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Shear viscosity η to electric conductivity σ_{el} ratio for the Quark Guon Plasma

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The transport coefficients of strongly interacting matter are currently subject of intense theoretical and phenomenological studies due to their relevance for the characterization of the quark-gluon plasma produced in ultra-relativistic heavy-ion collisions (uRHIC). We discuss the connection between the shear viscosity to entropy density ratio, η/s, and the electric conductivity, σ_{el}. We note that once the relaxation time is tuned to determine the shear viscosity η to have a minimum value $\eta/s = 1/4\pi$ near the critical temperature T_c, one simultaneously predicts an electric conductivity σ_{el}/T very close to recent lQCD data. More generally, we discuss why the ratio of η/s over σ_{el}/T supplies a measure of the quark to gluon scattering rates whose knowledge would allow to significantly advance in the understanding of the QGP phase. We also predict that $(\eta/s)/(\sigma_{el}/T)$, independently on the running coupling $\alpha_s(T)$, should increase up to about ~ 20 for $T \to T_c$, while it goes down to a nearly flat behavior around $\simeq 4$ for $T \geq 4T_c$.

53rd International Winter Meeting on Nuclear Physics,
26-30 January 2015
Bormio, Italy

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PoS(Bormio2015)011

1. Introduction

Relativistic Heavy Ion Collider (RHIC) at BNL and Large Hadron Collider (LHC) at CERN have produced a very hot and dense system of strongly interacting particles as in the early universe with energy densities and temperatures largely above the transition temperature $T_c \simeq 160$MeV [1] expected for the transition from nuclear matter to the Quark-Gluon Plasma (QGP) [2]. The phenomenological studies by viscous hydrodynamics [3, 4] and parton transport [7, 5, 6] of the collective behavior of such a matter has shown that the QGP has a very small shear viscosity to entropy density ratio η/s, quite close to the conjectured lower-bound limit for a strongly interacting system in the limit of infinite coupling $\eta/s = 1/4\pi$ [8]. This suggests that hot QCD matter could be a nearly perfect fluid with the smallest viscous dynamics ever observed.

Being the Hot QCD matter a plasma, another key transport coefficient, yet much less studied, is the electric conductivity σ_{el}. This transport coefficient represents the linear response of the system to an applied external electric field. Several processes occurring in uRHIC as well as in the Early Universe are regulated by the electric conductivity. Indeed HICs are expected to generate very high electric and magnetic field ($eE \simeq eB \simeq m_\pi^2$, with m_π the pion mass) in the very early stage of the collisions [9, 10]. In mass asymmetric collisions, like Cu+Au, the electric field directed from Au to Cu induces a current resulting in charge asymmetric collective flow directly related to σ_{el} [10]. Furthermore the emission rate of soft photons should be directly proportional to σ_{el}. Despite its relevance there is yet only a poor theoretical and phenomenological knowledge of σ_{el} and its temperature dependence. First preliminary studies in lQCD has extracted only few estimates with large uncertainties [11, 14] and only recently more safe extrapolation from the current correlator has been developed [16, 12, 13].

In this work we emphasize the main elements determining the conductivity for a QGP plasma and in particular the connection with the shear viscosity η [17]. In fact, while one may expect that the QGP is quite a good conductor due to the deconfinement of color charges, on the other hand, the very small η/s indicates large scattering rates which can largely damp the conductivity, especially if the plasma is dominated by gluons that do not carry any electric charge. The paper is organized as follows: in Section 1 we present our results for η/s giving some details on the quasiparticle model. In Section 2 we show our prediction for σ_{el} explaining why it is consistent with a low η/s. In Section 3 we investigate the ratio between the two transport coefficients proving that such a quantity can tell us about the relative quarks to gluons scattering rates.

