HEAVY–LIGHT SUSCEPTIBILITIES IN THE sQGP*

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Received 5 August 2022, accepted 20 September 2022, published online 14 December 2022

We extend our previously developed T-matrix framework for the strongly-coupled quark–gluon plasma at vanishing chemical potential ($\mu_q = 0$) to finite values and utilize it to evaluate various quark number susceptibilities, especially in heavy–light channels. Specifically, we introduce a μ_q dependence into the quark propagators and interaction kernel using two new parameters which are fitted to lattice-QCD (lQCD) data for the baryon number susceptibility, χ_2^B. Without further tuning, we calculate the heavy–light susceptibilities and find that the resulting χ_{11}^{uc} and χ_{22}^{uc} are qualitatively consistent with lQCD data. This agreement suggests that the emergence of broad D-meson and charm-light diquark bound states in a moderately hot QGP is compatible with lQCD results.

DOI:10.5506/APhysPolBSupp.16.1-A92

1. Introduction

In ultra-relativistic heavy-ion collisions (URHICs), a deconfined state of matter — quark–gluon plasma (QGP) — can be created at extreme temperatures. Historically, the QGP was expected to be a weakly coupled plasma since the coupling strength should reduce at high temperature due to the asymptotic freedom of Quantum Chromodynamics (QCD) [1]. Various quantities computed in lattice QCD (lQCD), such as the equation of state or quark-number susceptibilities, can be fairly well described by perturbative-QCD (pQCD) calculations [2] down to temperatures as low as $T \simeq 250\,\mathrm{MeV}$, which seems to support the aforementioned expectation. However, as URHIC experiments and their phenomenology progressed over the last two decades, it has become increasingly evident that the QGP created in URHICs behaves

* Presented at the 29th International Conference on Ultrarelativistic Nucleus–Nucleus Collisions: Quark Matter 2022, Kraków, Poland, 4–10 April, 2022.

as a strongly-coupled liquid with a small shear-viscosity-to-entropy ratio and a large friction force for heavy quarks diffusing through it [4, 5]. However, many of the approaches that are used to extract these transport properties are not directly sensitive to the microscopic structure of QCD matter along with systematic constraints from various lQCD "observables", such as heavy–light susceptibilities [6, 7], which have been qualitatively reproduced by weakly coupled approaches [2].

To address this issue, we here employ the T-matrix approach [8–12] whose previously calculated transport coefficients [9] are similar to those inferred from experimental results [13] while also being constrained by lQCD "data", *i.e.*, the equation of state (EoS), heavy-quark (HQ) free energy, and Euclidean quarkonium correlators. Thus far, this approach has not been applied to quark-number susceptibilities, which are available from lQCD [6, 7, 14, 15] with good precision and which are believed to be sensitive to the degrees of freedom in the system. This, in particular, should provide a valuable test of the hadronic resonances which emerge in the in-medium T-matrices well above the pseudo-critical temperature of $T_{\rm pc} \simeq 160$ MeV and which are instrumental in generating a large interaction strength between the massive partons in the QGP. Toward this end, based on Ref. [16], in the present proceedings we discuss the generalization of the T-matrix approach to finite chemical potential (μ_q) in Section 2 and the resulting susceptibilities in Section 3, and finish with a summary in Section 4.

2. *T*-matrix approach at finite chemical potential

The T-matrix approach is based on a diagrammatic framework, where series resummations are carried out through integral equations, dictated by large values of the underlying Born amplitudes containing nonperturbative interaction kernels. In particular, t-channel ladder diagrams are resummed, which allows it to include the physics of dynamically generated bound states.

The methods developed in our previous works [9, 12] enable the calculation of the grand potential (negative pressure) non-perturbatively, utilizing the self-consistent Luttinger–Ward formalism [17, 18] whose thermodynamic consistency is compatible with the T-matrix approximation. We employ this method to calculate the pressure at finite μ_q and then take the derivatives to obtain the susceptibilities. The grand potential, Ω, has the form of

$$\Omega \equiv -P = \mp \sum \mathrm{Tr}\left\{\ln\left(-G^{-1}\right) + \left[\left(G^0\right)^{-1} - G^{-1}\right] G\right\} \pm \Phi\,, \qquad (1)$$

where the G^0 denotes "bare" propagators and $G = ([G^0]^{-1} - \Sigma)^{-1}$ are fully dressed ones with self-energy Σ. The Luttinger–Ward functional (LWF), Φ, accounts for dynamically-generated bound states upon resummation of the

t-channel ladder diagrams

$$\begin{aligned} \Phi &= \frac{1}{2}\sum \mathrm{Tr}\left\{G\left[V+\frac{1}{2}VG^0_{(2)}V+\ldots+\frac{1}{\nu}VG^0_{(2)}VG^0_{(2)}\ldots.V+\ldots\right]G\right\} \\ &= -\frac{1}{2}\ln\left[1-VG^0_{(2)}\right]. \end{aligned} \tag{2}$$

