DISSIPATION, COLLECTIVE FLOW AND MACH CONES AT RHIC

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Fast thermalization and a strong buildup of elliptic flow of QCD matter as found at RHIC are understood as the consequence of perturbative QCD (pQCD) interactions within the 3+1 dimensional parton cascade BAMPS. The main contributions stem from pQCD bremsstrahlung $2 \leftrightarrow 3$ processes. By comparing to Au+Au data of the flow parameter $v_2$ the shear viscosity to entropy ratio $\eta/s$ has been extracted dynamically and lies in the range of $0.08$ and $0.2$. Also jet-quenching has been investigated consistently within a full dynamical picture of the heavy ion collision. The results for gluonic jets indicate a slightly too large suppression, but are encouraging to understand the two major phenomena, strong flow and jet-quenching, within a unified microscopic treatment of kinetic processes. In addition, simulations on the temporal propagation of dissipative shock waves lead to the observation that an $\eta/s$ ratio larger than $0.2$ prevents the development of well-defined shock waves on timescales typical for ultrarelativistic heavy-ion collisions.

1 Overview

The large elliptic flow parameter $v_2$ measured by the experiments at the Relativistic Heavy Ion Collider (RHIC) suggests that in the evolving QCD fireball a fast local equilibration of quarks and gluons occurs at a very short time scale $\leq 1$ fm/c, and that the locally thermalized state of matter created, the quark gluon plasma (QGP), behaves as a nearly perfect fluid. In addition, the phenomenon of jet–quenching has been another important discovery at RHIC. So far, it has not been possible to relate both phenomena by a common understanding of the underlying microscopic processes.

In this talk, we demonstrate that perturbative QCD (pQCD) collisional and, more importantly, radiative interactions can explain a fast thermalization of the initially nonthermal gluon system, the large collective effects of QGP created at RHIC and the smallness of the shear viscosity to entropy ratio in a consistent manner by using a relativistic pQCD–based on-shell parton cascade Boltzmann approach of multiparton scatterings (BAMPS). Also, due to the inclusion of radiative processes, BAMPS can simultaneously account for the quenching of high-momentum gluons. In addition, the possible propagation of dissipative shock waves in the QGP can be studied.

2 Elliptic Flow and Shear Viscosity

BAMPS is a parton cascade, which solves the Boltzmann equation and is based on the stochastic interpretation of the transition rate, which ensures full detailed balance for multiple scatterings. Gluon interactions included are elastic and screened Rutherford-like pQCD $gg \rightarrow gg$ scatterings
as well as pQCD inspired bremsstrahlung $gg \leftrightarrow ggg$ of Gunion-Bertsch type. In the default simulations, the initial gluon distributions are taken in a Glauber geometry as an ensemble of minijets with transverse momenta greater than 1.4 GeV, produced via semihard nucleon-nucleon collisions. The minijet initial conditions and the subsequent evolution using the present prescription of BAMPS for two sets of the coupling $\alpha_s = 0.3$ and 0.6 give nice agreements to the measured transverse energy per rapidity over all rapidities. Other initial conditions incorporating gluon saturation such like the color glass condensate are also possible.

The elliptic flow $v_2 = \langle (p^2_x - p^2_y)/p_T^2 \rangle$ can be directly calculated from microscopic simulations. The results are compared with the experimental data, assuming parton-hadron duality. The left panel of Fig. 1 shows the elliptic flow $v_2$ at midrapidity for various centralities (impact parameters). Except for the central centrality region either the results with $\alpha_s = 0.3$ and $e_c = 0.6$ GeVfm$^{-3}$ (green curves with open triangles) or those with $\alpha_s = 0.6$ and $e_c = 1$ GeVfm$^{-3}$ (red curves with open squares) agree perfectly with the experimental data. Within the Navier-Stokes approximation the shear viscosity $\eta$ is directly related to the so called transport rate and can be calculated dynamically and locally in a full and microscopical simulation (see the right panel of Fig. 1). Bremsstrahlung and its back reaction lower the shear viscosity to entropy density ratio $\eta/s$ significantly by a factor of 7, compared with the ratio when only elastic collisions are considered. According to the extraction by means of the full simulation given in Fig. 1, $\eta/s$ is most probably lying between 0.2 for $\alpha_s = 0.3$ and 0.08 for $\alpha_s = 0.6$. The latter value matches the lower bound of $\eta/s = 1/4\pi$ from the AdS/CFT conjecture. The shear viscosity slightly increases up to 20% when calculating it by means of Grads momentum method and using the 2nd order Israel-Stewart framework of dissipative relativistic hydrodynamics.