2. Shear viscosity

The shear viscosity η is known from the Green-Kubo relation to be given by $\eta = V/T\,\langle \Pi^{xy}(t=0)\Pi^{xy}(t=0)\rangle \cdot \tau$, where the initial value of the correlator of the transverse components of the energy-momentum tensor can be written in terms of thermal average as $\frac{\rho}{15T}\langle p^4/E^2\rangle$ [20, 21]. Hence for a system with different species it can be written as [23, 24]:

$$\eta = \frac{1}{15T}\left(\sum_{i=q,\bar{q}} \tau_i \rho_i \left\langle \frac{p^4}{E^2}\right\rangle_i + \tau_g \rho_g \left\langle \frac{p^4}{E^2}\right\rangle_g\right) \tag{2.1}$$

where T is the temperature, $\rho_{q,g}$ is respectively the quark and gluon density, $\tau_{q,g}$ relaxation time. In order to explain each term in Eq. (2.1), we start giving the definition of the relaxation time τ for

PoS(Bormio2015)011

quarks and gluons:

$$\tau_q^{-1} = \sum_{i=q,\bar{q},g} \langle \rho_i v_{rel}^{iq} \sigma_{tr}^{iq} \rangle = \langle \sigma(s)_{tr} v_{rel} \rangle (\rho_q \sum_{i=u,d,s}^{\bar{u},\bar{d},\bar{s}} \beta^{qi} + \rho_g \beta^{qg})$$
$$\tau_g^{-1} = \sum_{i=q,\bar{q},g} \langle \rho_i v_{rel}^{ig} \sigma_{tr}^{ig} \rangle = \langle \sigma(s)_{tr} v_{rel} \rangle \left(\rho_q^{tot} \beta^{qg} + \rho_g \beta^{gg} \right) \tag{2.2}$$

where σ_{tr}^{ij} is the transport cross-section, v_{rel}^{ij} is the relative velocity of the two scattering particles. As done within the Hard-Thermal-Loop (HTL) approach, we will consider the total transport cross section regulated by a screening Debye mass $m_D = g(T)T$, with $g(T)$ being the strong coupling:

$$\sigma_{tr}^{ij}(s) = \int \frac{d\sigma}{dt} \sin^2\Theta \, dt = \beta^{ij} \frac{\pi \alpha_s^2}{m_D^2} \frac{s}{s + m_D^2} h(a) \tag{2.3}$$

where $\alpha_s = g^2/4\pi$, the differential cross section is $\frac{d\sigma}{dt} = \frac{d\sigma}{dq^2} \simeq \alpha_s^2/(q^2+m_D^2)^2$ where $q^2 = \frac{s}{2}(1-\cos\theta)$, the coefficient β^{ij} depends on the pair of interacting particles: $\beta^{qq} = 16/9$, $\beta^{qq'} = 8/9$, $\beta^{qg} = 2$, $\beta^{gg} = 9$. The function $h(a) = 4a(1+a)[(2a+1)\ln(1+1/a) - 2]$, where $a = m_D^2/s$, regulates the anisotropy of the scatterings: for $m_D \to \infty$, $h(a) \to 2/3$ and one recovers the isotropic limit while $h(a) < 2/3$ for finite value of m_D, for more details see Ref. [20, 22, 17]. We notice that this factor are directly related to the quark and gluon Casimir factor, for example $\beta^{qq}/\beta^{gg} = (C_F/C_A)^2 = (4/9)^2$.

The other term to be described in Eq. (2.1) is the thermal average $\langle p^4/E^2 \rangle$ that in the massless case is simply $4\varepsilon T/\rho$. We notice that it is a good approximation to consider $\langle p^4/E^2 \rangle$ equal for quarks and gluons in Eq.(2.1): we have checked that $\langle p^4/E^2 \rangle_g \simeq \langle p^4/E^2 \rangle_q$ within a 5% unless their masses differs by a factor of 3-4.
The thermal average $\langle p^4/E^2 \rangle$ will be fixed employing a quasi-particle (QP) scheme tuned to reproduce the bulk thermodynamics evaluated by lQCD [25], similarly to [26]. The aim of a quasiparticle model is to describe a strongly interacting system in terms of weakly interacting particles whose masses arise from the non-perturbative effects. This means that the $\langle p^4/E^2 \rangle$ terms in Eq. (2.1) are essentially determined by the lQCD thermodynamics and do not rely on the detailed value of $m_{q,g}(T)$ in the QP model.