The two-body propagator, $G^0_{(2)} = -\beta^{-1}\sum_{\omega_n} G(iE_n-\omega_n)G(-i\omega_n)$, is an energy convolution over the Matsubara frequencies of two single-parton propagators, and V is their interaction kernel (or two-body potential). The resummation of the series in Eq. (2) is nontrivial due to the $1/\nu$ factor (necessary to eliminate double-counting), which can be performed using a matrix-log method developed in Refs. [9, 10]. The self-consistent self-energy Σ can be obtained by a functional derivative, $\delta\Phi/\delta G = \Sigma$ [18, 19] and expressed in terms of the T-matrix schematically as

$$\Sigma = \int \mathrm{d}\tilde{p}\, T\, G\,, \qquad T = V + VG^0_{(2)}T\,. \tag{3}$$

The T-matrix equation resums ladder diagrams, which matches the truncation of the LWF in Eq. (2).

Our input is specified by the "bare" propagators and potentials as

$$G^0(z,\boldsymbol{p}) = \frac{1}{z-\varepsilon_{\boldsymbol{p}}\pm\mu_i}\,, \qquad V(r) = -\frac{4}{3}\alpha_{\mathrm{s}}\frac{\mathrm{e}^{-m_d r}}{r} + \sigma\frac{\mathrm{e}^{-m_s r-(c_b m_s r)^2}}{m_s}\,, \tag{4}$$

where $\varepsilon_{\boldsymbol{p}} = \sqrt{M_i^2+\boldsymbol{p}^2}$ and the subscript i refers to either light ($i=q$) or charm ($i=c$) quarks. The two-body potentials used in Eqs. (2) and (3) are obtained from Fourier transforms and augmented with relativistic corrections in all available color channels. The parameter values for $\mu_i = 0$ are the same as the strongly-coupled solution in Ref. [10] unless otherwise stated. We introduce two additional parameters, b_s and b_m, to account for a chemical-potential dependence in the parton and screening masses as

$$M_i = M^i_{\mathrm{per}}\sqrt{1+b_m\left(\frac{\mu_q}{T}\right)^2} + M^i_V\,, \qquad m_d = m^0_d\sqrt{1+b_s\left(\frac{\mu_q}{T}\right)^2}\,. \tag{5}$$

The self-energy M^i_{per} is the perturbative part of the parton masses at zero chemical potential, which has been fixed in Ref. [10] by fitting the lQCD EoS, whereas M^i_V is self-consistently calculated from the potentials [10], which can also have a chemical-potential dependence through the μ_q-dependent potentials. The factor $\sqrt{1+b_{m/s}\left(\mu_q/T\right)^2}$ in M and m_d is motivated from hard-thermal loop (HTL) calculations [20].

3. Numerical studies

With the theoretical formalism described above, we calculate the pressure as a function of the light and charm-quark chemical potentials, $P(\mu_q, \mu_c)$, at a fixed temperature, using Eq. (1); the susceptibilities are obtained through numerical derivatives with respect to the μ_i [16].

To proceed, we first tune the two parameters b_m and b_s to reproduce the lQCD data on baryon number susceptibilities, χ_2^B [21, 22]. Their resulting temperature dependence is shown in the left panel of Fig. 1, while the comparison between the corresponding χ_2^B and lQCD data is shown in the left panel of Fig. 2. The resulting two-body potentials (middle panel of Fig. 1) exhibit a rather moderate screening even at sizable values for μ_q, with long-range remnants of the confining force surviving. With these "strong" potentials, the hadronic resonance structures, such as D-meson resonances, are supported at temperatures of $1.2\,T_{\rm pc}$ and above (see the right panel of Fig. 1). As mentioned above, these (dynamically generated) resonance states are essential for the transport properties of heavy flavor in the QGP [10, 23, 24].

