FLAVOR-DEPENDENT TRANSPORT PARAMETERS OF THE QUARK–GLUON PLASMA WITHIN THE QUASIPARTICLE MODEL*

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We study the transport properties of the deconfined QCD matter in pure SU(3) theory and full QCD with light and strange quark flavors. Applying the quasiparticle model to shear and bulk viscosities, as well as to electrical conductivity, we analyze flavor and temperature dependence of these parameters. The analytic expressions of the examined quantities are derived from the kinetic theory under the relaxation time approximation.

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1. Introduction

It is known that the quark–gluon plasma (QGP) is a strongly-coupled system [1] which can be reasonably described in terms of the ideal fluid dynamics. However, non-trivial transport properties of the non-equilibrated QGP remain of great interest to the elementary particle physics. The shear viscosity coefficient characterizes the resistance of a fluid against the momentum modifications, whereas the bulk viscosity reflects the response of the system to a change of its volume. The electrical or heat conductivities also reveal important information about the deconfined QCD matter. All transport parameters of the plasma depend on the degrees of freedom and the interactions between them. We present transport coefficients of the pure SU(3) gauge theory and of the QGP with 2 light (up, down) and 1 heavier (strange) quark flavors. For simplicity, we assume vanishing quark chemical potential, $\mu = 0$. The critical and pseudocritical temperatures are taken as $T_{\mathrm{c}} = 260$ MeV in pure Yang–Mills (YM) case and $T_{\mathrm{c}} = 155$ MeV in full QCD calculations.

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2. Quasiparticle model

The quasiparticle model (QPM) describes the quark–gluon plasma as a system of quarks and gluons with dynamically generated temperature-dependent masses, which carry all the interactions between the medium constituents. Hence, the quasiparticles are regarded as weakly interacting particles with effective masses. This assumption enables us to define equilibrium thermodynamic variables as standard phase-space integrals over the momentum-distribution functions. We consider the on-shell quasiparticles propagating with medium-dependent dispersion relations, $E_i = \sqrt{k^2 + m_i^2}$. The effective masses m_i^2 are obtained as

$$m_i^2 = \left(m_i^0\right)^2 + \Pi_i\,, \tag{1}$$

with bare masses $m_g^0 = 0$, $m_l^0 = 5$ MeV, $m_s^0 = 95$ MeV and dynamically generated self-energies $\Pi_i(G(T), N_{\mathrm{f}})$ which depend on the running coupling and the number of flavors. The effective coupling $G(T)$ is extracted from lattice QCD (lQCD) data in the way that the quasiparticle model reproduces the entropy density obtained from the lQCD simulations.

The approach presented in this section can be applied to YM thermodynamics of pure gluonic plasma using the simplification $N_{\mathrm{f}} = d_{l,\bar{l}} = d_{s,\bar{s}} = 0$. More details and numerical results on the coupling and masses can be found in [2].

3. Shear and bulk viscosities

To investigate the transport properties of the deconfined QCD matter, we employ the expressions for transport parameters derived from the kinetic theory in the relaxation time approximation [2–5]. The shear and bulk viscosities read

$$\eta = \frac{1}{15T} \sum_{i=g,l,\bar{l},s,\bar{s}} \int \frac{\mathrm{d}^3p}{(2\pi)^3} p^4 \frac{d_i \tau_i}{E_i^2} f_i^0 \left(1 \pm f_i^0\right)\,, \tag{2}$$

$$\zeta = \frac{1}{T} \sum_{i=g,l,\bar{l},s,\bar{s}} \int \frac{\mathrm{d}^3p}{(2\pi)^3} \frac{d_i \tau_i}{E_i^2} f_i^0 \left(1 \pm f_i^0\right) \left\{\left(E_i^2 - T^2 \frac{\partial m_i^2}{\partial T^2}\right) \frac{\partial P}{\partial \epsilon} - \frac{p^2}{3}\right\}^2 . \tag{3}$$

The values of the degeneracy factors d_i for quarks, antiquarks and gluons are $d_{l,\bar{l}} = 12$ for light flavors, $d_{s,\bar{s}} = 6$ for strange quarks and $d_g = 16$ for gluons. The relaxation times τ_i explicitly depend on various two-body scatterings between the constituents of the medium. The factor $(1 \pm f_i^0)$ contains thermal distribution function for bosons (fermions) with the corresponding sign (+ and −, respectively). In Eq. (3), the pressure and the energy density are calculated as for the ideal gas of massive quasiparticles. Different values of the relaxation times and an additivity of the viscosity coefficients allow us to calculate the components of the sums in Eqs. (2) and (3) separately, to study the flavor dependence of the transport parameters.

