What can we learn from hydrodynamic analysis of elliptic flow? *

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We can establish a new picture, the perfect fluid strongly coupled quark gluon plasma (sQGP) core and the dissipative hadronic corona, of the space-time evolution of produced matter in relativistic heavy ion collisions at RHIC. It is also shown that the picture works well also in the forward rapidity region through an analysis based on a new class of the hydro-kinetic model and is a manifestation of deconfinement.

1. INTRODUCTION

Recently, physicists at Brookhaven National Laboratory made an announcement that "RHIC serves the perfect liquid" [1]. The agreement of hydrodynamic predictions [2] of integrated and differential elliptic flow and radial flow patterns with Au+Au data at RHIC energies [3–6] is one of the main lines of the announcement. We first study the sensitivity of this conclusion to different hydrodynamic assumptions in the hadron phase. It is found that an assumption of chemical equilibrium with neglecting viscosity in the hadron phase in hydrodynamic simulations causes accidental reproduction of transverse momentum spectra and differential elliptic flow data. From a systematic comparison of hydrodynamic results with the experimental data, dissipative effects are found to be mandatory in the hadron phase. Therefore, what is discovered at RHIC is not only the perfect fluidity of the strongly coupled quark gluon plasma (sQGP) core but also its dissipative hadronic corona. Along the lines of these studies, we develop a hybrid dynamical model in which a *fully three-dimensional* hydrodynamic description of the QGP phase is followed by a kinetic description of the hadron phase [7]. We show rapidity dependence of elliptic flow from this hybrid model supports the above picture. Finally, we argue that this picture is a manifestation of deconfinement transition, namely, a rapid increase of entropy density in the vicinity of the QCD critical temperature as lattice QCD simulations have been predicted.

2. SQGP CORE AND DISSIPATIVE HADRONIC CORONA

A perfect fluid in the QGP phase and the first order phase transition to the hadron phase is assumed in most hydrodynamic simulations [8]. While one can find various assumptions in the hadron phase, e.g. (1) ideal and chemical equilibrium (CE) fluid,

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(2) ideal and chemically frozen fluid (or partial chemical equilibrium, PCE), or (3) non-equilibrium resonance gas via hadronic cascade models (HC). Hydrodynamic results are compared with the current differential elliptic flow data, $v_2(p_T)$, in Fig. 20 in Ref. [9] with putting an emphasis on the difference of assumptions in the hadron phase. The classes CE and HC reproduce the pion data well. On the contrary, results from the second class, PCE, deviate from these hydrodynamic results and experimental data. In order to claim the discovery of perfect fluidity from the agreement of hydrodynamic results with $v_2(p_T)$ data, we need to understand the difference among hydrodynamic results and the deviation from data. v_2 is roughly proportional to p_T in low p_T region for pions. In such a case, the slope of $v_2(p_T)$ can be approximated by $v_2/\langle p_T\rangle$. Integrated v_2 is generated in the early stage of collisions. Whereas *differential* v_2 can be sensitive to the late hadronic stage since $dv_2(p_T)/dp_T \approx v_2/\langle p_T\rangle$ indicates interplay between elliptic flow and radial flow. In Fig. 1, thermal freezeout temperature $T^{\rm th}$ dependence of $\langle p_T\rangle$ for

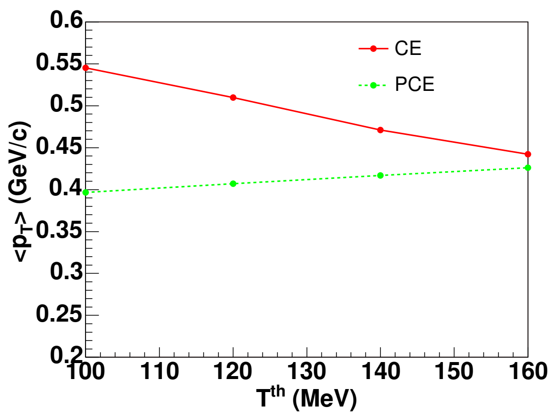

Figure 1. $\langle p_T\rangle$ for pions as a function of thermal freezeout temperature at b = 5 fm at RHIC. Solid (dashed) line shows a result with an assumption of an ideal, chemical equilibrium (chemically frozen) hadronic fluid.

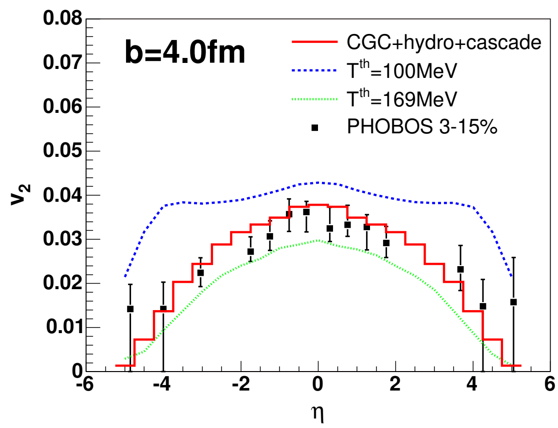

Figure 2. Pseudorapidity dependence of elliptic flow from hydro and hydro+hadronic cascade models are compared with data [5].