The quark and gluon masses are given by $m_g^2 = 3/4\, g^2 T^2$ and $m_q^2 = 1/3\, g^2 T^2$ in terms of a running coupling $g(T)$ that is determined by a fit to the lattice energy density, which allows to well describe also the pressure P and entropy density s above $T_c = 160\,\text{MeV}$. In Ref. [25] we have obtained:

$$g_{QP}^2(T) = \frac{48\pi^2}{(11N_c - 2N_f)\ln\left[\lambda\left(\frac{T}{T_c} - \frac{T_s}{T_c}\right)\right]^2} \tag{2.4}$$

with $\lambda = 2.6$, $T_s/T_c = 0.57$. We also notice that a self-consistent dynamical model (DQPM), that includes also the pertinent spectral function, has been developed in [6] and leads to nearly the same behavior of the strong coupling $g(T)$. For its general interest and asymptotic validity for $T \to \infty$, we also consider the behavior of the pQCD running coupling constant for the evaluation of transport relaxation time: $g_{pQCD}(T) = \frac{8\pi^2}{9} \ln^{-1}\left(\frac{2\pi T}{\Lambda_{QCD}}\right)$. On one hand, close to T_c, such a case misses the dynamics of the phase transition, on the other hand it allows to see explicitly what is the impact of a different running coupling.

PoS(Bormio2015)011

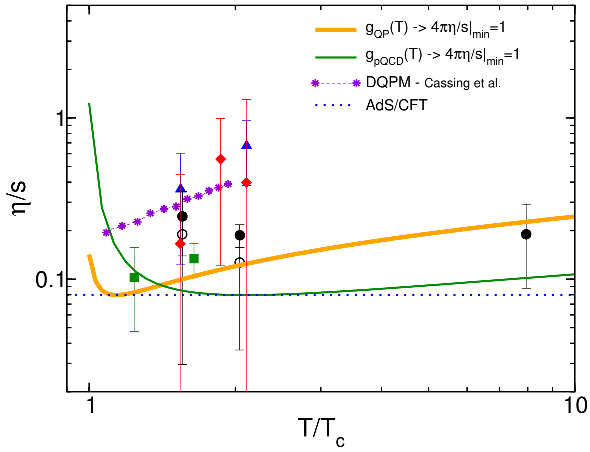

Figure 1: Shear viscosity to entropy density ratio η/s: dashed line represents QP model results, dot-dashed line is pQCD, open circles is DQPM [27]. Red thick solid line and blue thin solid line are obtained rescaling $g(T)$. Blue dotted line is AdS/CFT result from [8]. Symbols are lattice date: full squares [32], diamonds and triangles [33], open and full circles [28].

The fact that the QP model fits lQCD means that the thermal averages entering in Eq. (2.1) are the correct ones but this does not imply that one is describing also the scattering dynamics because fitting thermodynamical quantity does not give us any constraint on cross section or transport relaxation times. In other words we mean that, even if QP model seems to work quite well fitting $g(T)$ to thermodynamics, it is not obvious that relaxation times are those of the QP model evaluated with the same coupling $g(T)$. Moreover transport relaxation times in Eq. (2.2) are unknown in particular at the critical temperature T_c. Having in mind to avoid our ignorance about the microscopic description, we fix $\tau_{q,g}$ in order to reproduce the minimum $\eta/s = 1/4\pi$: one obtains $\tau_g \simeq \tau_q/2 \sim 0.2\,\mathrm{fm/c}$ at the minimum value of η/s and also $\eta/s(T)$ roughy linearly rising with T in agreement with quenched lQCD estimates, full circles [28].

In Fig. 1 we show η/s as a function of T/T_c: orange thick line is the result for the QP model using g_{QP}, green thin line is obtained using g_{pQCD}, violet stars-dashed the DQPM [27] and by symbols several lQCD results. We warn that the different lQCD data are obtained with different methods and actions.

