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Hadronic resonance gas, p_T spectra of charged particles, and elliptic flow in $\sqrt{s} = 200$ GeV Au + Au collisions

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Charged particles' p_T spectra and elliptic flow in 0%–60% Au + Au collisions at the Relativistic Heavy Ion Collider are analyzed in a hydrodynamic model with hot hadronic resonance gas (HRG) in the initial state. Physically conceivable HRG, thermalized in the time scale $\tau_i = 1$ fm, at a (central) temperature $T_i = 220$ MeV, with viscosity-to-entropy ratio $\eta/s = 0.24$, explains the p_T spectra in all the collision centralities reasonably well. However, centrality dependence of elliptic flow demands continual increase of the viscosity-to-entropy ratio with centrality.

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Recent experiments in Au + Au collisions at the Relativistic Heavy Ion Collider (RHIC) [1–4] produced convincing evidence that, in central and midcentral Au + Au collisions, a hot dense strongly interacting matter is created. Whether the matter can be identified as the lattice QCD-predicted quark gluon plasma (QGP) [5] or not is still a question for debate. Confirmatory identification of the matter with QGP requires complete elimination of the possibility that a hadronic state is produced in the initial collisions. It is yet to be performed. Information about the initial state is always indirect. QGP is a transient state and even if produced, exists for a short time scale, expands, cools, and eventually transforms into hadrons. Hadrons are the experimental observables, and any information about the initial state has to be obtained from the observed hadrons. Dynamical models are essential to extract information about the initial state from the experimental observables.

Relativistic hydrodynamics is one of the few dynamical models, which has been successfully applied in RHIC collisions to obtain information about the initial medium produced in Au + Au collisions. It is assumed that a fireball is produced in an Au + Au collision. Constituents of the fireball collide frequently to establish local thermal equilibrium sufficiently fast, and after a certain time τ_i, hydrodynamics become applicable. If the macroscopic properties of the fluid (e.g., energy density, pressure, velocity, etc.) are known at the equilibration time τ_i, the relativistic hydrodynamic equations can be solved to give the space-time evolution of the fireball until a given freeze-out condition such that interactions between the constituents become too weak to continue the evolution. By using a suitable algorithm (e.g., Cooper-Frye), information at the freeze-out can be converted into particle spectra and can be directly compared with experimental data. Thus, hydrodynamics, in an indirect way, can characterize the initial state of the medium produced in heavy ion collisions. Hydrodynamic equations are closed only with an equation of state, and one can investigate the possibility of phase transition in the medium.

Relativistic hydrodynamics with QGP in the initial state, thermalized in the time scale $\tau_i \approx 0.6$ fm, at an initial central energy density $\varepsilon_0 \approx 30$ GeV/fm^3, could explain a host of experimental data produced in $\sqrt{s} = 200$ GeV Au + Au collisions [6]. In an alternative to the initial QGP state, namely, the hot hadronic resonance gas (HRG), description to the experimental data gets much poorer [7]. Also, to reproduce the experimental multiplicity, hot HRG is required to be initialized at very high temperatures (e.g., $T_i \approx 270$ MeV). Density of HRG grows rapidly with temperature. At $T \approx 270$ MeV, density of hadrons is large $\rho_{\rm had} \sim 4$ fm^{-3}. At such a large density, hadrons will overlap extensively, and it is difficult to believe that they could retain their individual identity. It does appear that a consistent description of RHIC data could not be obtained in an HRG model. However, all the analysis of RHIC data with HRG in the initial state was performed in the ideal hydrodynamic limit. In recent years, there has been much progress in the practical application of viscous hydrodynamics [8–22]. Several codes were developed to numerically solve causal dissipative hydrodynamics and were applied successfully to analyze experimental data at RHIC collisions with QGP in the initial state. However, we have not come across any analysis of RHIC data with viscous HRG in the initial state. Viscous effects can be large in HRG. Model calculations [23–26] indicate that viscosity-to-entropy ratio of an HRG can be considerably larger than the ADS/CFT limit $\eta/s \geqslant 1/4\pi$ [27]. Since entropy is generated during evolution, unlike an ideal HRG, a viscous HRG can be initialized at a lower temperature such that hadrons retain their identity yet reproduce the experimental multiplicity. Indeed, in one of the earliest applications of one-dimensional viscous hydrodynamics, it was shown that WA80 single-photon spectra, although overpredicted in an ideal hadron gas evolution, were reasonably well explained when viscous effects were accounted for [28]. To exclude the possibility of hadron gas formation in initial Au + Au collisions, instead of QGP, it is important that RHIC data are analyzed in a viscous HRG model.