3 Jet-Quenching and Dissipative Shock Waves

Jet-quenching is generally specified in terms of the nuclear modification factor $R_{AA}$. We directly compute $R_{AA}$ by taking the ratio of the final $p_T$ spectra to the initial mini-jet spectra. For this a suitable weighting and reconstruction scheme of initial jet-like partons had to be developed. Figure 2 shows the result for the gluonic contribution to $R_{AA}$, exhibiting a clear suppression of...
The suppression of gluon jets is approximately a factor $3 \div 4$ stronger than seen in experimental pion data\cite{14}. An excessive quenching, however, was to be expected since at present the simulation does not include quarks, which are bound to lose considerably less energy due to their color factor and dominate the initially produced jets from $p_T \approx 20$ GeV. Indeed, comparing with state of the art results from Wicks et al.\cite{15} for the gluonic contribution to $R_{AA}$ (seen as the line in Fig. 2), which in their approach together with the quark contribution reproduces the experimental data, one finds better agreement. The inclusion of light quarks will provide important means of further verification and will be addressed in a future work.

In the context of jet-quenching, exciting jet-associated particle correlations\cite{16} have been observed, which indicates the formation of shock waves in form of Mach cones induced by supersonic partons moving through the quark-gluon plasma. Shock waves can only form and propagate if matter behaves like a fluid. At present it is not known whether the $\eta/s$ value deduced from $v_2$ data is sufficiently small to allow for the formation of shock waves. A step towards this problem is to consider the relativistic Riemann problem in viscous gluon matter\cite{11}.

In Fig. 3 we show the solution of the Riemann problem for various $\eta/s$ values as computed

![Figure 3](image-url)

**Figure 3**: (Color online) The pressure (left) and the velocity (right) profiles at time $t = 3.2$ fm/c. At $t = 0$, the pressure is $P_0 = 5.43$ GeVfm$^{-3}$ for $z < 0$ and $P_z = 0.33$ GeVfm$^{-3}$ for $z > 0$. 

**Figure 2**: (Color online) Gluonic $R_{AA}$ at midrapidity ($y \in [-0.5, 0.5]$) as extracted from simulations for central Au+Au collisions at 200 AGeV. The shaded area indicates the statistical error. For direct comparison the result from Wicks et al. for the gluonic contribution to $R_{AA}$ and experimental results from PHENIX for $\pi^0$ and STAR for charged hadrons are shown.
with BAMPS. The results demonstrate the gradual transition from the ideal hydrodynamical limit to free streaming of particles. A larger $\eta/s$ value results in a finite transition layer where the quantities change smoothly rather than discontinuously as in the case of a perfect fluid. A nonzero viscosity smears the pressure and velocity profiles and impedes a clean separation of the shock front from the rarefaction fan. A criterion for a clear separation, and thus the observability of a shock wave, is the formation of a shock plateau, as in the ideal fluid case. The formation of a shock plateau takes a certain amount of time. From Fig. 3 we infer that, for $\eta/s > 0.1$, a shock plateau has not yet developed at $t = 3.2 \, \text{fm}/c$, whereas for $\eta/s < 0.1$, it has already fully formed. Applying time scaling arguments, the formation of shock waves in gluon matter with $\eta/s > 0.2$ probably takes longer than the lifetime of the QGP at RHIC.\[11\]

In summary, within the pQCD based parton cascade BAMPS early thermalization, the build up of a large elliptic flow $v_2$, the smallness of the $\eta/s$ ratio, and the quenching of gluonic jets in Au+Au collisions at RHIC can be understood within one common setup. This is a committed and large scale undertaking. Further analyses on jet quenching, on particle correlations, on possible Mach cone like behaviour initiated by a jet, on quark degrees of freedom including hadronization, on initial conditions and on the exploration and use of dissipative hydrodynamics are underway to establish an even more global picture of heavy ion collisions.

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