Properties of $Z_c(3900)$ tetraquark in a cold nuclear matter

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The study of medium effects on properties of particles embedded in nuclear matter is of great importance for understanding the nature and internal quark-gluon organization as well as exact determination of the quantum numbers of especially the exotic states. In this context, we study the physical properties of one of the famous charmonium-like states, $Z_c(3900)$, in a cold dense matter. We investigate the possible shifts in the mass and current-meson coupling of the $Z_c(3900)$ state due to the dense medium at saturation density, $\rho_{sat}$, by means of the in-medium sum rules. We also estimate the vector self-energy of this state at saturation nuclear matter density. We discuss the behavior of the spectroscopic parameters of this state with respect to the density up to a high density corresponding to the core of neutron stars, $\rho \approx 5\rho_{sat}$. Both the mass and current-coupling of this state show nonlinear behavior and decrease with respect to the density of the medium: the mass reach to 30\% of its vacuum value at $\rho = 5\rho_{sat}$, while the current-coupling approaches to zero at $\rho \approx 2.1\rho_{sat}$.

I. INTRODUCTION

The standard hadrons are divided into $qq$ and $qqq/qqq$ systems. Neither the quark model nor the QCD don’t exclude the existence of the structures out of these configurations. Hence, search for exotic states is inevitable: now we have many exotic states observed in the experiment. We have also made a good progress in determination of different aspects of these states in theory. Most of the discovered exotic states are tetraquarks of the XYZ family. The term XYZ comes from the generalization of the names of the famous states X(3872), Y(4260) and Z$_c$(3900). The XYZ states are the charmonium/bottomonium-like resonances, which, because of their mass, cannot be placed in the charmonium/bottomonium picture: these resonances mainly with $QQqq$ quark content have different properties than the standard excited quarkonia states. In last decade, many XYZ states have been observed by the Belle, BESIII, BaBar, LHCb, CMS, D0, CDF, and CLEO-c collaborations [1], and their masses, widths and quantum numbers $J^{PC}$ have been predicted. Detailed analysis of the experimental status of these states and various theoretical models can be found in numerous new review articles [2–5].

In the first trials, the new charmonium-like resonances, discovered in the above experiments, were evaluated as the excited states of ordinary $cc$ charmonium states. However, the obtained data showed that some resonances do not conform to standard spectroscopy and thus some new non-conventional models have been developed. The new models proposed differ from each other in terms of their components and strong interaction mechanisms. There are plenty of studies for the physical picture interpretation of the charmonium-like states using the new models: for instance, QCD tetraquark [6, 7], weakly bound hadronic molecule [8–14], charmonium hybrids [15–19], threshold cups [20–23] and hadro-charmonium [24, 25]. Understanding the non-perturbative behaviour of QCD and the strong interaction dynamics that cause the production and structure of these non-conventional states are very important issues at the today’s experimental and theoretical studies.

As candidates of tetraquark states, $Z_{c}^{\pm}(3900)$ were reported simultaneously by the BESIII Collaboration [26] made in $e^+e^-$ annihilation at the vector resonance $Y(4260)$ and Belle Collaboration [27] with the same process but at or near the $Y(nS)$ $(n = 1, 2, ..., 5)$ resonances. For the full history see [28–30]. They were confirmed by the CLEO-c Collaboration using 586 pb$^{-1}$ of $e^+e^-$ annihilation data taken at the CESR collider at $\sqrt{s} = 4170$ MeV, the peak of the charmonium resonance (4160). They also reported evidence for $Z_{c}^{0}(3900)$ which is the neutral member of this isospin triplet [31]. In the process of the study [32] $e^+e^- \rightarrow \pi^\pm (D\bar{D}^*)^\mp$ at $\sqrt{s} = 4.26$ GeV using a 525 pb$^{-1}$ data collected at the BEPCII storage ring, the determined pole mass $M_{pole} = (3883.9 \pm 1.5(stat) \pm 4.2(syst))$ MeV/c$^2$ and pole width $\Gamma_{pole} = (24.8 \pm 3.3(stat) \pm 11.0(syst))$ MeV were reported with significance of 2$\sigma$ and 1$\sigma$, respectively. It was referred as $Z_{c}^{0}(3885)$. BESIII also observed a new neutral state $Z_c(3900)^0$ in a process $e^+e^- \rightarrow \pi^0\pi^0J/\psi$ with a significance of 10.4$\sigma$. The measured mass and width were $(3894.8 \pm 2.3(stat)\pm 3.2(syst))$ MeV/c$^2$ and $\Gamma_{pole} = (29.6 \pm 8.2(stat)\pm 8.2(syst))$ MeV, respectively [33]. In the study [34], after the full construction of the $D$ meson pair and the bachelor $\pi^\pm$ in the final state, the existence of the charged structure $Z_c^\pm(3885)$ was confirmed in the ($DD^*)^\mp$ system and its pole mass and width were measured as $M_{pole} = (3881.7 \pm 1.6(stat) \pm 1.6(syst))$ MeV/c$^2$ and pole width $\Gamma_{pole} = (26.6 \pm 2.0(stat) \pm 2.1(syst))$ MeV, respectively. In he processes $e^+e^- \rightarrow D^+D^-\pi^0$ + c.c. and $e^+e^- \rightarrow D^0D^{\ast-}\pi^+ + c.c.$ at $\sqrt{s} = 4.226$ and 4.257 GeV the neutral structure $Z_c(3885)^0$ was observed with the pole mass $(3885.7^{+4.3}_{-4.0}(stat)\pm 8.4(syst))$ MeV/c$^2$ and pole width $(35.7^{+1.1}_{-1.2}(stat) \pm 15(syst))$ MeV [35]. In a very recent study of D0 Collaboration, the authors presented evidence for the $Z_c^\pm (3900)$ state decaying to $J/\psi\pi^\pm$ in...
semi-inclusive weak decays of $b-$flavored hadrons [36].

