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Strongly interacting parton-hadron matter in- and out-off equilibrium

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Abstract. We study the equilibrium properties of strongly-interacting infinite parton-hadron matter, characterized by the transport coefficients such as shear and bulk viscosity and electric conductivity, and the non-equilibrium dynamics of heavy-ion collisions within the Parton-Hadron-String Dynamics (PHSD) transport approach, which incorporates explicit partonic degrees of freedom in terms of strongly interacting quasiparticles (quarks and gluons) in line with an equation of state from lattice QCD as well as the dynamical hadronization and hadronic collision dynamics in the final reaction phase. We discuss in particular the possible origin for the strong elliptic flow v_2 of direct photons observed at RHIC energies.

1. Introduction

One of the important findings from the heavy-ion experiments at ultra-relativistic energies was that the produced quark gluon plasma behaves as a strongly-interacting almost perfect fluid unlike a weakly-interacting gas [1, 2]. Recent relativistic viscous hydrodynamic calculations - using the Israel-Stewart framework - require a very small shear viscosity to entropy density ratio η/s of $0.08 - 0.24$ in order to reproduce the elliptic flow v_2 data at RHIC (cf. [3]). There is strong evidence from atomic and molecular systems that η/s should have a minimum in the vicinity of the phase transition (or rapid crossover) between the hadronic matter and the quark-gluon plasma [4], and that the ratio of bulk viscosity to entropy density ζ/s should be maximum or even diverge at a second-order phase transition [5]. It is also important to know the electromagnetic properties of the QGP since they influence the electromagnetic radiation in terms of photons and dileptons. The recent observation by the PHENIX Collaboration [6] that the elliptic flow $v_2(p_T)$ of 'direct photons' produced in minimal bias Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV is comparable to that of the produced pions was a surprise and in contrast to the theoretical expectations of small v_2 [7, 8, 9, 10].

In this contribution we present the highlights of the PHSD results [11, 12] on transport coefficients – the shear and bulk viscosities and electric conductivity – for 'infinite' parton-hadron matter in equilibrium as well as an example for non-equilibrium dynamics in heavy-ion collisions, in particular the direct photon spectra and collective flow v_2 (cf. Ref. [13]).

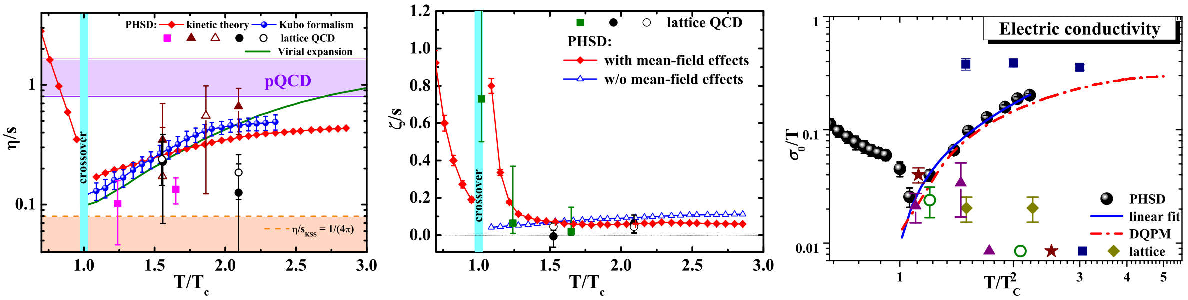

Figure 1. The PHSD results for the shear (left) and bulk (middle) viscosities of partonic and hadronic matter - as well as the electric conductivity (right) - as functions of temperature T/T_c.

2. PHSD model

The PHSD transport approach[14, 15]is based on generalized transport equations on the basis of the off-shell Kadanoff-Baym equations [16, 17] for Green's functions in phase-space representation (in first order gradient expansion beyond the quasiparticle approximation). The approach consistently describes the full evolution of a relativistic heavy-ion collision from the initial hard scatterings and string formation through the dynamical deconfinement phase transition to the strongly-interacting quark-gluon plasma (sQGP) as well as hadronization and the subsequent interactions in the expanding hadronic phase as in the Hadron-String-Dynamics (HSD) transport approach [18]. The partonic dynamics is based on the Dynamical QuasiParticle Model (DQPM) [19], which describes QCD properties in terms of single-particle Green's functions (in the sense of a two-particle irreducible (2 PI) approach) and reproduces lattice QCD results – including the partonic equation of state – in thermodynamic equilibrium (cf. review Ref. [20]).