We assume that, in Au + Au collisions, a baryon-free hot HRG, comprising all the hadron resonances with mass $m_{\rm res} \leqslant$ 2.5 GeV is produced. The hot HRG is assumed to thermalize

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in the time scale $\tau_i = 1$ fm. We also neglect all the dissipative effects except for the shear viscosity. The space-time evolution of the fluid is obtained by solving

$$\partial_\mu T^{\mu\nu} = 0, \tag{1}$$

$$D\pi^{\mu\nu} = -\frac{1}{\tau_\pi}(\pi^{\mu\nu} - 2\eta\nabla^{<\mu}u^{\nu>}) - [u^\mu\pi^{\nu\lambda} + u^\nu\pi^{\nu\lambda}]Du_\lambda. \tag{2}$$

Equation (1) is the conservation equation for the energy-momentum tensor $T^{\mu\nu} = (\varepsilon + p)u^\mu u^\nu - pg^{\mu\nu} + \pi^{\mu\nu}$, ε, p, and u being the energy density, pressure, and fluid velocity, respectively. $\pi^{\mu\nu}$ is the shear stress tensor (we have neglected bulk viscosity and heat conduction). Equation (2) is the relaxation equation for the shear stress tensor $\pi^{\mu\nu}$. In Eq. (2), $D = u^\mu\partial_\mu$ is the convective time derivative, $\nabla^{<\mu}u^{\nu>} = \frac{1}{2}(\nabla^\mu u^\nu + \nabla^\nu u^\mu) - \frac{1}{3}(\partial \cdot u)(g^{\mu\nu} - u^\mu u^\nu)$ is a symmetric traceless tensor. η is the shear viscosity, and τ_π is the relaxation time. It may be mentioned that in a conformally symmetric fluid, the relaxation equation can contain additional terms [17]. By assuming longitudinal boost invariance, the equations are solved with the code AZHYDRO-KOLKATA [16] in ($\tau = \sqrt{t^2 - z^2}$, x, y, $\eta = \frac{1}{2}\ln\frac{t+z}{t-z}$) coordinates.

The solution for Eqs. (1) and (2) requires initial energy density velocity distribution in the transverse plane at the initial time. We assume that, at the initial time $\tau_i = 1$ fm, the initial fluid velocity is zero $v_x(x, y) = v_y(x, y) = 0$. The initial energy density in an impact parameter **b** collision is assumed to be distributed as [6]

$$\varepsilon(\mathbf{b}, x, y) = \varepsilon_0[(1 - x)N_{\rm part}(\mathbf{b}, x, y) + xN_{\rm coll}(\mathbf{b}, x, y)], \tag{3}$$

where $N_{\rm part}(\mathbf{b}, x, y)$ and $N_{\rm coll}(\mathbf{b}, x, y)$ are the transverse profile of participant numbers and the binary collision numbers, respectively. $N_{\rm part}(\mathbf{b}, x, y)$ and $N_{\rm coll}(\mathbf{b}, x, y)$ can be calculated in a Glauber model. x in Eq. (3) is the fraction of hard scattering. Most of the hydrodynamic simulations are performed with the hard scattering fraction $x = 0.25$ or 0.13 [6,29]. Recently, in Ref. [30], it was shown that in collisions beyond 0%–10% centrality, simultaneous description of charged particles' p_T spectra and elliptic flow are best obtained with the hard scattering fraction $x = 0$. Only in 0%–10% centrality collisions, is the hard scattering fraction $x = 1$ preferred. In the following, in all the collision centralities, we assume the hard scattering fraction $x = 0$, by understanding that we may underpredict elliptic flow in very central collisions. ε_0 in Eq. (3) is the central energy density of the fluid in an impact parameter $\mathbf{b} = 0$ collision. Generally, ε_0 is obtained by fitting experimental data (e.g., multiplicity, p_T spectra, etc.). However, we fix ε_0 to the highest possible value for a physically conceivable HRG. For hadron size $\approx$0.5 fm, limiting hadron density (such that hadrons are not overlapped) is $\rho^{\rm had}_{\rm limit} = 1/V \approx 2$ fm^{-3}. $\rho^{\rm had}_{\rm limit} = 2$ fm^{-3} corresponds to limiting temperature or energy density $T_{\rm limit} = 220$ MeV, $\varepsilon_{\rm limit} = 5.1$ GeV/fm^3. We fix the central energy density at this limiting value $\varepsilon_0 = \varepsilon_{\rm limit} = 5.1$ GeV/fm^3. Recent lattice simulations [5], with almost physical quark masses ($m_\pi \approx 220$ MeV), predict a confinement-deconfinement transition temperature $T_c = 196 \pm 3$ MeV. Hadrons can exist at $T \approx 200$ MeV. Existence of HRG at $\sim$10% higher temperature $T = 220$ MeV is a definite possibility.