On theoretical side, for investigation of $Z_c(3900)$ resonance, a plenty of different models and approaches are used, some of them are mentioned here as examples. In a recent study [37], using the three-channel Ross-Shaw theory the authors have obtained constraint conditions that need to be satisfied by various parameters of the theory in order to have a narrow resonance close to the threshold of the third channel, it is relevant to the structure. Using the QCD sum rule method, the same state was considered as a compact tetraquark state of diquark-antidiquark configuration in [38–40] and a hadronic molecule in [41, 42]. In these studies, many parameters related to the $Z_c(3900)$ state were calculated. Its mass was already calculated within the framework of a non-relativistic quark model in [43], as well.

Despite a lot of the theoretical and experimental efforts, unfortunately, the nature and internal structures of most of the exotic states including $Z_c(3900)$ are not exactly clear. Hence, investigation of their properties at a dense/hot medium can play an important role. The experiments like PANDA will provide a possibility to explore these states at a dense medium. These studies will help us better understand the quark-gluon organization of the exotic states as well as their interactions with the particles existing in the medium. In our previous study, Ref. [44], we investigated the $X(3872)$ state by applying a diquark-antidiquark type current in the framework of in-medium QCD sum rule. We calculated the mass, current-meson coupling and also the vector self-energy of this state and found that these parameters strongly depend on the density of the medium. In the present study, we investigate the effects of a dense medium on the parameters of the $Z_c(3900)$ state and look for the behavior of the mass, current-meson coupling and vector self-energy of this charmonium-like state considering it as a compact tetraquark state.

After the introduction, the rest of the study is organized in the following way. In Sec. II, we derive the spectral densities associated to the state $Z_c(3900)$ by applying the two-point sum rule technique and obtain the QCD sum rules for the mass, current-meson coupling and vector self-energy using the obtained spectral densities. In section III, after fixing the auxiliary parameters using the standard prescriptions of the method, the numerical analysis of the physical observables both in vacuum and cold nuclear matter is performed. Section IV is devoted to discussion and concluding remarks.

II. IN-MEDIUM MASS AND CURRENT COUPLINGS OF THE $Z_c(3900)$

Hadrons are formed as a result of some non-perturbative effects at low energies very far from the asymptotic region of QCD. Hence, for investigation of their properties, some non-perturbative methods are needed. QCD sum rule appears as a reliable, powerful and predictive approach in this respect. In this approach, the hadrons are represented by interpolating currents, written considering the quark contents and all the quantum numbers of hadrons. From the theoretical studies in vacuum and the experimental data, the quantum numbers $J^{PC}=1^{-+}$ has been assigned for $Z_c(3900)$. The comparison of the theoretical predictions on some parameters of this state with the experimental data leads us consider a compact tetraquark of a diquark and an antidiquark structure for this state [39, 40]. Thus, the interpolating current representing the $cc\bar{d}d$ quark content and $J^{PC}=1^{-+}$ quantum numbers can be written as

$$J_\mu(x) = \frac{i\epsilon_{abc}\epsilon_{dec}}{\sqrt{2}} \left\{ u^T_a(x) C\gamma_\mu c_b(x) \left[ \bar{d}_d(x) \gamma_\mu C\bar{c}^T_c(x) \right] - \left[ u^T_a(x) C\gamma_\mu c_b(x) \left[ \bar{d}_d(x) \gamma_\mu C\bar{c}^T_c(x) \right] \right\},$$

where $\epsilon_{abc}$ and $\epsilon_{dec}$ are anti-symmetric Levi-Civita symbols in three dimension with color indices $a, b, c, d$ and $e$. The letter $T$ represents a transpose in Dirac space, $\gamma_5$ and $\gamma_\mu$ are Dirac matrices and $C$ is the charge conjugation operator.

