Charged particle's p_T spectra and elliptic flow in $\sqrt{s_{NN}}$ =200 GeV Au+Au collisions: QGP vs. hadronic resonance gas

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We show that if the hadronic resonance gas (HRG), with viscosity to entropy ratio $\eta/s \approx 0.24$, is physical at temperature $T \approx 220$ MeV, charged particles p_T spectra and elliptic flow in Au+Au collisions at RHIC, over a wide range of collision centrality do not distinguish between initial QGP fluid and initial hadronic resonance gas. Unambiguous identification of bulk of the matter produced in Au+Au collisions require clear demonstration that HRG is unphysical at temperature T > 200 MeV. It calls for precise lattice simulations with realistic boundary conditions.

Experiments at Relativistic Heavy Ion Collider (RHIC) produced convincing evidences that in central and mid central Au+Au collisions, a hot, dense, strongly interacting matter is created[1],[2],[3],[4]. Whether the matter can be identified as the lattice QCD predicted Quark Gluon Plasma(QGP) or not is still a question of debate. The problem is closely related to quark confinement; quarks are unobservable and any information about the initial state has to be obtained from observed hadrons only. QGP, even if produced in Au+Au collisions, is a transient state, it expands, cools, hadronises, cools further till interactions between the hadrons become too weak to continue the evolution. Hadronisation is a nonperturbative process. Whether or not the hadronisation process erases any memory of the constituent quarks is uncertain. If the hadronisation process erases the memory, from the observed hadrons one can not comment on the initial QGP phase. Present search for QGP at RHIC is on the premise that the hadronisation process does not erase the memory and from the observed hadrons, using a dynamical model like hydrodynamics, one can backtrace to the initial QGP phase. Hydrodynamic equations are closed with an Equation of State (EOS) and one can incorporate the possibility of phase transition in the model. Indeed, a host of experimental data in Au+Au collisions at RHIC is well explained in a hydrodynamical model with QGP in the initial state [5]. The alternative, namely hadronic resonance gas (HRG) in the initial state generally give poorer description to the data [6], that too with HRG at very high temperature, $T_i \approx$ 270 MeV. At such high temperature hadrons density is very large $\rho_{had} \sim 4 \ fm^{-3}$ and it is difficult to believe that they retain their individual identity. However, situation changes if viscous effects are included. Model calculations [7],[8],[9],[10] indicate that for a hadronic resonance gas, viscosity to entropy ratio is considerably larger than the ADS/CFT limit, $\eta/s > 1/4\pi$ [11]. Since entropy is generated during evolution, unlike an 'ideal' HRG, a 'viscous' HRG can be initialized at a lower temperature such

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that hadrons retain their identity yet reproduce the experimental multiplicity. In the following, we show that if the hadrons retain their identity at temperature $T\approx 220$ MeV, charged particles p_T spectra and elliptic flow in 0-40% Au+Au collisions, do not distinguishes between initial HRG with viscosity to entropy ratio $\eta/s\approx 0.24$ and initial QGP with $\eta/s=0.08$. Unambiguous identification of the matter with QGP will require clear proof that HRG has a limiting temperature $T\leq 200$ MeV or the confinement-deconfinement transition occur at a temperature ≤ 200 MeV.

Most reliable information about the confinementdeconfinement transition temperature is obtained in lattice simulations of QCD. It is now established that the confinement-deconfinement transition is not a thermodynamic phase transition, rather a cross-over. Since it is cross-over, there is no unambiguous temperature where the transition take place. Inflection point of the Polyakov loop is generally quoted as the (pseudo)critical temperature for the confinement-deconfinement transition. Currently, there is debate over the value of the pseudo critical temperature. HotQCD collaboration, with physical strange quark mass and somewhat larger than physical u and d quark masses $(m_s/m_{u,d} = 10)$ claimed that both the chiral and confinement-deconfinement transition takes place at a common temperature $T_c =$ 192(4)(7). [12],[13],[14],[15],[16]. For more physical u and d masses $(m_s/m_{u,d}=20)$, the critical temperature shift by ~ 5 MeV to lower side [17]. Wuppertal-Budapest collaboration, with physical strange and light quark masses $(m_s/m_{u,s} = 28)$, on the other obtained a different result. [18],[19], [20], [21]. Chiral transition temperature $T_c=157$ (3)(3) MeV is ~ 20 MeV less than the confinement-deconfinement transition temperature $T_c=170(4)(4)$ MeV. Several other observables, e.g. quark susceptibility, pressure etc in Wuppertal-Budapest simulations is also shifted by 20-30 MeV compared to HotQCD. The ~ 20 MeV shift in the confinementdeconfinement transition temperature is not properly understood. Possible reasons could be larger physical quark masses in HotQCD simulations. Also, one notes that though both the collaborations use staggered fermions, the fermion actions are different. It is still unproven that in the continuum limit, staggered fermions represent