Figure 1 shows the results on the shear viscosity to entropy density ratio which characterizes the dissipation of the energy in the medium. On the left, we present the results for pure Yang–Mills theory. The appearance of a minimum in the η/s ratio is understood as a natural consequence of the first-order phase transition in pure YM theory, whereas its value crucially depends on the dynamical details embraced in the cross section and the entropy density via the effective running coupling. The obtained smallness, $\eta/s \simeq 1/4\pi$, came out from the model dynamics, without any fine-tuning of the parameters. It is conceivable that since the underlying YM Lagrangian is conformal, the dynamics compels the η/s to become nearly the KSS bound conjectured based on the AdS/CFT correspondence. We compare our results to available lQCD data and the FRG approach, finding a remarkable agreement with the first-principle calculations. In Fig. 1 (right), individual contributions from different types of particles to the specific shear viscosity of the QGP are shown. One can see that the main contribution to the total ratio comes from the light quark sector. The presence of dynamical quarks in the system significantly increases the values of the total η/s ratio and smoothens its behavior near the crossover (in comparison to the pure SU(3) results around the first-order phase transition).

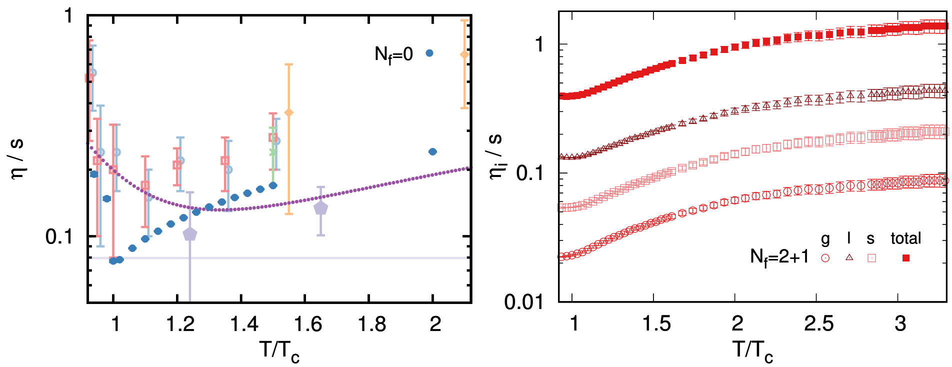

Fig. 1. Left: Shear viscosity to entropy density ratio for pure Yang–Mills theory in the QPM (full circles). For comparison, the corresponding lQCD results were collected. The horizontal line indicates the KSS-bound ($1/4\pi$) and the result obtained by the functional diagrammatic approach is shown by the dotted line (all references can be found in [2]). Right: Shear viscosity to entropy density ratio for full QCD with $N_{\rm f} = 2 + 1$ (full squares). Individual contributions coming from light quarks (triangles), strange quarks (open squares) and gluons (circles) are given separately.

We present the bulk viscosity to entropy density ratio in Fig. 2. The results for pure SU(3) theory are shown in the left figure. The bulk viscosity for quasigluon plasma appeared to be close to the results obtained within the holographic approach for the bulk viscosity of black holes [6]. The general tendency agrees with recent lattice QCD data [7]. In contrast to the specific shear viscosity, the bulk viscosity to entropy density ratio has a peak in the vicinity of the critical temperature and then vanishes as temperature grows. The results obtained for $N_\mathrm{f} = 0$ and $N_\mathrm{f} = 2+1$ are close to each other at lower temperatures and exhibit around a ten times difference already at $3\,T/T_\mathrm{c}$ (unlike the shear viscosity where the difference between YM theory and full QCD case is distinct in the explored temperature range). In the case of the specific bulk viscosity of the QGP for $N_\mathrm{f} = 2+1$ (Fig. 2, right), we observe an intriguing similarity between the contributions of strange quarks and gluons, although there is an apparent difference between them in the case of the shear viscosity.

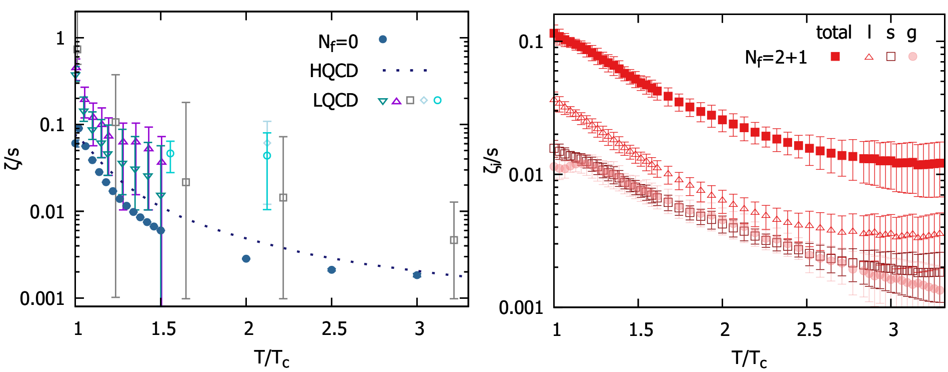

Fig. 2. Left: Bulk viscosity to entropy density ratio for the pure YM theory obtained in the QPM (full circles), as well as in the holographic QCD calculations [6] (dashed line). Various lattice QCD data points are taken from [8], the recent one is calculated by [7] (open triangles). Right: Bulk viscosity to entropy density ratio of the QGP for $N_\mathrm{f} = 2+1$. Full squares show the total ratio, whereas open bullets represent contributions coming from different type of quasiparticles.