In the framework of QCD sum rule, we aim to obtain the sum rules for the mass, current coupling and vector self-energy of the exotic state $Z_c$ in cold nuclear matter. In the generalization of the vacuum QCD sum rules to finite density, we start with the same correlation function of interpolating currents as the vacuum with a difference that, in this case, the time ordering product of the interpolating currents are sandwiched between the ground state of a finite density medium instead of vacuum [45]. So, we start with the following in-medium two point correlation function as the building block of the method:

$$\Pi_{\mu\nu}(p) = i \int d^4x e^{ipx} \langle \psi_0| T[J_\mu(x)J^\dagger_\nu(0)]|\psi_0\rangle,$$
A. The phenomenological window

The phenomenological side of the correlation function is determined in a few steps: firstly, it is saturated by a full set of hadronic states carrying the same numbers as the interpolating current, and then the contribution of the ground state is isolated. As a result, we get

$$\Pi^{\text{Phe}}_{\mu\nu}(p) = -\frac{m_Z^2 f_{Z_c}^2}{p^2 - m_Z^2} \left[ -g_{\mu\nu} + p_{\mu} p_{\nu} \right] + ..., \quad (3)$$

where $p^*$ is the in-medium momentum and dots denote contributions arising from higher resonances and continuum states. The decay constant or current-meson coupling is expressed in terms of the polarization vector $\varepsilon_\mu$ of $Z_c$ as

$$\langle \psi_0 | J_\mu | Z_c(p) \rangle = f_{Z_c}^2 m_Z^2 \varepsilon_\mu, \quad (4)$$

which further simplifies Eq. (3). By summing over the polarization vectors, we can recast the phenomenological side of the correlation function into the form

$$\Pi^{\text{Phe}}_{\mu\nu}(p) = -\frac{m_Z^2 f_{Z_c}^2}{p^2 - m_Z^2} \left[ -g_{\mu\nu} + p_{\mu} p_{\nu} \right] + ..., \quad (5)$$

To proceed, we introduce two self-energies: the scalar self-energy $\Sigma_s = m_Z^2 - m_{Z_c}$, and the vector self-energy $\Sigma_v$ appears in the expression of the in-medium momentum, $p^*_\mu = p_\mu - \Sigma_v u_\mu [46]$, where $u_\mu$ is the four velocity vector of the cold nuclear medium. We work in the rest frame of the medium, i.e. $u_\mu = (1,0)$ . As a result, one can write

$$\Pi^{\text{Phe}}_{\mu\nu}(p) = -\frac{m_Z^2 f_{Z_c}^2}{p^2 - m_Z^2} \left[ -g_{\mu\nu} + p_{\mu} p_{\nu} \right] - \Sigma_v p_\mu u_\nu - \Sigma_v p_\nu u_\mu + \Sigma_v^2 u_\nu u_\mu \right] + ..., \quad (6)$$

where $\mu^2 = m_Z^2 - \Sigma_v^2 + 2p_0 \Sigma_v$, with $p_0 = p.u$ being the energy of the quasi-particle. The Borel transformed form (Borel with respect to $p^2$) of the phenomenological representation reads

$$\Pi^{\text{Phe}}_{\mu\nu}(p) = f_{Z_c}^2 e^{-\mu^2/M^2} \left[ -g_{\mu\nu} m_Z^2 \right] + p_{\mu} p_{\nu} - \Sigma_v p_\mu u_\nu - \Sigma_v p_\nu u_\mu + \Sigma_v^2 u_\nu u_\mu \right] + ..., \quad (7)$$

where $M^2$ is the Borel mass parameter to be fixed later using the standard recipe of the method.

B. The OPE or QCD window

The QCD side of the calculations can be obtained by inserting the interpolating current $J_\mu(x)$ into the correlation function and performing all possible contractions of the quark pairs. The resultant equation is a expression in terms of the in-medium light ($S^{ij}_q$) and heavy quark ($S^{ij}_q$) propagators:

$$\Pi^{\text{OPE}}_{\mu\nu}(p) = -\frac{i}{2} \varepsilon_{abc} \varepsilon_{a'b'c'} \varepsilon_{dec} \varepsilon_{d'e'e'} \times \int d^4x e^{ipx} \left\{ \mathcal{T}_r \left[ \gamma_5 \hat{S}^a_{c'}(x) \gamma_5 S^{bb'}_{c}(x) \right] \right. \times \mathcal{T}_r \left[ \gamma_\mu \hat{S}^b_{c}(x) \gamma_\nu \hat{S}^{dd'}_{c}(x) \right] - \mathcal{T}_r \left[ \gamma_\mu \hat{S}^a_{c}(x) \gamma_\nu \hat{S}^{dd'}_{c}(x) \right] \times \mathcal{T}_r \left[ \gamma_5 \hat{S}^a_{c}(x) \gamma_5 \hat{S}^{bb'}_{c}(x) \right] - \mathcal{T}_r \left[ \gamma_5 \hat{S}^a_{c}(x) \gamma_5 S^{dd'}_{c}(x) \right] \times \mathcal{T}_r \left[ \gamma_5 \hat{S}^{a'b'}_{c}(x) \gamma_\nu \hat{S}^{dd'}_{c}(x) \right] \times \mathcal{T}_r \left[ \gamma_5 \hat{S}^a_{c}(x) \gamma_5 S^{bb'}_{c}(x) \right] + \mathcal{T}_r \left[ \gamma_5 \hat{S}^{a'b'}_{c}(x) \gamma_\nu \hat{S}^{dd'}_{c}(x) \right] \times \mathcal{T}_r \left[ \gamma_5 \hat{S}^a_{c}(x) \gamma_5 S^{bb'}_{c}(x) \right] \times \mathcal{T}_r \left[ \gamma_5 \hat{S}^{a'b'}_{c}(x) \gamma_\nu \hat{S}^{dd'}_{c}(x) \right] \right\} \langle \psi_0 \rangle, \quad (8)$$