3. Electric conductivity

The electric conductivity can be formally derived from the Green-Kubo formula and it is related to the relaxation of the current-current correlator for a system in thermal equilibrium. It can be written as $\sigma_{el} = V/(3T)\,\langle \vec{J}(t=0)\cdot\vec{J}(t=0)\rangle\cdot\tau$, where τ is the relaxation time of the correlator whose the initial value can be related to the thermal average $\frac{\rho\, e^2}{3T}\langle p^2/E^2\rangle$ [18], where ρ and E is the density and energy of the charge carriers. Generalizing to the case of QGP one can write:

$$\sigma_{el} = \frac{e^2}{3T}\left\langle \frac{\vec{p}^{\,2}}{E^2}\right\rangle \sum_{j=q,\bar{q}} f_j^2\,\tau_j\rho_j = \frac{e_\star^2}{3T}\left\langle \frac{\vec{p}^{\,2}}{E^2}\right\rangle \tau_q\rho_q \tag{3.1}$$

PoS(Bormio2015)011

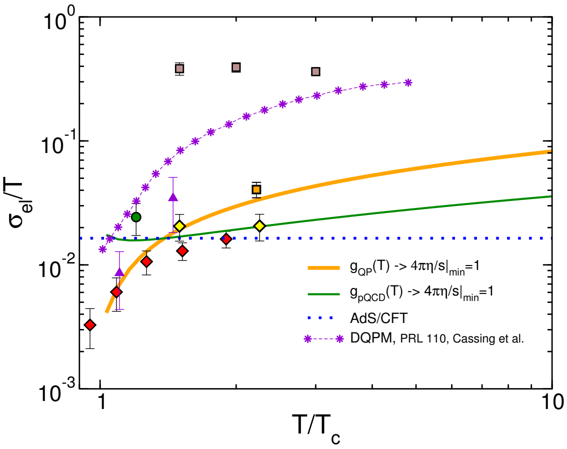

Figure 2: Electric conductivity σ_{el}/T as a function of T/T_c: orange thick solid line and green thin solid line are respectively QP and pQCD considering the same τ_q of η/s. Blue dotted line are AdS/CFT results from [29]. Violet stars-dashed line represent DQPM [19]. Symbols are Lattice data: grey squares [11], violet triangles [12], green circle [13], yellow diamond [14], orange square[15] and red diamonds [16].

where $e_\star^2 = e^2 \sum_{j=u,d,s}^{\bar{u},\bar{d},\bar{s}} f_j^2 = 4e^2/3$ with f_j the fractional quark charge. Eq. (3.1) in the non-relativistic limit reduces to the Drude formula $\frac{\tau e^2 \rho}{m}$. We remark that the correct thermal averages entering the transport coefficients, Eq. (2.1) and Eq (3.1), have been determined fitting $g(T)$ to lQCD thermodynamics, but this does not imply that with the same $g(T)$ one has the correct description also of the scattering dynamics. A main point we want to stress is that, once the relaxation time is set to an $\eta/s(T) = 0.08$, the σ_{el}/T predicted, with the same τ_q as for η/s, is in quite good agreement with most of the lQCD data, shown by symbols in Fig. 2 (see caption for details). Therefore a low σ_{el}/T is obtained at variance with the early lQCD estimate, Ref. [11], as a consequence of the small $\tau_{q,g}$ that are associated with $\eta/s \simeq 0.08$. In Fig. 2 we show also the predictions of DQPM (violet stars-dashed line) [19, 27].
In Fig.2, we also plot the $\mathcal{N} = 4$ Super Yang Mills (blue dotted line) electric conductivity [29] that predicts a constant behavior for $\sigma_{el}/T = e^2 N_c^2/(16\pi) \simeq 0.0164$. We note that in our framework one instead expects that, even if the η/s is independent on the temperature, the σ_{el} should still have a strong T-dependence. This can be seen noticing that one can write, with good approximation, $\eta/s \simeq T^{-2}\tau\rho$, being $\langle p^4/E^2 \rangle \simeq \varepsilon T/\rho$, and $\sigma_{el}/T \simeq g^{-1}(T) T^{-2} \tau\rho$, being $\langle p^2/E^2 \rangle \simeq T/m(T)$, which leads to a simple relation between shear viscosity and electric conductivity $\sigma_{el}/T \simeq g^{-1}(T)\eta/s$. This leads to a steep decrease of σ_{el}/T close to T_c due to the increasing of the non-perturbative coupling for $T \to T_c$ or, from a classical point of view, to the growing of the charge carrier's intertia.

