Eur. Phys. J. A **29**, 19–22 (2006)
DOI 10.1140/epja/i2005-10291-y

THE EUROPEAN PHYSICAL JOURNAL A

What can we learn from hydrodynamic analysis at RHIC?

T. Hirano[a]

Department of Physics, Columbia University, New York 10027, NY, USA

Received: 14 November 2005 /
Published online: 2 August 2006 –

Abstract. We can establish a new picture, the perfect fluid 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 that this is a manifestation of the rapid increase of the entropy density in the vicinity of QCD critical temperature, namely, deconfinement.

PACS. 24.85.+p Quarks, gluons, and QCD in nuclei and nuclear processes – 25.75.-q Relativistic heavy-ion collisions – 24.10.Nz Hydrodynamic models

1 Introduction

Recently, physicists at Brookhaven National Laboratory made an announcement in the American Physical Society annual meeting in Florida, USA, April 18, 2005, 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 in a way that chemical equilibrium imitates a sort of dissipation. 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 surrounding the core of the sQGP. 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 will show that the rapidity dependence of the elliptic flow from this hybrid model supports the above picture in sect. 3. Finally, we will argue in sect. 4 that this picture is a manifestation of the deconfinement transition, namely, a rapid increase of the entropy density in the vicinity of the QCD critical temperature as lattice QCD simulations have been predicted [8].

[a] e-mail: hirano@phys.columbia.edu

2 sQGP core and dissipative hadronic corona

A perfect fluid in the QGP phase is assumed in most hydrodynamic simulations. While one can find various assumptions in the hadron phase [2], *e.g.*: 1) an ideal fluid in chemical equilibrium (CE), 2) an ideal fluid in which particle ratios are fixed (or in partial chemical equilibrium, PCE), or 3) a 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] by putting emphasis on the difference of these assumptions in the hadron phase. The classes CE and HC reproduce the data for pions and protons well. This is considered to be one of the evidence of success of an ideal QGP fluid at RHIC. Contrary to its success, results from the second class, PCE, deviate from the other hydrodynamic results and experimental data though the class PCE as an ideal fluid describes chemical compositions of the hadronic matter in a more realistic way than the class CE does. 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 within the PCE assumption. The difference of assumptions in the hadron phases reduces to the difference of the final slope of the differential elliptic flow $\mathrm{d}v_2(p_T)/\mathrm{d}p_T$. v_2 is roughly proportional to p_T in the low-p_T region for pions. In such a case, the slope of $v_2(p_T)$ can be approximated by $v_2/\langle p_T\rangle$ since one can easily show $\mathrm{d}v_2(p_T)/\mathrm{d}p_T = v_2/\langle p_T\rangle$ when $v_2(p_T)$ is *exactly* proportional to p_T. The integrated v_2 is generated in the early stage of collisions. Whereas the *differential* v_2 can be sensitive to the late hadronic stage since $\mathrm{d}v_2(p_T)/\mathrm{d}p_T \approx v_2/\langle p_T\rangle$ indicates the interplay between the elliptic flow (integrated v_2) and the radial flow (mean transverse momentum $\langle p_T\rangle$).

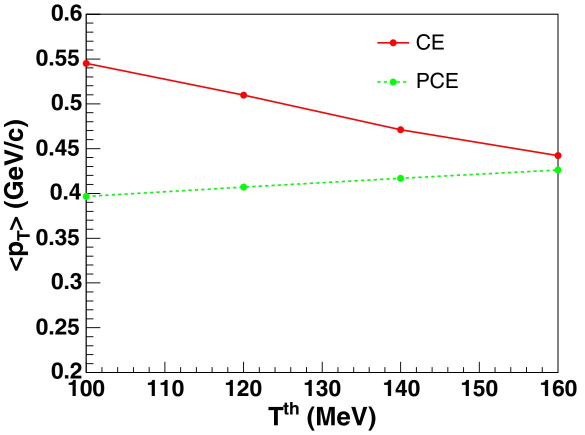

Fig. 1. Mean transverse momentum for pions as a function of the thermal freezeout temperature at $b = 5$ fm in $\sqrt{s_{NN}} = 200$ GeV Au + Au collisions. The solid (dashed) line shows a result with an assumption of an ideal, chemical equilibrium (chemically frozen) hadronic fluid.