Dissipative hydrodynamics also require initialization of the shear stress tensor $\pi^{\mu\nu}$ as well as the relaxation time τ_π. We assume that shear stress tensors are initialized at the boost-invariant values $\pi^{xx} = \pi^{yy} = 2\eta(x, y)/3\tau_i$, $\pi^{xy} = 0$ [16]. For the relaxation time τ_π, we use the Boltzmann estimate $\tau_\pi = 6\eta/4p \approx \frac{6}{T}\frac{\eta}{s}$. Finally, hydrodynamic models require a freeze-out condition. We assume that the fluid freeze-out at a fixed temperature $T_F = 110$ MeV.

The only unspecified parameter in the model is the viscosity coefficient η. We assume that throughout the evolution, the ratio of viscosity-to-entropy density η/s remains a constant and simulates Au + Au collisions for four values of η/s, (i) $\eta/s = 0$ (ideal fluid), (ii) $\eta/s = 1/4\pi = 0.08$ (ADS/CFT lower limit of viscosity), (iii) $\eta/s = 0.16$, and (iv) $\eta/s = 0.24$. Assumption of constant η/s fixes the variation of viscosity with temperature $\eta \propto s \propto T^3$. In Figs. 1 and 2, simulated charged particles' p_T spectra and elliptic flow are compared with experimental data. In Fig. 1, in six panels, PHENIX data [31] for charged particles' p_T spectra in 0%–10%, 10%–20%, 20%–30%, 30%–40%, 40%–50%, and 50%–60% Au + Au collisions are shown. The dashed, dashed-dotted, short-dashed, and solid lines in the figure are simulated spectra from evolution of hot HRG, with viscosity-to-entropy ratio $\eta/s = 0$, 0.08, 0.16, and 0.24, respectively. If viscous effects are neglected, hot HRG, initialized with central temperature $T_i = 220$ MeV, does not explain the data, the data are largely underpredicted. For example, at $p_T \approx 1.75$ GeV, in all the collision centralities, ideal hot hadronic gas underpredict

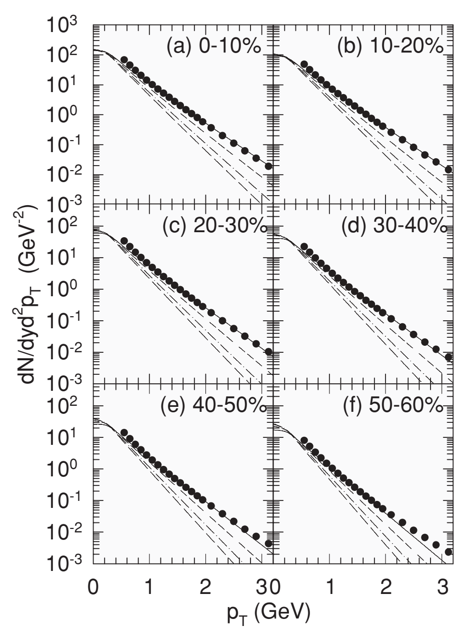

FIG. 1. In six panels, PHENIX measurements [31] for charged particles' p_T spectra in 0%–10%, 10%–20%, 20%–30%, 30%–40%, 40%–50%, and 50%–60% Au + Au collisions are shown. The dashed, dashed-dotted, short-dashed, and solid lines are simulated spectra from evolution hot HRG with $\eta/s = 0$, $\eta/s = 0.08$, $\eta/s = 0.16$, and $\eta/s = 0.24$, respectively.