where $\hat{S}_{q(c)} = CST_{q(c)} C$.

The in-medium light and heavy quark propagators at coordinate space in the fixed point gauge and $m_q \rightarrow 0$ limit are given as

$$S^{ij}_q(x) = \frac{i}{2\pi^2} \frac{3 \delta^{ij}}{(x^2)^2} \not{q} + \chi_q^{ij}(x) \bar{\chi}_q^{ij}(0)$$

and

$$S^{ij}_c(x) = \frac{i}{2\pi^4} \int \frac{d^4k}{(2\pi)^4} e^{-ik\cdot x} \left\{ \frac{\delta^{ij}}{k - m_c} - \frac{g_s F^{ij}_{\mu}(0)}{2\pi} \frac{\sigma^{\mu\nu}(k - m_c)}{(k^2 - m_c^2)^2} \right\} + \frac{\pi^2}{3} \frac{\alpha_s GG}{\pi} \delta^{ij} m_c \left\{ \frac{k^2 + m_c}{(k^2 - m_c^2)^2} \right\} \times \bar{\chi}_q^{ij}(0) \langle \psi_0 \rangle, \quad (10)$$

In above equations, $\chi_q^{ij}$ and $\bar{\chi}_q^{ij}$ are the Grassmann background quark fields and

$$F^{ij}_{\mu}(x) = F^{ij}_{\mu\nu} A, \quad A = 1, 2, ..., 8, \quad (11)$$

where $F^{ij}_{\mu\nu}$ are classical background gluon fields, and $\lambda^{ij,A}$, with $\lambda^{ij,A}$ being the standard Gell-Mann matrices. The next step is to use the expressions of the quark propagators in Eq. (8). This leads to two main contributions: perturbative and nonperturbative. The perturbative contributions, which represent the short distance effects are calculated directly by applying the Fourier, Borel and continuum subtraction procedures. The nonperturbative or long distance contributions are expressed in terms of the in-medium quark, gluon and mixed condensates. For the explicit expressions of the condensates and the details of their expansions in terms of different operators see, for instance, Ref. [44]. After insertion of the in-medium condensates in terms of...
various operators, the Fourier and Borel transformations as well as continuum subtraction are also applied to the nonperturbative part of the QCD side.

The QCD side of the correlation function can be decomposed over the selected Lorentz structures as

$$
\Pi_{\mu\nu}^{QCD}(p) = -\mathcal{Y}_1^{QCD}(p^2)g_{\mu\nu} + \mathcal{Y}_2^{QCD}(p^2)P_{\mu}P_{\nu}
- \mathcal{Y}_3^{QCD}(p^2)P_{\mu}u_{\nu} - \mathcal{Y}_4^{QCD}(p^2)u_{\mu}u_{\nu}
+ \mathcal{Y}_5^{QCD}(p^2)u_{\mu}u_{\nu},
$$

(12)

where the invariant functions $\mathcal{Y}_i^{QCD}$ ($i = 1, \ldots, 5$) in Eq. (12) are given in terms of the following dispersion integrals:

$$
\mathcal{Y}_i^{QCD}(p^2) = \int_{4m_c^2}^{\infty} \frac{\rho_i^{QCD}(s)}{s - p^2} ds,
$$

(13)

where $\rho_i^{QCD}(s)$ are the two-point spectral densities related to the imaginary parts of the selected coefficients.

The main purpose of the QCD side of the calculations is to calculate these spectral densities. To this end and after insertion of the quark propagators into the correlation function we use the relation

$$
\frac{1}{(x^2)^m} = \int \frac{d^Dk}{(2\pi)^D} e^{-ikx} (-1)^{m+1} x^{D-2m} \frac{\Gamma[D/2-m]}{\Gamma[D/2]} \frac{1}{(1-x)^{D/2-m}},
$$