3. Transport coefficients

In Fig. 1we present the PHSD results for the shear and bulk viscosities of partonic and hadronic matter - as well as the electric conductivity - as functions of temperature T/T_c ($T_c = 158$ MeV). In order to study the dynamical hadronic and partonic systems in equilibrium we have performed the PHSD simulations in a finite box with periodic boundary conditions. The ratio of the shear viscosity to entropy density $\eta(T)/s(T)$ from PHSD shows a minimum (with a value of about 0.1) close to the critical temperature T_c, while it approaches the perturbative QCD (pQCD) limit at higher temperatures in line with lattice QCD results. For $T < T_c$, i.e. in the hadronic phase, the ratio η/s rises fast with decreasing temperature due to a lower interaction rate of the hadronic system and a significantly smaller number of degrees-of-freedom.

The bulk viscosity $\zeta(T)$ – evaluated in the relaxation time approach – is found to strongly depend on the effects of mean fields (or potentials) in the partonic phase. We find a significant rise of the ratio $\zeta(T)/s(T)$ in the vicinity of the critical temperature T_c, which is also in agreement with that from lQCD calculations. This rise has to be attributed to mean-fields (or potential) effects that in PHSD are encoded in the temperature dependence of the quasiparticle masses, which is related to the infrared enhancement of the resummed (effective) coupling $g(T)$.

We also find that the dimensionless ratio of the electric conductivity over temperature σ_0/T rises above T_c approximately linearly with T up to $T = 2.5T_c$, but approaches a constant above $5T_c$, as expected qualitatively from perturbative QCD (pQCD) (cf. Ref. [12] for details). Our findings imply that the QCD matter even at $T \approx T_c$ is a much better electric conductor than Cu or Ag (at room temperature). We note that our result for σ_0/T close to T_c is in agreement with the most recent lQCD calculations which is important for our further discussion since the photon emission rate from the QGP or the hadronic system is controlled by the electric conductivity.

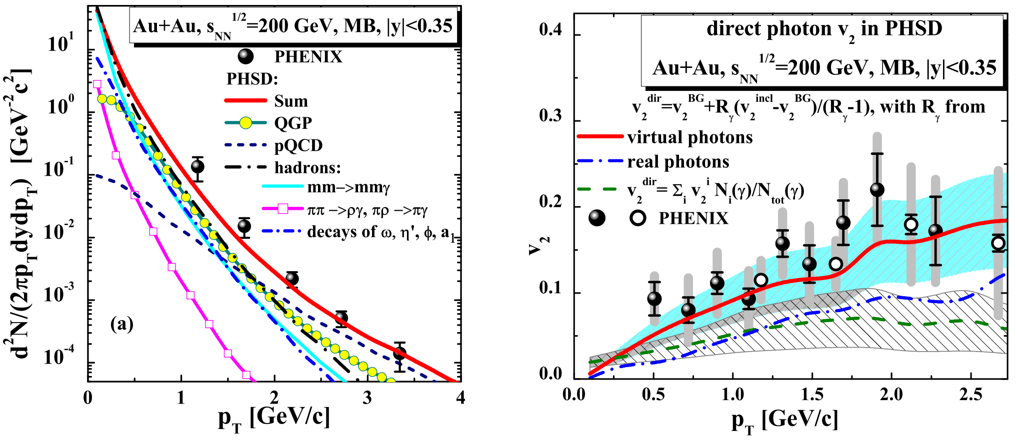

Figure 2. Left hand side: Direct photons (sum of all photon production channels except the π- and η-meson decays) from the PHSD approach (red solid line) in comparison to the data of the PHENIX Collaboration [21, 22] for minimal bias collisions of Au+Au at $\sqrt{s_{NN}} = 200$ GeV (black symbols). **Right hand side:** Elliptic flow of direct photons (hadron decays excluded) in the PHSD approach for minimal bias Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV in comparison to the data from Refs. [6, 23]. The results from the PHSD are displayed by the solid red line, equation (2), and by the dashed green line, by applying Eq. (1).

