

TRANSPORT PROPERTIES OF HOT GLUONIC MATTER*

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We discuss the temperature dependence of the scaled jet quenching parameter of hot gluonic matter within a quasiparticle approach. A pronounced maximum in the vicinity of the transition temperature is observed, where the ratio of the scaled jet quenching parameter and the inverse specific shear viscosity increases above typical values for weakly coupled systems.

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1. Introduction

Understanding the nature of QCD matter at high temperatures and densities means understanding the relevant degrees of freedom and their interaction. Immense efforts have been invested both in theory and in experiment in order to study the transport properties of strongly interacting matter, which can be described by certain transport coefficients. They determine the evolution and relaxation of conserved charge densities within dynamical systems. Shear (η) and bulk (ζ) viscosities, for example, describe the hydrodynamic response of a medium to energy and momentum density fluctuations. A firm knowledge of these transport coefficients would have a wide range of implications in cosmology, astrophysics and in nuclear physics.

Measurements at RHIC and LHC revealed that the matter produced in relativistic heavy-ion collisions behaves like an almost perfect fluid, *cf. e.g.* the reviews in [1, 2]. Indeed, the measured flow pattern is best described

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by assuming only small dissipative effects with a specific shear viscosity η/s (s is the entropy density in the system) of at most a few times the conjectured lower (KSS-)bound [3] $(\eta/s)_{\text{KSS}} = 1/(4\pi)$ which is based on holographic principles.

Another outstanding observation, made in central collisions of relativistic heavy nuclei, is that final state hadrons are strongly suppressed at large transverse momenta [4–8]. This phenomenon of jet quenching indicates that the produced matter is opaque, *i.e.* that coloured charges suffer from a sizeable energy loss while traversing the medium [9]. An important transport coefficient in the context of energy loss is the jet quenching parameter \hat{q} [10, 11] defined as the average squared transverse momentum transfer to a highly energetic particle per unit length due to multiple elastic scatterings with medium constituents. The parameter \hat{q} , thus, governs the transverse momentum broadening of propagating colour charges per unit length [10]. The probability for the formation of gluon bremsstrahlung depends sensitively on the efficiency by which a bremsstrahlung gluon decoheres from its emitter. As random scatterings with medium constituents accelerate this process, also the radiative energy loss of partons in the multiple scattering regime is governed by \hat{q} .

An intriguing question is whether different transport coefficients are fundamentally related with each other. In this work, we study the possible connection between η and \hat{q} within a quasiparticle approach, focusing on the case of pure hot, deconfined gluonic matter. In particular, the influence of a temperature dependent quasiparticle dispersion relation is investigated.

2. Relating shear viscosity and jet quenching parameter

In [12] it was demonstrated that η and \hat{q} are formally connected, when one assumes *(i)* that the strongly interacting medium is effectively describable within a partonic quasiparticle framework and *(ii)* that the interaction between an energetic parton and the partonic quasiparticles is of the same structure and strength as the interaction among the medium constituents. In this case, one finds the relation [12]

$$\frac{\hat{q}}{T^3} \simeq \frac{\rho}{12s} \frac{\langle p \rangle \langle \hat{s} \rangle}{T^3} \left(\frac{\eta}{s} \right)^{-1}, \quad (1)$$

where ρ is the quasiparticle density in the thermal medium with temperature T , $\langle p \rangle$ the average quasiparticle momentum and $\langle \hat{s} \rangle$ the average center-of-mass energy squared in soft, elastic quasiparticle scatterings.

When, in particular, a thermal ensemble of free massless bosons is considered, Eq. (1) becomes

$$\frac{\hat{q}}{T^3} \approx 1.25 \left(\frac{\eta}{s} \right)^{-1}. \quad (2)$$

According to [12], this relation is generally true for any weakly coupled partonic quasiparticle system, while for a strongly coupled system $\hat{q}/T^3 \gg (\eta/s)^{-1}$ is conjectured. In the following, we will investigate the relation Eq. (1) within a phenomenological quasiparticle model (QPM) [13, 14], in which gluonic quasiparticles obey a temperature dependent dispersion relation.

3. Viscosity coefficients of hot gluonic matter within a quasiparticle picture

In quantum field theories, transport coefficients such as the shear or bulk viscosity can be calculated within the framework of linear response theory from Kubo-relations [15, 16]. Likewise, kinetic theory, *e.g.* in the form of a linearized Boltzmann equation, can be applied as a rigorous tool for evaluating the transport properties of systems with weak interaction strength [17]. Here, the underlying assumption is that the dynamics of the system is describable in terms of weakly interacting quasiparticle excitations. Such a picture leads to a lower bound in η/s as consequence of the uncertainty principle, *cf.* [18].

By extrapolating perturbative QCD results for η/s [19] towards the confinement–deconfinement transition temperature T_c [20], one cannot explain the small values deduced from experiment. This, however, does not necessarily imply that any picture based on quasiparticle excitations is inadequate for describing the properties of the produced matter. Within the QPM [13, 14], based on an effective kinetic theory approach of Boltzmann–Vlasov type, the shear and bulk viscosities have been determined in [21] for the pure gluon plasma in relaxation time approximation and their ratio was studied in [22]. In this approach, the medium is viewed as being composed of quasigluons with the same quantum numbers and obeying the same quantum statistics as partonic gluons. They follow, however, a medium-modified dispersion relation featuring a temperature-dependent gluon mass which accommodates non-perturbative effects in the vicinity of T_c , *cf.* [14].