4. Ratio

An interesting quantity under our investigation is to consider the ratio between η/s and σ_{el}/T: the first transport coefficient depends on τ_q and τ_g while the second one only on τ_q, hence, taking the ratio, one obtains a quantity that carries information about the relative quark to gluon scattering rates as we show below.

PoS(Bormio2015)011

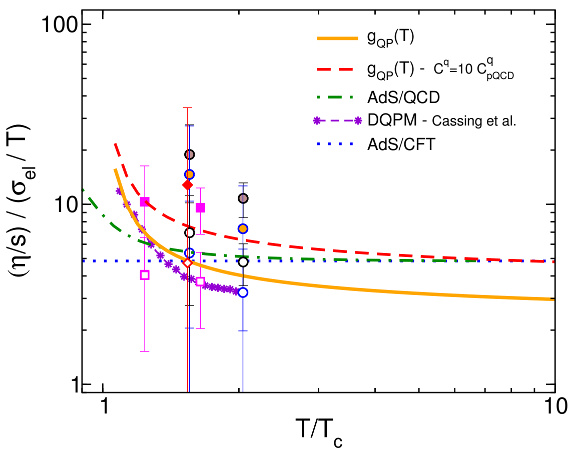

Figure 3: Shear viscosity η/s to σ/T ratio as a function of T/T_c: orange solid line is the QP model, violet stars-dashed line DQPM [27]. Red dashed line is obtained using $C^q = 10C^q_{pQCD}$. Blue dotted line represents AdS/CFT results [8, 29] while green dashed line AdS/QCD results [34]. Symbols are obtained using available lattice data (see text for details).

We note that the ratio $(\eta/s)/(\sigma_{el}/T)$ can be written, from Eq. (3.1) and Eq. (2.1), as:

$$\frac{\eta/s}{\sigma_{el}/T} = \frac{6}{5}\frac{1}{T s e_\star^2}\frac{\langle p^4/E^2\rangle}{\langle p^2/E^2\rangle}\left(1+\frac{\tau_g}{\tau_q}\frac{\rho_g}{\rho_q^{tot}}\right). \tag{4.1}$$

The previous equation is written in terms of generic relaxation times.The main feature of such a ratio is its independence of the T behaviour of the $g(T)$ coupling: using Eq. (2.2) the ratio of transport relaxation times appearing in Eq. (4.1) can be written as:

$$\frac{\tau_g}{\tau_q} = \frac{C^q + \frac{\rho_g}{\rho_q}}{6+\frac{\rho_g}{\rho_q}C^g} \tag{4.2}$$

where the coefficient $C^q = (\beta^{qq} + \beta^{q\bar{q}} + 2\beta^{q\bar{q}'} + 2\beta^{qq'})/\beta^{qg}$ and $C^g = \beta^{gg}/\beta^{qg}$ is the relative magnitude between quark-(anti-)quark and gluon-gluon with respect to gluon-quark scatterings. Using the standard pQCD factors for β_{ij}, $C^q|_{pQCD} = \frac{28}{9} \simeq 3.1$ and $C^g|_{pQCD} = \frac{9}{2}$.
In Fig. 3 we show $(\eta/s)/(\sigma_{el}/T)$ as a function of T/T_c: the orange solid line is the the prediction for the ratio using $g_{QP}(T)$, but it is clear from the Eq. (4.1) that the ratio is completely independent on the running coupling itself, so we do not show the correspondig curve for $g_{pQCD}(T)$ because it is the same of $g_{QP}(T)$.