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QCD. The difference in the pseudo critical temperature may also be due to different 'staggered' fermion action in the two simulations. Additionally, lattice results for the transition temperature can be up by ~ 30 MeV. All the lattice simulation uses periodic boundary condition, while in a realistic situation e.g. heavy ion collisions, the deconfined region is bordered by a confined phase. Exploratory quenched study suggests that with realistic boundary condition transition temperature can be up by 30 MeV [22]. Considering the uncertainties associated with lattice simulations, the pseudo critical temperature for the confinement-deconfinement transition temperature could be as high as $T_c \approx 220$ MeV. Qualitatively, for hadron size ≈ 0.5 fm, limiting hadron density (such that hadrons are not overlapped) is $\rho_{limit}^{had} = 1/V \approx 2$ fm^{-3} . For HRG, $\rho_{had} \approx 2fm^{-3}$ corresponds to limiting temperature $T_{limit} = 220$ MeV, value close to the highest possible pseudo critical temperature, as argued above. $T \approx 220 \text{ MeV}$ is possibly the highest temperature at which hadrons can retain their individual identity. At higher temperature hadrons will overlap extensively and lose their identity.

In the following we simulate Au+Au collisions in two scenarios, (i) no phase transition (NPT) scenario when a HRG with limiting temperature T=220 MeV is produced in the initial collisions and (ii) a phase transition (PT) scenario when QGP is produced. Space-time evolution of HRG/QGP fluid is obtained by solving,

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

$$D\pi^{\mu\nu} = -\frac{1}{\tau_{\pi}}(\pi^{\mu\nu} - 2\eta\nabla^{<\mu}u^{\nu>})$$

$$- [u^{\mu}\pi^{\nu\lambda} + u^{\nu}\pi^{\nu\lambda}]Du_{\lambda}. \tag{2}$$

Eq.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). Eq.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, $\nabla^{<\mu}u^{\nu>}=\frac{1}{2}(\nabla^{\mu}u^{\nu}+\nabla^{\nu}u^{\mu})-\frac{1}{3}(\partial.u)(g^{\mu\nu}-u^{\mu}u^{\nu})$ 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 relaxation equation can contain additional terms [23]. Assuming longitudinal boost-invariance, the equations are solved with the code 'AZHYDRO-KOLKATA' [24],[25],[26],[27] in $(\tau=\sqrt{t^2-z^2},x,y,\eta=\frac{1}{2}ln\frac{t+z}{t-z})$ coordinates.

Hydrodynamic equations (Eq.1 and 2) are closed only with an equation of state (EOS) $p = p(\varepsilon)$. In the NPT scenario, we use EOS for the non-interacting hadronic resonance gas, comprising all the resonances with mass $m_{res} \leq 2.5$ GeV. In the PT scenario, we use a lattice based EOS [28], where the high temperature phase is modeled by the recent lattice simulation [13]. At the cross-over temperature T_{co} =196 MeV, the EOS smoothly

changes to that of the hadronic resonance gas.

Solution of Eq.1 and 2 require initial energy density, velocity distribution in the transverse plane at the initial time. A freeze-out prescription is also needed. In the PT scenario, we assume that QGP fluid is thermalised in the time scale τ_i =0.6 fm [5]. Compared to QGP, a hadronic resonance gas is expected to thermalise late. We assume the canonical value, τ_i =1 fm as the initial time in the NPT scenario. Both in the PT and NPT scenario, initial fluid velocity is assumed to be zero. In an impact parameter **b** collision, the initial energy density is assumed to be distributed as [5],

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

where $N_{part}(\mathbf{b}, x, y)$ and $N_{coll}(\mathbf{b}, x, y)$ are the transverse profile of participant numbers and binary collision numbers. f in Eq.3 is the fraction of hard scattering. Most of the hydrodynamic simulations are performed with hard scattering fraction f=0.25 or 0.13 [5],[29]. We assumed f = 0.25 in PT scenario. Hard scattering fraction is assumed to be zero in the NPT scenario. ε_0 in Eq.3 is the central energy density of the fluid in impact parameter **b**=0 collision. In the PT scenario, for a fixed freezeout temperature T_F =150 MeV, ε_0 is varied to best reproduce experimental charged particles p_T spectra in 0-10% Au+Au collision. In the NPT scenario, we used the limiting value, ε_0 =5.1 GeV/fm^3 , corresponding to central temperature T_i =220 MeV. HRG initialised at central energy density $\varepsilon_0 = 5.1 \ GeV/fm^3$ do not produce adequate number of hadrons from the freeze-out surface at T_F =150 MeV. We lower the freeze-out temperature to T_F =110 MeV. Dissipative hydrodynamics also require initialisation of the shear stress tensors $\pi^{\mu\nu}$. In both the scenarios, we initialise $\pi^{\mu\nu}$ at the boost-invariant values, $\pi^{xx} = \pi^{yy} = 2\eta(x,y)/3\tau_i$, $\pi^{xy} = 0$ [27]. For the relaxation time τ_{π} , we use the Boltzmann estimate, $\tau_{\pi} = 6\eta/4p$.