(14)

to bring $x$ to the exponential. By this way, the resultant expressions contain four four-integrals: one over four-$k$ coming from the above relation one initially existing in the correlation function (integral over four-$x$) and the last two over four-$k_1$ and four-$k_2$ coming from the heavy quarks propagators. The next step is to perform the four integral over $x$, which give a Dirac delta function. We use this function to perform integral over $k_1$. The remaining two integrals over four-$k_2$ and four-$k$ are performed using the Feynman parametrization and the formula

$$
\int d^4 \epsilon \frac{(-\epsilon^2)^m}{(\epsilon^2 + \Delta)^n} = \frac{i\pi^2 (-1)^{m-n} \Gamma[m+2] \Gamma[n-m-2]}{\Gamma[2] \Gamma[n] (-\Delta)^{n-m-2}}.
$$

(15)

Finally, by applying the relation

$$
\Gamma \left[ \frac{D}{2} - n \right] \left( - \frac{1}{\Delta} \right)^{D/2-n} = \frac{(-1)^{n-1}}{(n-2)!} (-\Delta)^{n-2} \ln(-\Delta),
$$

(16)

and expansion of $\ln(-\Delta)$, we get the imaginary parts of the $\mathcal{Y}_i^{QCD}$ functions.

We apply the Borel transformation with respect to the variable $p^2$ and perform subtraction procedure according to the standard prescriptions of the method. As a result, we get

$$
\mathcal{Y}_i^{QCD}(M^2, s_0^2) = \int_{4m_c^2}^{s_0^2} ds \rho_i^{QCD}(s) e^{-\frac{M^2}{s}},
$$

(17)

where $s_0^2$ is the in-medium continuum threshold parameter separating the contributions of the ground state $Z_c$ and higher resonances and continuum. It will be fixed later. The spectral density related to each structure is the sum of the spectral densities of the perturbative (pert), two-quark ($qq$), two-gluon ($gg$) and mixed quark-gluon ($qgq$) parts:

$$
\rho_i^{QCD}(s) = \rho_i^{pert}(s) + \rho_i^{qq}(s) + \rho_i^{gg}(s) + \rho_i^{qgq}(s).
$$

(18)

As an example, for the $g_{\mu\nu}$ structure, we present the explicit forms of these spectral densities:

$$
\rho_1^{pert}(s) = -\frac{1}{3072\pi^6} \int_0^1 dz \int_0^{1-z} dw \frac{1}{\xi^8} \left[ wz \left( swz(w + z - 1) - m_c^2 \right) \left( w^3 + w^2(2z - 1) + 2w(z - 1)z + (z - 1)^2z^2 \right) \right.
+ 26m_c^2 w^2 \left( w^4 + w^3(3z - 2) + w^2(4z^2 - 5z + 1) + w(z^-3 - 5z + 2) + (z - 1)^2z^2 \right) \left. + 35s^2w^2z^2(w + z - 1)^2 \right] \Theta[L(s, z, w)],
$$

(19)
\[ \rho_1^{\rho s}(s) = \frac{1}{4\pi^4} \int_0^1 dz \int_0^1dw \left\{ \frac{m_w}{4\rho^5} \left[ -im_c \left[ m_c^2 \left( 4w^6z + w^5(24z^2 - 8z + 1) \right) \right] + w^5(32z^3 - 44z^2 + 6z - 1) + w^3z(60z^3 - 80z^2 + 55z - 2) + w^2z^2(40z^3 - 68z^2 + 95z - 34) + 6wz^3(2z^2 - 4z^2 + 13z - 11) + 33(z - 1)^2z^4 \right] + wz(4p_0^2(4w^3z + w^2(16z^2 - 4z + 1) - 12w(z - 1)z^2 + z^2) - 3s(4w^3z + w^2(16z^2 - 4z + 1) + 12w(z - 1)z^2 + 17z^2)) \right\} \left\{ u^1 D_0 u \right\} + \frac{1}{1536(w - 1)\xi^2\rho^6} \left[ m_c^2 (w - 1)(w^2 + w(z - 1)z^2 + 12w^2z + 2w^2z^2) \right] \right\} \Theta[L(s, z, w)], \]
\[
\rho_{1}^{\text{gg}}(s) = \int_{0}^{1} dz \int_{0}^{1-z} dw \left[ \rho_{1,1}^{\text{gg}}(s) + \rho_{1,2}^{\text{gg}}(s) + \rho_{1,3}^{\text{gg}}(s) + \rho_{1,4}^{\text{gg}}(s) + \rho_{1,5}^{\text{gg}}(s) \right] \Theta[L(s, z, w)],
\]