In fig. 1, the thermal freezeout temperature T^{th} dependence of $\langle p_T \rangle$ for pions including the contribution from resonance decays is shown from hydrodynamic simulations [10]. Here the impact parameter $b = 5$ fm and the collision energy $\sqrt{s_{NN}} = 200$ GeV are assumed in the hydrodynamic simulations. $\langle p_T \rangle$ for pions in the chemically frozen hadronic fluid decreases with decreasing T^{th} (increasing proper time τ). This is due to longitudinal pdV work done by fluid elements. Whereas $\langle p_T \rangle$ in the chemical equilibrium case increases during expansion. This counterintuitive result appears due to the assumptions of entropy conservation and chemical equilibrium. The total number of particles in a fluid element decreases with proper time τ due to mass effects in the hadron phase. The mass of the particles contributes to the entropy density significantly at low temperature and the proportionality between the entropy density and the number density violates in the temperature range under consideration. Then the total energy that a fluid element possesses initially is partly used for pdV work due to expansion as well as the case for chemically frozen fluids. As a fluid element expands, the remaining energy is distributed among the smaller number of particles in chemical equilibrium. These are the reasons why the different behavior of $\langle p_T \rangle$ appears according to the assumption of chemical equilibrium/freezeout. Note that increase of $\langle p_T \rangle$ results in a "reheating" behavior of a fluid element: Temperature in the chemical equilibrium hadronic fluid drops more slowly than that in the chemically frozen fluid does as if there exists a sort of dissipation [11]. Under the chemical equilibrium assumption in ideal hydrodynamic simulations, increasing $\langle p_T \rangle$ is commonly utilized so far to fix T^{th} by fitting the 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 [12] due to a lack of radial flow. The same is true for the differential elliptic flow: $\mathrm{d}v_2(p_T)/\mathrm{d}p_T \approx v_2/\langle p_T \rangle$ is reproduced by canceling increasing behaviors of both v_2 and $\langle p_T \rangle$ under the chemical equilibrium assumption [10]. The agreement of the results from the CE model with p_T spectra and $v_2(p_T)$ data is reached only when one neglects the particle ratio and the system keeps chemical equilibrium until kinetic freezeout. So, among the three classes mentioned above, the HC model turns out to be the only model which is able to reproduce the particle ratio, p_T spectra and $v_2(p_T)$ data at once in a proper way. Therefore a picture of the dissipative hadronic corona together with the perfect fluid sQGP core, which is properly implemented in the HC model, is consistent with these experimental data observed at RHIC.

3 3D hydro and hadronic cascade model

The establishment of a dynamical model for a detailed description of the whole space-time evolution is one of the main goals in the physics of relativistic heavy-ion collisions. Dynamical models for the description of the whole space-time evolution will be needed to draw the transport properties of the QGP from the experimental data. A dynamical framework has been developed [12] to describe three important aspects of relativistic heavy-ion collisions, namely colour glass condensate (CGC) for collisions of two nuclei, ideal 3D hydrodynamics for space-time evolution of locally thermalised matter, and jet quenching for high-p_T non-thermalised matter. According to the discussion in the previous section, we incorporate a hadronic cascade model JAM [13] into our previous framework, the "CGC+hydro+jet" model [12], to establish a more realistic description of space-time evolution as discussed in the previous section.

Figure 2 shows pseudorapidity dependences of v_2 from this hybrid model and from ideal 3D hydrodynamics with $T^{\mathrm{th}} = 100$ and 169 MeV. Here the critical temperature and the chemical freezeout temperature are taken as being $T_c = T^{\mathrm{ch}} = 170$ MeV in the hydrodynamic model. In the hybrid model, in which the hydrodynamic description of the sQGP ideal fluid is followed by the kinetic theory of resonance gases, the switching temperature from a hydrodynamic description to a kinetic one is taken as $T_{\mathrm{sw}} = 169$ MeV. Ideal hydrodynamics with $T^{\mathrm{th}} = 100$ MeV which is so chosen to generate enough radial flow gives a trapezoidal shape of $v_2(\eta)$ [11,14]. A large deviation between data [5] and the ideal hydrodynamic result is seen especially in forward/backward rapidity regions. However, just after hadronization ($T^{\mathrm{th}} = 169$ MeV), an ideal sQGP fluid gives a triangle shape as shown by the dotted line in fig. 2. (Note that the contribution from resonance decays dilutes slightly the elliptic flow generated in the QGP phase [15] but that the shape is not so changed.) This means that the large v_2 in forward/backward rapidity regions in ideal hydrodynamic simulations with $T^{\mathrm{th}} = 100$ MeV is mainly generated in the perfect fluid of the hadron phase. When hadronic rescattering effects are taken through the hadronic cascade model instead of the perfect fluid description of the hadron phase, v_2 is not so generated in the forward region due to the dissipation

