{S}_{a}^{\mu}(x) \right] \right\}, \]

where \( \tilde{S}_{(c)} = CST_{(c)} C \), and \( q \) stands for \( u, d \) or \( s \) quark. We make use of the in-medium light and heavy quark propagators in coordinate space. Against our previous studies on the properties of \( Z_c(3900) \) and \( Z(4430) \) states [6, 18], we keep the light quark mass in the calculations in order to take into account especially the strange quark mass effects:

\[
S_i^j(x) = \frac{i}{2\pi^2} \delta^{ij} \frac{1}{(x^2)^3} \left\{ \delta \left[ \frac{3}{2} \frac{m_q}{4\pi^2} \delta^{ij} \frac{1}{x^2} + \lambda_q^i(x) \bar{\lambda}_q^j(0) \right] ight. 
\]  

where \( \lambda_q^i \) and \( \bar{\lambda}_q^j \) are the Grassmann background quark fields and we use the short-hand notation

\[ F_{ij}^{\mu\nu} = F_{ij,A} \zeta^{A_{ij}} \], \quad A = 1, 2, ..., 8, \]

with \( F_{ij,A}^{\mu\nu} \) being the classical background gluon fields. Here, \( t^{ij,A} = \frac{\lambda_{ij}^A}{2} \)

\[ \text{III. NUMERICAL RESULTS} \]

The numerical calculations of the mass, current coupling and vector self-energy in medium and the mass and current coupling in vacuum require values of input parameters such as quark masses, nuclear matter saturation density, expectation values of the in-medium quark, gluon and mixed condensates, etc. They are taken as:

\[ m_u = 2.16^{+0.29}_{-0.26} \text{MeV}, \quad m_s = 93^{+11}_{-6} \text{MeV}, \quad m_c = 1.27 \pm 0.02 \text{GeV}, \quad \rho^{sat} = 0.113 \text{GeV}^3, \quad \langle u\bar{u}\rangle_\rho = \frac{1}{2} \rho \text{ GeV}^3, \quad \langle s\bar{s}\rangle_\rho = 0, \quad \langle \bar{u}u \rangle_0 = (0.272)^3 \text{GeV}^3, \]
The auxiliary parameters, convergence of the OPE and pole depend on. To fix them, the standard criteria of the
standard Borel parameter and continuum threshold in the charmed
y shows a strong dependence on the density and
energy shows a strong dependence on the density and
with the increasing in the density, while the vector self-
Z(3985)$- state. Our calculations show that the working
windows $9 GeV^2 \leq M^2 \leq 12 GeV^2$ and $126 GeV^2 \leq s_0 \leq 130 GeV^2$ satisfy all the requirements of the method. Using the input values in b-channel we get

$$m_{Z_{cs}} = 10732^{+97}_{-46} \text{ MeV},$$
$$f_{Z_{cs}} = (3.58 \pm 0.73) \times 10^{-2} \text{ GeV}^4,$$

in vacuum. The future experiments may search for the charged hidden-bottom open strange state, $Z_{cs}^-$, with quantum numbers $J^{PC} = 1^{-+}$ and quark composition $bbs\bar{u}$ around the 10730 MeV mass.

**IV. SUMMARY AND CONCLUSIONS**

Inspired by the recent observation of the charged hidden-charmed open strange $Z_{cs}(3985)^-$ state by the BESIII Collaboration, we performed a QCD sum rule analysis for the spectroscopic parameters of this state both in vacuum and a medium with finite density. For its mass in vacuum we obtained $m_{Z_{cs}} = 3846^{+34}_{-16}$ MeV, which is in accord with the experimental value, $m = 3982.5_{-2.8}^{+1.8}$ MeV. From this result, we conclude that the assignments $J^{PC} = 1^{++}$ and $ccb\bar{s}$ for the quantum numbers and quark structure of this state works well. We calculated the current coupling constant of this state in vacuum as well, which can be used in investigation of the electromagnetic, weak or strong decays of $Z_{cs}$ state as an important input parameter. We also estimated the mass and current coupling of the b-partner of this state, $Z_{bs}$, in vacuum and in the same picture. The obtained value for the mass of this hypothetical resonance, $m_{Z_{bs}} = 10732^{+97}_{-46}$ MeV, may be checked via different non-perturbative approaches as well as future experiments.

We also reported the values of mass, current coupling constant and vector self-energy of $Z_{cs}$ state at the sat-
uration density of a nuclear medium. We investigated the behavior of the spectroscopic parameters of this state in terms of the density and observed that they are linearly changed by increasing in the value of the density: the mass slightly decreases while the vector self-energy considerably increases with respect to the density. Our results may be helpful for future heavy ion collision experiments and those aiming to study the behavior of the exotic states at finite densities.

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