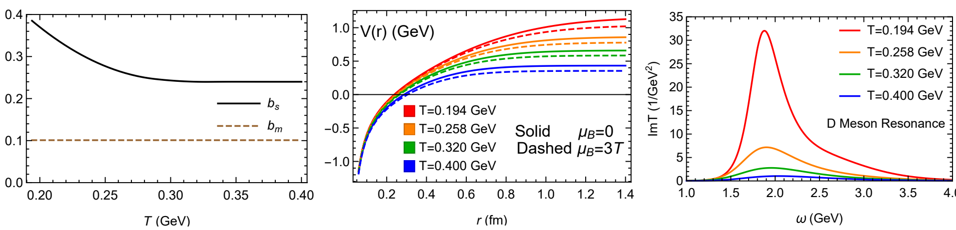

Fig. 1. Left panel: the new parameters, b_s and b_m, as obtained from the fit to χ_2^B; middle panel: the color-singlet potentials at finite chemical potential; right panel: D-meson resonances in the imaginary part of the T-matrix at zero $\mu_{q/c}$.

The HQ and heavy–light susceptibilities are obtained without retuning the b-parameters shown in Fig. 1. In particular, the pure charm susceptibilities $\chi_{2/4}^c$ are not affected by the finite-μ_q extension, *i.e.*, independent of the two new parameters and, therefore, direct predictions of the zero-μ theory in Refs. [9, 10]. They turn out to be close to each other and consistent with lQCD data, see the middle panel of Fig. 2. Compared to quasiparticle results, the off-shell effects generate a noticeable enhancement. The two heavy–light susceptibilities, χ_{11}^{uc} and χ_{22}^{uc}, plotted in the right panel of Fig. 2, also show fair agreement with lQCD data [6, 7]. In weakly coupled HTL calculations at low orders [2, 25], χ_{11}^{uc} is zero. This is the first time that this susceptibility has been computed in a strongly-coupled approach beyond the mean-field approximation, with the results found to be qualitatively consistent with lQCD data.

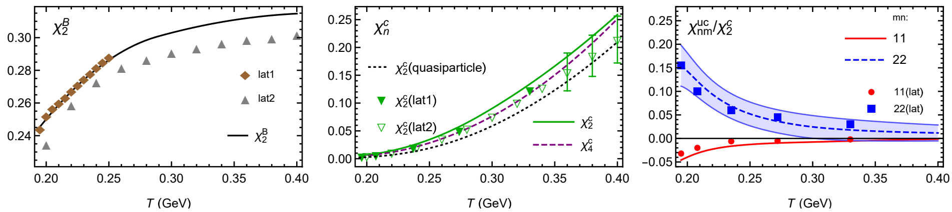

Fig. 2. Baryon number susceptibility χ_2^B (left); charm number susceptibilities $\chi_{2/4}^c$ (middle); off-diagonal heavy–light susceptibilities χ_{11}^{uc} and χ_{22}^{uc} normalized by χ_2^c (right).

4. Summary

We have extended a strongly-coupled approach to the QGP — the thermodynamic T-matrix — to finite chemical potential and utilized it to study quark number susceptibilities. Introducing two parameters that control the chemical potential dependence of the screening and parton masses, we can fit lQCD data for the baryon number susceptibility, χ_2^B. Without further tuning, we predict the charm susceptibilities, $\chi_{2/4}^c$, and find them to be consistent with lQCD results. Furthermore, the extracted heavy–light susceptibilities, χ_{11}^{uc} and χ_{22}^{uc}, also show fair agreement with lQCD results. This suggests that the strongly-coupled picture of the QGP obtained in the T-matrix approach is consistent with lQCD susceptibilities. Together with the constraints from several other types of lQCD data (*e.g.*, for the EoS, HQ free energies, and Euclidean quarkonium correlators) and the ability to generate transport parameters that are similar to those inferred from experiments, the in-medium T-matrix seems to provide a viable model for the microscopic description of the QGP, characterized by large parton scattering rates that highlight the quantum nature of the medium. A key role in this picture is played by remnants of the confining force surviving well above $T_{\rm pc}$, thereby dynamically generating hadronic resonances that provide the necessary partonic interaction strength.

This work is supported by the Fundamental Research Funds for the Central universities and by the U.S. National Science Foundation (NSF) through grant Nos. PHY-1913286 and PHY-2209335.

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