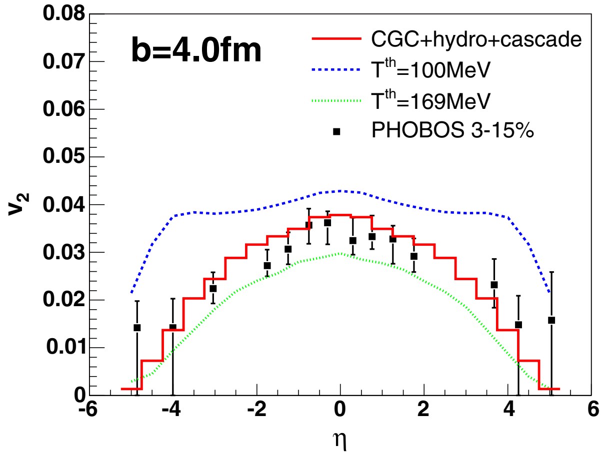

Fig. 2. The pseudorapidity dependences of the elliptic flow from hydro and hydro+hadronic cascade models are compared with data [5]. The dashed and dotted lines are the results from ideal hydrodynamics with $T^{\rm th}$ = 100 and 169 MeV, respectively. The solid line is a result from a hydro+cascade hybrid model.

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 [16]. Note that the eccentricity in the CGC initial condition is found to be larger than that in conventional participant scaling profiles. This is crucial to reproduce the v_2 data in central collisions (3–15%) in our approach. For results from conventional parametrization based on Glauber approaches for the initial conditions, the deviation between ideal hydrodynamics [2] and the data [3–6], which was seen previously in peripheral collisions, is interpreted only by the late hadronic viscosity [17]. On the other hand, the hybrid approach with CGC initial conditions overpredicts the v_2 data unless the early QGP viscosity is considered in peripheral collisions. This suggests that one needs a much better understanding of initial conditions [18] to draw the information about the transport properties of the sQGP from the elliptic flow data.

4 Summary: what have we learned?

At least in central collisions (up to ∼ 20%), we can establish a new picture of the space-time evolution of produced matter, namely the "perfect fluid sQGP core and the dissipative hadronic corona", from a careful comparison of hydrodynamic results with experimental data observed at RHIC. Note that, in semi-central to peripheral collisions, there is room for the existence of additional dissipative effects in the QGP phase from a recent quantitative analysis [17] of v_2 data. This comes from presently unknown details of the initial stage in relativistic heavy-ion collisions. Further theoretical efforts for the understanding of the initial stage [18] are highly needed to obtain a more conclusive picture. In any case, a possibility of the picture, "perfect fluid sQGP core and dissipative hadronic corona", is intriguing.

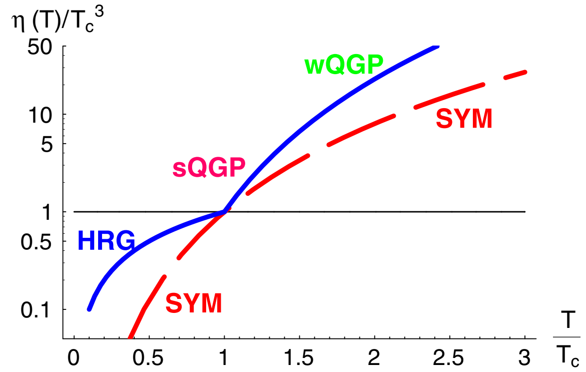

Fig. 3. Illustration of the approximately monotonic increase of the absolute value of the shear viscosity with temperature. SYM, HRG, and wQGP represent, respectively, the supersymmetric Yang-Mills model, hadronic resonance gas, and weakly coupled QGP.

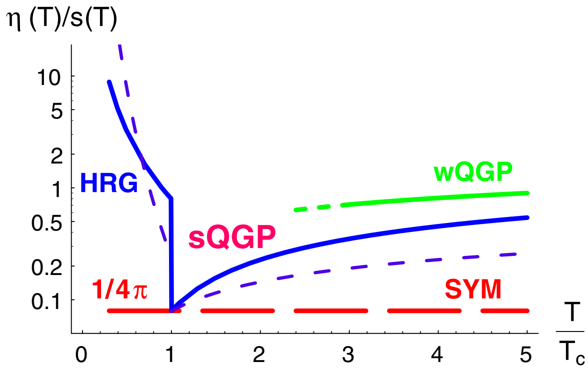

Fig. 4. Illustration of the rapid variation of the *dimensionless ratio* of the shear viscosity, $\eta(T)$, to the entropy density, $s(T)$. The solid and short-dashed lines above T_c asymptotically merge wQGP result at the high-temperature region. We introduce a parameter which controls how fast the sQGP result reaches the wQGP one. The solid and short-dashed lines below T_c correspond to the sound velocity in the resonance gas model $c_s^2 = 1/3$ and $1/6$, respectively. The long-dashed line is $\eta/s = 1/4\pi$ from SYM [19].