The ratio is instead sensitive just to the relative strength of the quark (anti-quark) scatterings with respect to the gluonic ones, hence we suggest that a measurement in lQCD can shed light on the relative scattering rates of quarks and gluons, providing an insight into their relative role. We remark that we have computed the ratio in a very large temperature range $1-10\,T_c$: at large temperatures ($T > 5-10\,T_c$) deviation from the obtained value, $(\eta/s)/(\sigma_{el}/T) \simeq 3$, would be quite surprising and could teach us something new. As $T \to T_c$ a steep increase is predicted that is essentially regulated by $\langle p^2/E^2\rangle$. We also show a recent AdS/QCD prediction [34] by green dot-dashed line which predicts the same increasing of our results near the critical temperature.

PoS(Bormio2015)011

As we can see from Eq. (4.1), the ratio depends on the relative magnitude of quarks and gluons scattering rates: what is the behavior of the ratio if quark-quark or gluon-gluon cross sections have an enhancement? When the QGP approaches the phase transition, the confinement dynamics becomes dominant and the $q\bar{q}$ scattering, precursors of mesonic states, and di-quark qq states, precursor of baryonic states, are strongly enhanced by a resonant scattering respect to other channels, as found in a T-matrix approach in the heavy quark sector [31]. For this reason, we explore the sensitivity of the ratio $(\eta/s)/(\sigma_{el}/T)$ on the magnitude of C^q and C^g. The red dashed line shows the behavior for an enhancement of the quark scatterings, $C^q = 10C^q_{pQCD}$. We can see in Fig. 3 that this would lead to an enhancement of the ratio by about a 40%. We do not show the behaviour of the ratio to a possible enhancement of only the gg scattering because, even for $C^g = 10C^g_{pQCD}$, the ratio changes up to few percent respect to the orange line. We report in Fig. 3 also the ratio from the DQPM model, as deduced from [27] and we can see that, even if it is not evaluated through Eq. (4.1), it is in very good agreement with our general prediction. In Fig. 3 we also display by symbols the ratio evaluated from the available lQCD data, considering for η/s those smaller than four times the minimum value, while for σ_{el}/T we choose red diamonds [16] as a lower limit (filled symbols) and the others in Fig. 2 as an upper limit (open symbols), excluding only the grey squares. We warn to consider these estimates only as a first rough indications, in fact the lattice data collected of η/s and σ_{el} are obtained with different actions among them and have quite different T_c with respect to the most realistic one, $T_c \sim 160\,MeV$, that we employed to tune the QP model [25].

5. Conclusions

In this work we point out the direct relation between the shear viscosity η and the electric conductivity σ_{el}. In particular, we have discussed why most recent lQCD data [16, 12, 13] predicting an electric conductivity $\sigma_{el} \simeq 10^{-2}T$ (for $T < 2T_c$) , appears to be consistent with a fluid at the minimal conjectured viscosity $4\pi\eta/s \simeq 1$. The QP model predicts an increasing σ_{el}/T as a function of temperature: our result supports AdS/QCD predictions [34].

We found the ratio $(\eta/s)/(\sigma_{el}/T)$ is independent of the uncertainties of the running coupling $g(T)$. Furthemore, due to the fact that gluons do not carry an electric charge, the ratio is regulated by the relative strength and chemical composition of the QGP through the term $(1+\tau_g\rho_g/\tau_q\rho_q^{tot})$. Our study provides a criterion to interpret the ratio and understanding the relative role of quarks and gluons in the QGP thanks to the developments of lQCD techniques. Deviations from our predictions for $(\eta/s)/(\sigma_{el}/T)$ especially at high temperature $T \sim 2-3T_c$.

Acknowledgments

V.G. acknowledge the support of the ERC-StG Grant under the QGPDyn project.

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