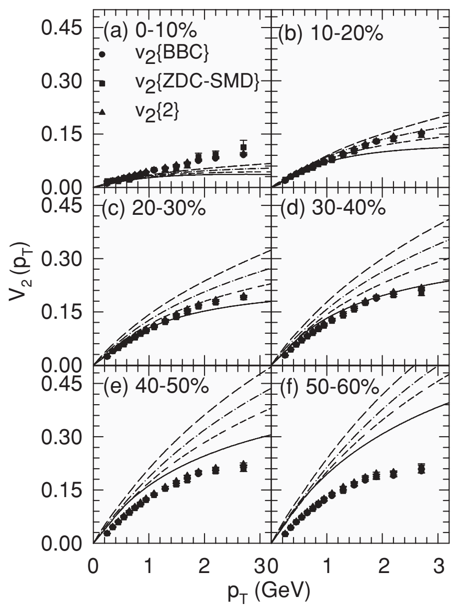

FIG. 2. In six panels, PHENIX measurements [32] for charged particles' elliptic flow in 0%–10%, 10%–20%, 20%–30%, 30%–40%, 40%–50%, and 50%–60% Au + Au collisions are shown. The dashed, dashed-dotted, short-dashed, and solid lines are simulated flow from evolution hot HRG with $\eta/s = 0$, $\eta/s = 0.08$, and $\eta/s = 0.16$, and $\eta/s = 0.24$, respectively.

PHENIX data by a factor of $\sim$6. Data at higher p_T are even more underpredicted. When viscous effects are included, particle yield increases, more at high p_T than at low p_T, and discrepancy with experiment and simulated spectra diminishes. At $p_T \approx 1.75$ GeV, data are underpredicted by a factor of $\sim$4 in evolution of minimally viscous HRG ($\eta/s = 0.08$) and by a factor of $\sim$2 in evolution of HRG with $\eta/s = 0.16$. Experimental data are reasonably reproduced with viscosity-to-entropy ratio $\eta/s = 0.24$. Indeed, in all the centrality ranges of collisions, simulated spectra from evolution of HRG with viscosity-to-entropy ratio $\eta/s = 0.24$, agree with the experiment within $\sim$10%. It is very interesting to note that the $\eta/s = 0.24$, obtained from the analysis is in close agreement with theoretical estimates of the viscosity-to-entropy ratio of a hot HRG $\eta/s = 0.24$–0.30 [23,26].