A fairly good quantitative agreement with the available lattice QCD results [23, 24] was obtained [21]. Both, specific shear and bulk viscosities, were found to exhibit a pronounced behaviour. At high T , η/s is large and shows the parametric dependencies known from perturbative QCD [19], while it has a minimum near T_c . In contrast, ζ/s is found to become large near T_c , similar to [25], while it vanishes logarithmically with increasing temperature.

4. Jet quenching parameter

Via Eq. (1), the scaled jet quenching parameter \hat{q}/T^3 can be obtained from η/s calculated within the QPM for pure gluodynamics. The result is shown in Fig. 1 (left panel). The pronounced maximum in \hat{q}/T^3 is a consequence of the minimum in η/s in the vicinity of T_c , *cf.* [21]. The solid curve is obtained for the QPM and relaxation time parametrizations used in [21], whereas the dashed curve is the result of the corresponding parametrizations advocated in [26]. We note that for the latter, η/s is quantitatively comparable with the results presented in [21], however, its minimum value is slightly below the KSS-bound.

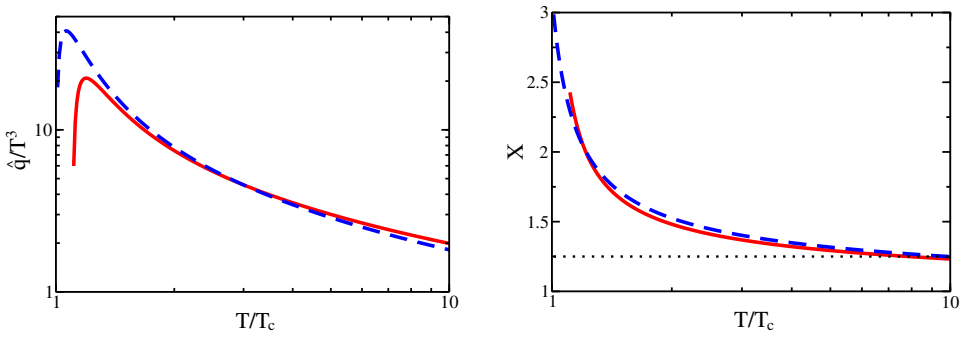


Fig. 1. Left: Scaled jet quenching parameter \hat{q}/T^3 as a function of T/T_c . Right: Ratio X , *cf.* the text for details.

As evident from the left panel of Fig. 1, the scaled jet quenching parameter is significantly enhanced just above T_c as compared to the high-temperature region, while for $T \rightarrow T_c^+$ it drastically drops down again. This implies that the energy loss of energetic partons depends sensitively on the temperature of the surrounding matter. Such a behaviour could have a strong impact on related observables. For example, in [27] it was argued that for a simultaneous description of both nuclear modification factor and elliptic flow of hadrons an energy loss mainly occurring around T_c is crucial. Similar conclusions were drawn in [28].

As proposed in [12], the ratio $X = (\hat{q}/T^3)/(\eta/s)^{-1}$ could indicate if the considered medium is a weakly or a strongly coupled system. In line with the non-trivial temperature dependence in η/s and \hat{q}/T^3 in the QPM, the ratio X is also a function of T . This is shown in Fig. 1 (right panel), where we compare X obtained for the two different parametrization sets from [21] (solid curve) and from [26] (dashed curve) with the constant value $X \approx 1.25$ for a gas of free massless bosons (dotted horizontal line), *cf.* Eq. (2). At high temperatures, the ratio X in the QPM approach becomes as small as 1.25 indicating that the described system is indeed weakly coupled. However,

as $T \rightarrow T_c^+$, X increases significantly as a consequence of the medium-modified gluon dispersion relation. For strong coupling, based on analytic results for η/s [29] and \hat{q} [30] obtained in $\mathcal{N} = 4$ supersymmetric Yang–Mills theory in the limit of large 't Hooft coupling λ , one finds for the ratio $X = \Gamma(3/4)\sqrt{\lambda\pi}/(4\Gamma(5/4))$, which is large for large λ . For a reasonably chosen value $\lambda = 6\pi$ cf. [30], however, one finds $X \approx 2.602$ which can also be obtained within the QPM, cf. Fig. 1 (right panel).

5. Conclusions

We studied the temperature dependence of the jet quenching parameter \hat{q} of hot, deconfined gluonic matter within a phenomenological quasiparticle approach. For this purpose, we made use of a general relation between \hat{q} and the shear viscosity η valid for any weakly coupled partonic quasiparticle system [12]. From η , as previously determined in the QPM [21], \hat{q}/T^3 is found to show a pronounced maximum close to T_c , while falling off steeply with increasing T . This implies that the energy loss of energetic partons traversing the coloured medium exhibits a significant temperature dependence. The relation between \hat{q} and η expressed by the ratio X shows a non-trivial behaviour with T due to the medium-modified gluon dispersion relation. At large T , X is as small as typically assumed for weakly coupled systems [12], while as $T \rightarrow T_c^+$ it becomes quantitatively comparable with reasonable estimates for strongly coupled systems [12, 30].

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