What can we learn from hydrodynamic analysis at RHIC?

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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 rapid increase of entropy density in the vicinity of QCD critical temperature, namely deconfinement.

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1. Introduction

Recently, physicists at Brookhaven National Laboratory made an announcement in the American Physical Society annual meeting at 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, 4, 5, 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 rapidity dependence of elliptic flow from this hybrid model supports the above picture in Sec. 3. Finally, we will argue in Sec. 4 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 [8].

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] with putting an 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 differential elliptic flow \( dv_2(p_T)/dp_T \). \( v_2 \) 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 \( v_2(p_T)/p_T \) since one can easily show \( dv_2(p_T)/dp_T = v_2/p_T \) when \( v_2(p_T) \) is exactly proportional to \( p_T \). Integrated \( v_2 \) is generated in the early stage of collisions. Whereas differential \( v_2 \) can be sensitive to the late hadronic stage since \( dv_2(p_T)/dp_T \approx v_2/p_T \) indicates interplay between elliptic flow (integrated \( v_2 \)) and radial flow (mean transverse momentum \( \langle p_T \rangle \)).

In Fig. 1 thermal freezeout temperature \( T^{th} \) dependence of \( \langle p_T \rangle \) for pions including contribution from resonance decays are shown from hydrodynamic simulations [10]. Here the impact parameter \( b = 5 \) fm and 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 \( \tau \)). 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 \( \tau \) due to mass effects in the hadron phase. Mass of particles contributes to the entropy density significantly in low temperature and the proportionality between the entropy
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Fig. 1. Mean transverse momentum for pions as a function of thermal freezeout temperature at \( b = 5 \text{ fm} \) in \( \sqrt{s_{NN}} = 200 \text{ GeV} \) Au+Au collisions. Solid (dashed) line shows a result with an assumption of an ideal, chemical equilibrium (chemically frozen) hadronic fluid.

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 \( p_T \) 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 differential elliptic flow: \( dv_2(p_T)/dp_T \approx v_2/\langle p_T \rangle \) is reproduced by canceling increasing 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 reached only when one neglects particle ratio and the system keeps chemical equilibrium until kinetic freezeout. So, among three classes mentioned above,
establish a more realistic description of space-time evolution as
Fig. 3. Illustration of the approximately monotonic increase of absolute value of the shear viscosity with temperature. SYM, HRG, and wQGP represent, respectively, supersymmetric Yang-Mills model, hadronic resonance gas, and weakly coupled QGP.

discussed in the previous section.

Figure 2 shows pseudorapidity dependences of $v_2$ from this hybrid model and ideal 3D hydrodynamics with $T_{th} = 100$ and 169 MeV. Here critical temperature and chemical freezeout temperature are taken as being $T_c = T_{ch} = 170$ MeV in the hydrodynamic model. In the hybrid model, in which 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 $T_{sw} = 169$ MeV. Ideal hydrodynamics with $T_{th} = 100$ 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 ($T_{th} = 169$ 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 the large $v_2$ in forward/backward rapidity regions in ideal hydrodynamic simulations with $T_{th} = 100$ MeV is mainly generated in the perfect fluid of hadron phase. 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
Fig. 4. Illustration of the rapid variation of the dimensionless ratio of the shear viscosity, $\eta(T)$, to the entropy density, $s(T)$. Solid and Short dashed lines above $T_c$ asymptotically merge wQGP result at high temperature region. We introduce a parameter which controls how fast the sQGP result reaches the wQGP one. Solid and short lines below $T_c$ corresponds to sound velocity in the resonance gas model $c_s^2 = 1/3$ and 1/6 respectively. Long dashed line is $\eta/s = 1/4\pi$ from SYM [19].

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 4 5 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 $\sim 20\%$), we can establish a new picture of space-time evolution of produced matter, namely “perfect fluid sQGP core and
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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 a room for 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 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.

What is the physics behind this picture? $\eta/s$ is known to be a good dimensionless measure in natural unit $\hbar = k_B = c = 1$ to see the effect of viscosity, where $\eta$ is the shear viscosity and $s$ is the entropy density. Figures 3 and 4 show possible scenarios for temperature dependence of $\eta$ and $\eta/s$ deduced from the discussion in the previous sections. $\eta/s$ 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 $\eta/s$ 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.

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Notes

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References

1. [http://www.bnl.gov/bnlweb/pubaf/pr/PR_displays.asp?prID=05-38](http://www.bnl.gov/bnlweb/pubaf/pr/PR_displays.asp?prID=05-38)
2. P. Huovinen, in Quark Gluon Plasma 3, (World Scientific Pub., 2004, eds. R.C. Hwa, X.N. Wang) p. 600; P. F. Kolb and U. Heinz, ibid. p. 634; D. Teaney, J. Lauret and E. V. Shuryak, [nucl-th/0110037](http://arxiv.org/abs/nucl-th/0110037) T. Hirano, Acta Phys. Polon. B 36, 187 (2005).
3. K. H. Ackermann et al. [STAR Collaboration], Phys. Rev. Lett. 86, 402 (2001); C. Adler et al. [STAR Collaboration], ibid. 87, 182301 (2001); ibid.
89, 132301 (2002); Phys. Rev. C 66, 034904 (2002); J. Adams et al. [STAR Collaboration], nucl-ex/0409033
4. K. Adcox et al. [PHENIX Collaboration], Phys. Rev. Lett. 89, 212301 (2002); S. S. Adler et al. [PHENIX Collaboration], ibid. 91, 182301 (2003);
5. B. B. Back et al. [PHOBOS Collaboration], Phys. Rev. Lett. 89, 222301 (2002); nucl-ex/0406021; nucl-ex/0407012
6. H. Ito [BRAHMS Collaboration], talk given at 18th International Conference on Ultrarelativistic Nucleus-Nucleus Collisions: Quark Matter 2005 (QM 2005), Budapest, Hungary, 4-9 Aug 2005.
7. C. Nonaka and 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. K. Adcox et al. [PHENIX Collaboration], nucl-ex/0410003
10. T. Hirano and M. Gyulassy, nucl-th/0506049
11. T. Hirano and K. Tsuda, Phys. Rev. C 66, 054905 (2002).
12. T. Hirano and Y. Nara, Nucl. Phys. A 743, 305 (2004).
13. Y. Nara, N. Otuka, A. Ohnishi, K. Niita and 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. and B. Tavares, nucl-th/0511021.
17. T. Hirano, U. Heinz, D. Kharzeev, R. Lacey, and 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 and A. O. Starinets, Phys. Rev. Lett. 94, 111601 (2005); G. Policastro, D. T. Son and A. O. Starinets, ibid. 87, 081601 (2001); A. Starinets, these proceedings.