The analysis clearly indicates that at least for the charged particles' p_T spectra, it is not necessary that QGP fluid is produced in $\sqrt{s} = 200$ GeV Au + Au collisions. Physically conceivable hot HRG, with viscosity-to-entropy ratio $\eta/s = 0.24$, could reproduce the spectra. Elliptic flow analysis, on the other hand, gives a different result. In Fig. 2, PHENIX measurements [32] for charged particles' elliptic flow in 0%–10%, 10%–20%, 20%–30%, 30%–40%, 40%–50%, and 50%–60% Au + Au collisions are shown. The PHENIX collaboration measured charged particles' v_2 up to $p_T \approx 8$ GeV. In Fig. 2, only measurements up to $p_T = 3$ GeV are shown. Hydrodynamic models are not well suited for high p_T particles. To study nonflow effects that are not correlated with the reaction plane, as well as fluctuations of v_2, the PHENIX Collaboration obtained v_2 from two independent analyses, (i) event plane method from two independent subdetectors $v_2\{BBC\}$ and $v_2\{ZDC - SMD\}$ and (ii) two-particle cumulant $v_2\{2\}{\cdot}v_2\{2\}$ from the two-particle cumulant and $v_2\{BBC\}$ or $v_2\{ZDC - BBC\}$ from event plane methods agree within the systematic error. It may also be mentioned here that $v_2\{2\}$ in PHENIX is lower than $v_2\{2\}$ in STAR measurements, but they agree within the systematic error. All three measurements of v_2 are shown in Fig. 2. As before, the dashed, dashed-dotted, short-dashed, and solid lines in Fig. 2 are simulated flow with $\eta/s = 0$, 0.08, 0.16, and 0.24, respectively. Unlike the p_T spectra, centrality dependence of elliptic flow is not explained with a single value for the viscosity-to-entropy ratio. Data demand more viscous fluid in more peripheral collisions. For example, in 0%–10% centrality collisions, experimental flow are underpredicted in ideal HRG. With viscous HRG, flow is even more underpredicted. We have assumed participant scaling for the initial energy density. As mentioned earlier, very central collisions prefer binary collision number scaling of initial energy density [30]. Spatial eccentricity is comparatively large in binary collision scaling, and elliptic flow in 0%–10% collision will be better explained if initial energy density scales with binary collision numbers. In 10%–20% centrality collisions, experimental flow is underpredicted with $\eta/s = 0.16$ and 0.24. Data demand HRG with viscosity in the range $\eta/s = 0$–0.08. Elliptic flow in 20%–30% centrality collisions prefers more viscous HRG $\eta/s \approx 0.16$. HRG with $\eta/s \approx 0.24$ approximately explains flow in 30%–40% centrality collisions. Elliptic flow in 40%–50% and 50%–60% Au + Au collisions demand HRG with $\eta/s > 0.24$. Continual increase of viscosity with centrality can be understood. In an HRG, viscosity-to-entropy ratio increases with decreasing temperature. Initial temperature of the fluid also decreases as the collisions become more and more peripheral. For example, central temperature of the fluid is $T_i \approx 219$ MeV in a 0%–10% collision. In a 30%–40% collision, central temperature is $T_i \approx 210$ MeV. Hadronic fluid will be more viscous in a peripheral collision than in a central collision. Elliptic flow, which is a sensitive observable, can detect the small variation in temperature.

However, it is difficult to explain why the stated change in temperature is not reflected in the p_T spectra. Although centrality dependence of elliptic flow requires continual increase of viscosity, charged particles' p_T spectra definitely do not demand such an increase. Rather, the p_T spectra are well explained with a fixed value for viscosity $\eta/s \approx 0.24$ (see Fig. 1). It appears that a viscous hydrodynamic model, with HRG in the initial state, is incapable of simultaneous explanation of centrality dependence of charged particles' p_T spectra and elliptic flow. Here, we may note that hydrodynamics, with QGP in the initial state, also requires a continual increase of viscosity to explain the centrality dependence of elliptic flow [20], however, particle spectra are explained with a fixed viscosity to entropy [22].

Before we summarize, we note that we have used some specific initial conditions for the hydrodynamical model [e.g., initial (central) energy density $\varepsilon_i = 5.1$ GeV/fm^3, initial or thermalization time $\tau_i = 1$ fm, and freeze-out temperature $T_F = 110$ MeV]. The initial energy density was fixed from the physical requirement that constituents of the HRG do not overlap extensively and lose their identity. Hydrodynamic model analysis of RHIC data with QGP in the initial state indicates thermalization time for QGP $\tau_i = 0.6$ fm. Compared to QGP, an HRG is expected to take a longer time to achieve thermalization, and the thermalization time for the HRG was fixed at the canonical value $\tau_i = 1$ fm. Similarly, freeze-out temperature $T_F = 110$ MeV was indicated in the hydrodynamic model analysis of RHIC data [6]. All physically supported parameters set were not examined.

In summary, we have studied the possibility of explaining charged particles' p_T spectra and elliptic flow without invoking QGP. We assume that a hot HRG is formed in initial Au + Au collisions. The hot hadronic gas thermalizes in the time scale $\tau_i \approx 1$ fm to central temperature $T_i \approx 220$ MeV. While an ideal HRG does not explain the charged particles' p_T spectra (data are largely under predicted), a viscous hadronic gas, with viscosity-to-entropy ratio $\eta/s \approx 0.24$, explains the p_T spectra in all the centrality ranges of collisions. However, elliptic flow data are more sensitive and demand more viscous HRG in peripheral collisions than in central collisions. We conclude that with the initialization and freeze-out parametrization presented here, a viscous hydrodynamic model containing only HRG, is incapable of simultaneous explanation of centrality dependence of charged particles' p_T spectra and elliptic flow in $\sqrt{s} = 200$ GeV Au + Au collisions at the RHIC.

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