What is the physics behind this picture? η/s is known to be a good dimensionless measure (in natural unit $\hbar = k_B = c = 1$) 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 dependences of η and η/s deduced from the discussion in the previous sections. η/s must be small in the QGP phase, which might be comparable with a value $1/4\pi$ conjectured as the minimum one among any kinds of fluids [19], 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 is expected 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.

This work was supported in part by the United States Department of Energy under Grant No. DE-FG02-93ER40764. The author would like to thank U. Heinz, D. Kharzeev, M. Gyulassy, R. Lacey and Y. Nara for collaboration and fruitful discussion.

References

1. `http://www.bnl.gov/bnlweb/pubaf/pr/PR_display.asp?prID=05-38`.
2. P. Huovinen, in *Quark Gluon Plasma 3*, edited by R.C. Hwa, X.N. Wang (World Scientific, 2004) p. 600; P.F. Kolb, U. Heinz, in *Quark Gluon Plasma 3*, edited by R.C. Hwa, X.N. Wang (World Scientific, 2004) p. 634; D. Teaney, J. Lauret, E.V. Shuryak, nucl-th/0110037; T. Hirano, Acta Phys. Pol. B **36**, 187 (2005).
3. STAR Collaboration (K.H. Ackermann *et al.*), Phys. Rev. Lett. **86**, 402 (2001); STAR Collaboration (C. Adler *et al.*), Phys. Rev. Lett. **87**, 182301 (2001); Phys. Rev. Lett. **89**, 132301 (2002); Phys. Rev. C **66**, 034904 (2002); STAR Collaboration (J. Adams *et al.*), nucl-ex/0409033.
4. PHENIX Collaboration (K. Adcox *et al.*), Phys. Rev. Lett. **89**, 212301 (2002); PHENIX Collaboration (S.S. Adler *et al.*), Phys. Rev. Lett. **91**, 182301 (2003);
5. PHOBOS Collaboration (B.B. Back *et al.*), Phys. Rev. Lett. **89**, 222301 (2002); nucl-ex/0406021; nucl-ex/0407012.
6. BRAHMS Collaboration (H. Ito), talk given at the *18th International Conference on Nucleus-Nucleus Collisions, Quark Matter 2005 (QM 2005), Budapest, Hungary, 4-9 August 2005*.
7. C. Nonaka, S. Bass, nucl-th/0510038. (This paper employs different hydrodynamic and hadronic cascade codes from the present paper.)
8. See, for example, F. Karsch, Lect. Notes Phys. **583**, 209 (2002).
9. PHENIX Collaboration (K. Adcox *et al.*), nucl-ex/0410003.
10. T. Hirano, M. Gyulassy, nucl-th/0506049.
11. T. Hirano, K. Tsuda, Phys. Rev. C **66**, 054905 (2002).
12. T. Hirano, Y. Nara, Nucl. Phys. A **743**, 305 (2004).
13. Y. Nara, N. Otuka, A. Ohnishi, K. Niita, S. Chiba, Phys. Rev. C **61**, 024901 (2000).
14. T. Hirano, Phys. Rev. C **65**, 011901 (2002);
15. T. Hirano, Phys. Rev. Lett. **86**, 2754 (2001).
16. Recently, the effect of event-by-event fluctuation in the initial conditions is found to reduce v_2 in forward and backward rapidity regions. It is concluded that a lack of thermalisation is not needed when fluctuation is taken into account: R. Andrade, F. Grassi, Y. Hama, T. Kodama, O. Socolowski jr., B. Tavares, nucl-th/0511021.
17. T. Hirano, U. Heinz, D. Kharzeev, R. Lacey, Y. Nara, nucl-th/0511046.
18. One can find many papers in these proceedings for recent progress to understand non-equilibrium aspects of gauge theories and an initial prethermalisation stage in relativistic heavy-ion collisions.
19. P. Kovtun, D.T. Son, A.O. Starinets, Phys. Rev. Lett. **94**, 111601 (2005); G. Policastro, D.T. Son, A.O. Starinets, Phys. Rev. Lett. **87**, 081601 (2001); A. Starinets, these proceedings.