pions including contribution from resonance decays are calculated at a RHIC energy by utilizing hydrodynamic simulations [10]. $\langle p_T\rangle$ for pions in the chemically frozen hadronic fluid decreases with decreasing $T^{\rm th}$. This is due to longitudinal pdV work done by fluid elements. Whereas $\langle p_T\rangle$ in the chemical equilibrium case increases during expansion. The total number of particles in a fluid element decreases due to the assumptions of chemical equilibrium and entropy conservation in the hadron phase. Then the total energy is distributed among the smaller number of particles as a fluid element expands. These are the reasons why the different behavior of $\langle p_T\rangle$ appears according to the assumption of chemical equilibrium/freezeout. Under the chemical equilibrium assumption in ideal hydrodynamic simulations, increasing $\langle p_T\rangle$ is commonly utilized so far to fix $T^{\rm th}$ by fitting

p_T slope. However, this is attained only by neglecting data of particle ratio. If particle ratios are fixed properly in hydrodynamic simulations to reproduce the data, p_T slopes, especially for protons, are hardly reproduced. The same is true for differential elliptic flow: $dv_2(p_T)/p_T \approx v_2/\langle p_T \rangle$ is reproduced by canceling increase behaviors of both v_2 and $\langle p_T \rangle$ under chemical equilibrium assumption [10]. Agreement of the results from the CE model with p_T spectra and $v_2(p_T)$ data is merely an accident in the sense that this model makes full use of neglecting particle ratio to reproduce them. So the HC model turns out to be the only model which is able to reproduce particle ratio, p_T spectra and $v_2(p_T)$ data. Therefore a picture of the dissipative hadronic corona together with the perfect fluid sQGP core is consistent with these experimental data observed at RHIC.

3. 3D HYDRO AND HADRONIC CASCADE MODEL

According to the discussion in the previous section, we incorporate a hadronic cascade model, JAM [11], into our previous framework, the "CGC+hydro+jet" model [12]. Figure 2 shows pseudorapidity dependences of v_2 from this hybrid model and ideal 3D hydrodynamics with $T^{\text{th}} = 100$ and 169 MeV. Here critical temperature and chemical freezeout temperature are taken as being $T_c = T^{\text{ch}} = 170$ MeV in the hydrodynamic model. In the hybrid model, the switching temperature from a hydrodynamic description to a kinetic one is taken as $T_{\text{sw}} = 169$ MeV. Ideal hydrodynamics with $T^{\text{th}} = 100$ MeV which is so chosen to generate enough radial flow gives a trapezoidal shape of $v_2(\eta)$ [13]. A large deviation between data [5] and the ideal hydrodynamic result is seen especially in forward/backward rapidity regions. When hadronic rescattering effects are taken through the hadronic cascade model instead of perfect fluid description of the hadron phase, v_2 is not so generated in the forward region due to the dissipation and, eventually, is consistent with the data. So the perfect fluid sQGP core and the dissipative hadronic corona picture works well also in the forward region.

4. SUMMARY: WHAT HAVE WE LEARNED?

We can establish a new picture of space-time evolution of produced matter from a careful comparison of hydrodynamic results with experimental data observed at RHIC. What is the physics behind this picture? η/s is known to be a good measure to see the effect of viscosity where η is the shear viscosity and s is the entropy density. Figures 3 and 4 show possible scenarios for temperature dependence of η and η/s deduced from the discussion in the previous sections. η/s is small in the QGP phase, which might be comparable with the minimum value $1/4\pi$ [14], and the perfect fluid assumption can be valid. While η/s becomes huge in the hadron phase and the dissipation cannot be neglected. Shear viscosities of both phases are found to give $\eta \sim 0.1$ GeV/fm^2 around T_c [10]. So shear viscosity itself appears to increase with temperature monotonically. The "perfect fluid" property of the sQGP is thus not due to a sudden reduction of the viscosity at the critical temperature T_c, but to a sudden increase of the entropy density of QCD matter and is therefore an important signature of deconfinement.

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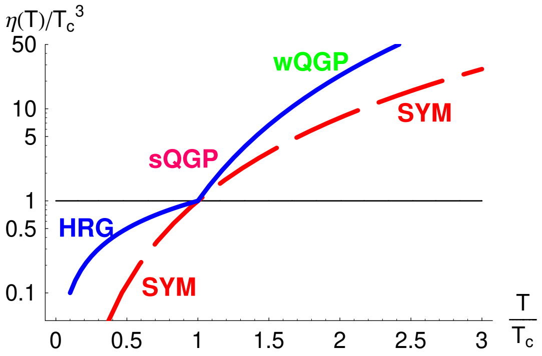

Figure 3. Illustration of the shear viscosity as a function of temperature. SYM, HRG, and wQGP represent, respectively, supersymmetric Yang-Mills model, hadronic resonance gas, and weakly coupled QGP.

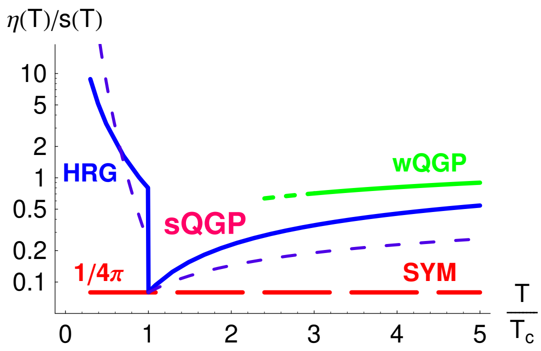

Figure 4. Illustration of the rapid variation of the *dimensionless ratio* of the shear viscosity, $\eta(T)$, to the entropy density, $s(T)$.

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