4. Electrical conductivity

Similarly to the viscosity coefficients, electrical conductivity was derived within the kinetic theory [9] as follows:

$$\sigma = \frac{1}{3T} \sum_{i=u,\bar{u},d,\bar{d},s,\bar{s}} \int \frac{\mathrm{d}^3p}{(2\pi)^3} \frac{p^2}{E_i^2}\, q_i^2\, d_i\, \tau_i\, f_i^0 \left(1 - f_i^0\right) , \tag{4}$$

where electric charges of quarks are $q_u = -q_{\bar{u}} = 2/3\,e$ and $q_{d,s} = -q_{\bar{d},\bar{s}} = -1/3e$. Due to the different electric charges, the up and down quarks are treated separately. Thus, the degeneracy factors are $d_{u,\bar{u}} = d_{d,\bar{d}} = d_{s,\bar{s}} = 6$. Since gluons do not carry any electric charge, they do not contribute to the electrical conductivity and in the case of $N_\mathrm{f} = 0$, the system does not conduct the electric charge at all.

The resulting electrical conductivity of the QGP is shown in Fig. 3. On the left panel, we compare the values obtained within the presented QPM with the other effective models, such as parton–hadron string dynamics (PHSD), dynamical quasiparticle model (DQPM) and another model with quasiparticle degrees of freedom. We find an agreement between QPM results and two other effective studies (PHSD, DQPM), although there are essential differences between them, such as the effective coupling or the widths of quasiparticles. The apparent difference between our curve and the dashed line comes mostly from the fact that the relaxation times in our model depend on the quasiparticle masses, while the relaxation times in [9] are taken as for massless particles. One also sees that our result appears in between the several sets of the lQCD data. The right-hand side of Fig. 3 shows fractions of the electrical conductivity originated from the presence of different particle species. The main contribution is given by the up quarks due to their larger electric charge, while the down and strange quark contributions have similar values because of the same electric charges.

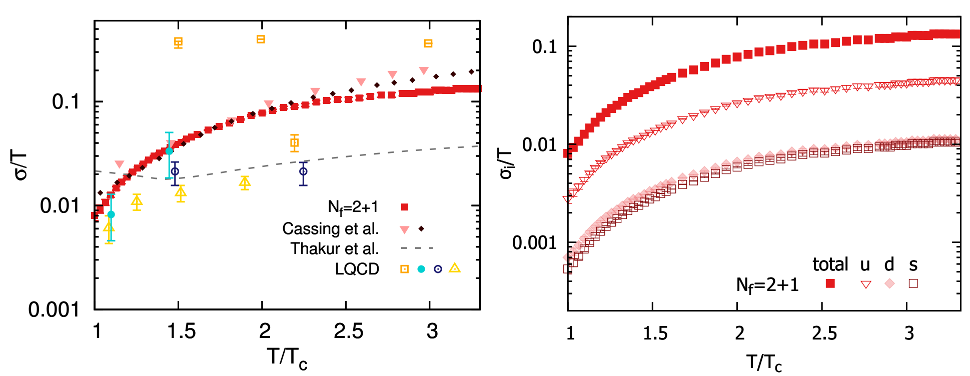

Fig. 3. Left: Total electrical conductivity of the QGP scaled with the temperature (full squares). Additionally, we show the results from the PHSD model (full triangles) and DQPM (full diamonds) by [10]. Another QPM result and various lQCD data are taken from [9]. Right: Ratio of the electrical conductivity to the temperature for full QCD: total value (full squares) is compared to the particular contributions from up (triangles), down (diamonds) and strange (open squares) quarks.

5. Conclusions

We studied the temperature and flavor dependence of the transport parameters of the QGP in pure YM theory and in QCD with 2+1 quark flavors in a framework of the quasiparticle model and kinetic theory in the relaxation time approximation. The results for shear viscosity, bulk viscosity and electrical conductivity were compared to the lattice gauge theory calculations and the data obtained within the other effective models. We find that adding physical degrees of freedom essentially modifies the transport properties of the system, which might be important for future hydrodynamical calculations.

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