where

\[
\rho_{1,1}^{\text{gg}}(s) = \frac{1}{96\pi^{4}} \left[ -\frac{m_{c}}{\kappa} \left( 4u_{0}^{2}w + w^{3}(24z^{2} - 8z + 1) + w^{4}(52z^{3} - 44z^{2} - 2z - 1) + 3w^{3}z \times (60z^{3} - 80z^{2} + 31z + 6) + w^{2}z^{2}(40z^{3} - 68z^{2} + 71z - 18) + 2wz^{3}(6z^{3} - 12z^{2} + 35z - 29) + 33(z - 1)z^{4} \left( w^{2} + w(z - 1) + (z - 1)z \right) \right) ^{3} + wz(w + z - 1) \left( 4p_{0}^{2}(4u_{0}w z + 3w^{2}z^{2} - 210z^{4} + 463z^{3} - 642z^{2} + 490z - 82) + w^{3}(z - 1)^{2}z^{3}(52z^{3} - 52z^{2} + 229z - 164) + 3w(z - 1)^{3}z^{3}(4z^{2} - 4z + 17) + (z - 1)^{3}z^{5} - s(12wz^{3} + w^{5}(4z^{2} - 8z + 3) + w^{7}(252z^{5} - 324z^{4} + 121z - 9) + w^{6}(480z^{4} - 900z^{3} + 713z^{2} - 195z + 9) + w^{5}(624z^{5} - 152z^{4} + 1730z^{3} - 986z^{2} + 159z - 3) + w^{4}(576z^{5} - 169z^{4} + 2500z^{3} - 2600z^{2} + 709z - 49) + 2w^{3}z^{2}(186z^{5} - 630z^{4} + 1125z^{3} - 1218z^{2} + 635z - 98) + w^{2}(z - 1)^{2}z^{3}(156z^{3} - 276z^{2} + 589z - 292) + w(z - 1)^{3}z^{4}(36z^{2} - 36z + 193) + 51(z - 1)^{3}z^{5}) \right] \left( \langle u D_{0} \bar{D}_{0} w \rangle \right)_{p},
\]

\[
\rho_{1,2}^{\text{gg}}(s) = \frac{1}{12\pi^{4}} \left[ m_{c}w^{2} \xi \left( w(z + 1) + (z - 1)z \right) \right] - wz \xi \times \left( 8p_{0}^{2}(3w^{4} + w^{3}(7z - 6) + w^{2}(7z - 6) + w^{2}(10z^{2} - 14z + 3) + wz(6z^{2} - 13z + 7) + 3(z - 1)^{2}z^{2} - s(5w^{4} + 2w^{3}(6z - 5) + w^{2}(17z^{2} - 24z + 5) + 2wz(5z^{2} - 11z + 6) + 5(z - 1)^{2}z^{2}) \right) \left( \langle \bar{d} D_{0} d_{0} \rangle \right)_{p},
\]

\[
\rho_{1,3}^{\text{gg}}(s) = \frac{1}{90\pi^{4}} \left[ m_{c} \left( wz(w + z - 1)(2p_{0}^{2}(4u_{0}w z + 3w^{2}z^{2} - 210z^{4} + 463z^{3} - 642z^{2} + 490z - 82) + w^{3}(z - 1)^{2}z^{3}(52z^{3} - 52z^{2} + 229z - 164) + 3w(z - 1)^{3}z^{3}(4z^{2} - 4z + 17) + (z - 1)^{3}z^{5} - s(12wz^{3} + w^{5}(4z^{2} - 8z + 3) + w^{7}(252z^{5} - 324z^{4} + 121z - 9) + w^{6}(480z^{4} - 900z^{3} + 713z^{2} - 195z + 9) + w^{5}(624z^{5} - 152z^{4} + 1730z^{3} - 986z^{2} + 159z - 3) + w^{4}(576z^{5} - 169z^{4} + 2500z^{3} - 2600z^{2} + 709z - 49) + 2w^{3}z^{2}(186z^{5} - 630z^{4} + 1125z^{3} - 1218z^{2} + 635z - 98) + w^{2}(z - 1)^{2}z^{3}(156z^{3} - 276z^{2} + 589z - 292) + w(z - 1)^{3}z^{4}(36z^{2} - 36z + 193) + 51(z - 1)^{3}z^{5}) \right] \left( \langle \bar{u} g_{\sigma} G_{\ell} \rangle \right)_{p},
\]
In this section, the QCD sum rules presented in Eq. (92) are used to investigate the behavior of the mass, current-meson coupling and vector self energy of $Z_c$ state in cold nuclear matter. To this end we need the values of some input parameters and in-medium condensates entering the expressions of the obtained sum rules. The in-medium expectation values of different operators together with some other input parameters used in the calculations are: $\rho^{aat} = 0.11^3$ GeV$^3$, $\rho_0 = 3887.2 \pm 2.3$ MeV [1], $\langle \bar{q}q \rangle_\rho = \frac{3}{2} \rho$, $\langle \bar{q}q \rangle_0 = (-0.241)^3$ GeV$^3$ [47], $\langle \bar{q}q \rangle_\rho = \langle \bar{q}q \rangle_0 + \frac{g_{\pi N}}{2m_q}_\rho = 0.00345$ GeV [1], $\langle \bar{q}q \rangle_\rho = (0.33 \pm 0.04)^4$ GeV$^4$, $\langle \bar{q}q \rangle_\rho = (0.05 \pm 0.1)^2$ GeV$^2$, $\rho_0 = 0.18$ GeV $\rho$, $\langle \bar{q}q \rangle_\rho = 0$, $\langle \bar{q}q \rangle_\rho = 0.8$ GeV$^2$ [47], $\langle \bar{q}q \rangle_\rho = 3^2$ GeV$^2$, $\rho_0 = 0.05 \pm 0.15$ GeV, $\rho_0 = 0.33$ GeV$^2$ $\rho$, $\rho_0 = 0.031$ GeV$^2$ $\rho$ - $\frac{1}{2}$ $\langle \bar{q}q \rangle_\rho = 0.12$ [45, 48]. The pion-nucleon sigma term $\sigma_{\pi N} = 0.045$ GeV [49] is used. The quark masses are taken as $m_u = 2.16^+_{0.09} - 2.26$ MeV, $m_d = 4.67^+_{0.48} - 0.17$ MeV and $m_c = 1.27 \pm 0.02$ GeV [1].