4. Photon production in heavy-ion collisions

In Ref [13] we have applied the PHSD approach to photon production in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV and studied the transverse momentum spectrum and the elliptic flow v_2 of photons from hadronic and partonic production channels. We found that the PHSD calculations reproduce the transverse momentum spectrum of direct photons - measured by the PHENIX Collaboration in Refs. [21, 22] - as shown in the l.h.s. of Fig. 4. Furthermore, the PHSD also describes the data on the elliptic flow of inclusive photons [13]. In order to extract the flow of 'direct photons' from the inclusive one, the hadron decay background has to be subtracted. This can be done by two procedures:

Procedure 1. We calculate the direct photon v_2 (in PHSD) by summing up the elliptic flow of the individual channels contributing to the direct photons, using their contributions to the spectrum as the relative p_T-dependent weights, $w_i(p_T)$, i.e.

$$v_2(\gamma^{dir}) = \sum_i v_2(\gamma^i) w_i(p_T) = \sum_i v_2(\gamma^i) N_i(p_T) / \sum_i N_i(p_T), \tag{1}$$
$$\text{where } i = (q\bar{q} \to g\gamma, qg \to q\gamma, \pi\pi/\rho \to \rho/\pi\gamma, mm \to mm\gamma, \text{pQCD}).$$

The index i denotes the binary production channels, both the partonic quark-gluon interaction channels and the meson reactions which cannot be separated presently experimentally by model-independent methods. The direct photon elliptic flow calculated in this way is presented in Fig. 2 (r.h.s.) by the dashed green line and clearly underestimates the PHENIX data from Ref. [6] in line with Refs. [7, 8, 9, 10].

Procedure 2. The experimental collaboration has extracted the elliptic flow of direct photons $v_2(\gamma^{dir})$ from the measured inclusive photon $v_2(\gamma^{incl})$ by subtracting the hadron decay sources (π_0, η, ω, η', ϕ, a_1) as follows [6]:

$$v_2(\gamma^{dir}) = \left(R_\gamma v_2(\gamma^{incl}) - v_2(\gamma^{BG}) \right) / (R_\gamma - 1) = v_2(\gamma^{BG}) + \frac{R_\gamma}{R_\gamma - 1} (v_2(\gamma^{incl}) - v_2(\gamma^{BG})) \tag{2}$$

where $R_\gamma = N^{incl}/N^{BG}$ denotes the ratio of the inclusive photon yield to that of the "background" (i.e. the photons stemming from the decays of π_0, η, ω, η', ϕ and a_1 mesons),

$v_2(\gamma^{BG})$ is the elliptic flow of the background photons; one can assume $v_2(\gamma^{BG}) \approx v_2(\pi_0)$ [13]. The ratio R_γ was obtained experimentally in Ref. [22] by analyzing the yield of dileptons with high transverse momentum $p_T > 1$ GeV and low invariant mass M. We recall here that we have studied the dilepton production at the top RHIC energy within the PHSD approach in Ref. [24]. The PHSD results reproduce well the PHENIX and STAR dilepton data differentially in the invariant mass M and transverse momentum p_T, only underestimating the excess observed by PHENIX at low M and low p_T. Note, however, that for the relatively high transverse momenta of dileptons ($p_T > 1$ GeV) the agreement of the PHSD calculations with the PHENIX data is quite good. We obtain $R_\gamma \approx 1.2$ by analyzing the yield of dileptons in the invariant mass window $M = 0.15 - 0.3$ GeV. Alternatively, we can use the calculated inclusive *real* photon spectrum to find the ratio $R_\gamma = N(\gamma)^{incl}/N(\gamma)^{BG}$. In this case we obtain $R_\gamma \approx 1.08$ from the real photons in PHSD. The difference between the values of R_γ – extracted from the dilepton spectra and the real photon spectra – is caused by the fact that in the dilepton mass window $M = 0.15 - 0.3$ GeV the background from the pion decays effectively “dies out”, while the pion decay contribution is prominent for $M \to 0$.

Following the procedure of equation (2) in the PHSD, we obtain the red solid line in Fig. 2 (r.h.s.), if we use the ratio R_γ from the virtual photons in the invariant mass window $M = 0.15 - 0.3$ GeV, and the blue dash-dotted line, if we use the ratio R_γ from the calculated real photon spectrum. The two lines differ by about a factor of two. The difference between the two extraction procedures for the direct photon flow $v_2(p_T)$ can be attributed to different definitions for the ratio of the inclusive and background photons (R_γ).

In conclusion, our findings imply that there is presently no clear signal for 'unconventional physics' (beyond the strong interaction on the partonic and hadronic level) in the photon data from the PHENIX Collaboration within error bars. The strong v_2 of direct photons - which is comparable to the hadronic v_2 - in PHSD is attributed to hadronic channels, i.e. to meson binary reactions which are not subtracted in the data. On the other hand, the strong v_2 of the 'parent' hadrons, in turn, stems from the interactions in the QGP. Accordingly, the presence of the QGP shows up 'indirectly' in the direct photon elliptic flow.

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