Besides these inputs, the sum rules in Eqs. (29) require fixing of two auxiliary parameters: Borel mass parameter $M^2$ and the in-medium continuum threshold $s_0^\rho$. To proceed, we need to determine their working regions, such that the in-medium mass, current coupling the vector self energy show mild variations with respect to the changes in these parameters. The upper and lower limits for $M^2$ is determined via imposing some conditions according to the standard prescriptions of the method (for details in the case of doubly heavy baryons see for instance [50, 51]). The working window for $s_0^\rho$ is obtained such that the maximum possible pole contribution is obtained and the physical observables show weak dependence on the auxiliary parameters. These requirements lead to the working windows for auxiliary parameters displayed in Table (1). As is seen from Fig. (1), the average pole contribution changes in the interval $[57\% - 23\%]$ corresponding to $M^2 = [3 - 5]$ GeV$^2$.
in the case of tetraquarks. Our analyses show that the OPE series of sum rules converge very nicely within the working windows of the auxiliary parameters.

Prior to the investigation of the behavior of the in-medium physical quantities, we would like to extract the vacuum mass value for $Z_c$ state. The in-medium sum rules in the limit $\rho \to 0$ lead to the average value of vacuum mass as (3932 +125 /−86 ) MeV. We compare this value with the experimental data and other theoretical predictions in vacuum in Table (II). As is seen, our prediction for the vacuum mass of $Z_c$ obtained via in-medium sum rules in $\rho \to 0$ limit is consistent with other presented results within the errors arising mainly from the choice of the auxiliary parameters $M^2$ and $s_0$. Note that for Ref. [52], we presented only one of the results obtained via different scenarios. This result is the closest result to the average experimental value.

Now, we proceed to display the behavior of physical quantities under consideration, with respect to the Borel mass and continuum threshold parameters at saturation nuclear matter density, $\rho^{sat} = 0.113 \text{ GeV}^3$. In this respect, we plot the ratio of the in-medium mass to vacuum mass, $m^*_Z/m_{Z_c}$, and the ratio of the in-medium current meson coupling to it’s vacuum value, $f^*_Z/f_{Z_c}$, in Fig. (2). As it is clearly seen, the physical quantities show elegant stability against the changes in the parameters $M^2$ and $s_0$, in their working regions. At the saturation nuclear matter density the in-medium mass of $Z_c$ state decreases to approximately 77% of it’s vacuum mass and the shift in average current coupling value of the state due to nuclear medium is about 15%. In Fig. (3), the quantities $m^*_Z/m_{Z_c}$ and $\Sigma_{\nu}/m_{Z_c}$, with respect to $M^2$ at the average value of continuum threshold and saturation nuclear matter density are shown. As already mentioned, the average negative shift in the modified mass of $Z_c$ state due to cold nuclear matter (scalar self energy) is about 23% of the vacuum mass, whereas the vector self-energy, $\Sigma_{\nu}$, is obtained to be approximately 32% of the vacuum value.

The main objective in the present study is to investigate the variations of the physical quantities with respect to density of the nuclear medium. To this end, we plot Fig. (4), displaying $m^*_Z/m_{Z_c}$ and $f^*_Z/f_{Z_c}$ as functions of $\rho/\rho^{sat}$ at average values of the continuum threshold and Borel parameter. The saturation nuclear matter mass density is $\rho^{sat} = 2.7 \times 10^{15} \text{ g/cm}^3$, which is equivalent

| Method | $m_{Z_c}$ |
|--------|--------|
| PS IMQCDSR ($\rho \to 0$) | (3932 +125 /−86 ) MeV |
| Experiment | (3887.2 ± 2.3 ) MeV |
| [13] QCDSR | (3.88 ± 0.17 ) GeV |
| [53] QCDSR | (3.91 +0.11 /−0.09 ) GeV |
| [54] QCDSR | (3.89 +0.09 /−0.09 ) GeV |
| [52] AAD | (3893.2+3.7 /−2.7 ) MeV |
| [40] QCDSR | (3001+125 /−148 ) MeV |
| [19] QCDSR | (3.86 ± 0.27 ) GeV |

TABLE II: Experimental result and theoretical predictions of different methods for the vacuum mass of $Z_c$ state. PS means present study, AAD means amplitude analysis of the data and IMQCDSR refers to the in-medium QCD sum rules.

FIG. 1: The pole contribution in the $Z_c$ channel as a function of $M^2$ at saturation nuclear matter density and different fixed values of the in-medium continuum threshold.

FIG. 2: $m^*_Z/m_{Z_c}$ and $f^*_Z/f_{Z_c}$ as functions of $M^2$ at the saturated nuclear matter density, $\rho^{sat} = 0.113 \text{ GeV}^3$ and at fixed values of the continuum threshold.

FIG. 3: $m^*_Z/m_{Z_c}$ and $f^*_Z/f_{Z_c}$ as functions of $M^2$ at the saturated nuclear matter density, $\rho^{sat} = 0.113 \text{ GeV}^3$ and at fixed values of the continuum threshold.
to $\rho^{sat} = 0.16 \text{ fm}^{-3}$. However, we need to know the behavior of hadrons at higher densities, which will be accessible in heavy ion collision experiments. Neutron stars as natural laboratories are very compact and dense that may produce hyperons and even heavy baryons and exotic states based on the processes that may occur inside them. For a neutron star with mass $\sim 1.5 M_\odot$ the relevant core density is approximately $(2\rho^{sat} - 3\rho^{sat})$ and for the mass $\sim 2 M_\odot$ the same density is about $5\rho^{sat}$ [55]. Therefore, we would like to discuss the behavior of the mass and coupling constants up to densities comparable with the densities of the neutron stars. However, as it is clear from Fig. (4), the in-medium sum rules give reliable results up to $\rho/\rho^{sat} = 1$ and $\rho/\rho^{sat} = 1.1$ for $m^{*}_{Z_c}/m_{Z_c}$ and $f^{*}_{Z_c}/f_{Z_c}$, respectively. Hence, we need to extrapolate the results to include the higher densities. Our analyses show that the following fit functions well describe the ratios under consideration:

$$m^{*}_{Z_c}/m_{Z_c} = e^{-0.252x},$$

(30)

and

$$f^{*}_{Z_c}/f_{Z_c} = -0.251x^2 + 0.054x + 1.028,$$

(31)

where $x = \rho/\rho^{sat}$. From Fig. (4), we see that the fit results coincide with the sum rules predictions at lower densities. The results show that the mass exponentially decreases with respect to $x$ and reaches to roughly 30% of the vacuum mass at a density $5\rho^{sat}$. The coupling constant, however, rapidly changes with respect to $x$ and goes to zero at $x = 2.1$. This point may be considered as a pseudocritical density, at which hadrons are melted.

IV. DISCUSSION AND CONCLUSION

Despite a lot of experimental and theoretical effort, the structure, quark-gluon organization and nature of most exotic states remain unclear. The tetraquark state $Z_c(3900)$ is among the charmonium-like resonances that deserve more investigations in vacuum and a dense/hot medium in order to fix its nature. We considered it as a compact tetraquark and assigned a diquark-antidiquark structure to it with quantum numbers $J^{PC} = 1^{+-}$. We constructed in-medium sum rules to calculate its mass, current-coupling and vector self-energy in the cold nuclear matter. The result obtained for its mass at $\rho \to 0$ limit is compatible with the experimental data and vacuum theory predictions. At saturation density, the mass and current coupling receive negative shifts with respect to the vacuum values. These shifts amount 23% and 15% for the mass and current coupling, respectively. This state receives a repulsive vector self-energy with amount of 32% of its vacuum mass value at saturation nuclear matter density.

The in-medium experiments aim to reach higher densities. The neutron stars as the compact and dense objects are natural laboratories with densities 2 – 5 times greater than the saturation nuclear matter density. The processes occur in high densities may produce different kinds of hadrons, even the exotic states. Such experiments that take place in high densities will serve a good opportunity to study the exotic states like $Z_c$. Hence, to provide some phenomenological predictions, we investigated the behavior of the state under consideration with respect to density of the medium at higher densi-
ties. The in-medium sum rules are truncated at around $\rho/\rho^{sat} = (1 - 1.1)$. Thus, we used some fit functions in order to extrapolate the results to a density around $5\rho^{sat}$. The mass and current coupling constant decrease exponentially and quadratically with respect to density, respectively. The mass reaches to 30% of the vacuum mass at a density $5\rho^{sat}$. The current coupling however, rapidly decreases and goes to zero at a density $2.1\rho^{sat}$, which may be considered as a pseudocritical density for melting of the exotic charmonium-like states.

Investigation of properties of hadrons at finite temperature and density constitutes one of the main directions of the research in high energy and nuclear physics. Understanding the hadronic behavior under extreme conditions can help us not only understand the internal structure and nature of hadrons and get knowledge on the QCD as the theory of the strong interaction, but also can help us in analyzing the results of future experiments as well as in understanding different possible phases of matter.

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