Results of our simulations for charged particles p_T spectra and elliptic flow in 0-40% Au+Au collisions are shown in Fig.1 and 2. We have assumed that through out the evolution, viscosity to entropy ratio remains a constant. In PT scenario, we have simulated Au+Au collisions for four values of viscosity, (i) $\eta/s=0$ (ideal fluid) (ii) $\eta/s=1/4\pi\approx0.08$ (ADS/CFT limit), (iii) $\eta/s=0.12$ and (iv) $\eta/s=0.16$. Corresponding central energy densities are $\varepsilon_0=35.5$, 29.1, 25.6 and 20.8 (GeV/fm^3) respectively. In the NPT scenario, we simulate Au+Au collisions for five values of viscosity, $\eta/s=0$, 0.08, 0.12, 0.24 and 0.30.

In Fig.1, we have compared simulated charged particles p_T spectra in 0-40% Au+Au collisions with the PHENIX data [30]. The left panels (a-d) show the fit to the data in the NPT scenario. The solid lines from bottom to top corresponds to $\eta/s=0$, 0.08, 0.16, 0.24 and 0.30 respectively. Simulation results in the PT scenario are shown in the right panel (e-h). The lines from bottom to top are for viscosity to entropy ratio $\eta/s=0$,

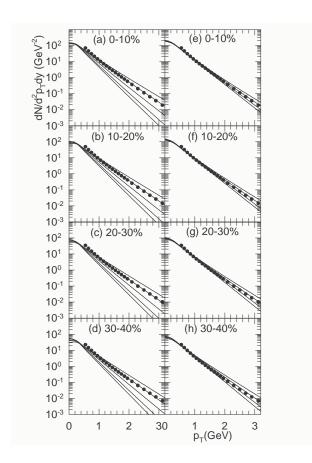


FIG. 1: PHENIX data [30] for charged particles p_T spectra in 0-40% Au+Au collisions are compared with hydrodynamic simulations in NPT (the left panel) and PT scenario (the right panel). See the text for details.

0.08, 0.12 and 0.16 respectively. One observes that ideal HRG, initialised to central temperature T_i =220 MeV, do not explain the p_T spectra, data are largely under predicted. Discrepancy between simulated spectra and experiment diminishes with increasing viscosity and data are best explained with η/s =0.24. Description to the data deteriorates if viscosity is further increased. In the PT scenario also, best fit to the 0-40% data is obtained in viscous QGP evolution, with η/s =0.08-0.12. Ideal QGP or QGP fluid with η/s > 0.12 give comparatively poorer description. To be quantative about the fit to the data in two different scenarios, we have computed χ^2 values for the fits obtained to the 0-40% data,

$$\chi^{2}/N = \frac{1}{N} \sum_{i} \frac{(ex(i) - th(i))^{2}}{err(i)^{2}}$$
 (4)

We include both the statistical and systematic errors in the analysis. The χ^2/N values are shown in Fig.3a. In the NPT scenario, χ^2/N as a function of η/s shows a minima at $\eta/s=0.24$, when $(\chi^2/N)_{min}=3.3$. It is very interesting to note that the $\eta/s=0.24$, obtained from the analysis is in close agreement with theoretical estimates of viscosity to entropy ratio of a hot hadronic resonance

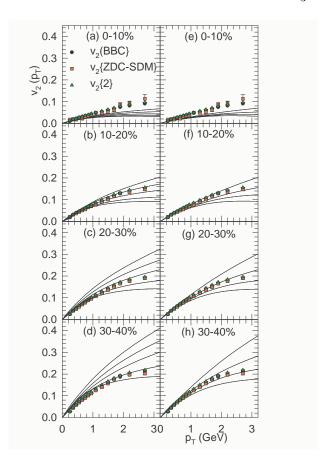


FIG. 2: (color online) same as in Fig.1 but for elliptic flow.

gas, $\eta/s=0.24$ -0.30 [7]. In the PT scenario also, best fit to the 0-40% data is obtained in viscous QGP evolution, with $\eta/s=0.08$, when $(\chi^2/N)_{min}=5.6$. Comparable fit is obtained with QGP viscosity $\eta/s=0.12$. Quantatively, with the initial conditions as used here, charged particles p_T spectra in 0-40% Au+Au collisions are better explained with HRG than QGP in the initial state.

In fig.2, we have compared simulated elliptic flow in 0-40% Au+Au collisions with PHENIX measurements [31]. PHENIX collaboration obtained v_2 from two independent analysis, (i) event plane method from two independent subdetectors, $v_2\{BBC\}$ and $v_2\{ZDC - SMD\}$ and (ii) two particle cumulant $v_2\{2\}$. All the three measurements of v_2 are shown. They agree within the systematic errors. Simulated flows in the NPT scenario are shown in the left panels, the lines (top to bottom) correspond to HRG with $\eta/s=0.0.08, 0.16, 0.24$ and 0.3 respectively. Flows in the PT scenario with QGP viscosity $\eta/s=0$, 0.08, 0.12 and 0.16 are shown in the right panels. For elliptic flow also, we have computed χ^2 values for the fits. The results are shown in Fig.3b. In the PT scenario, best fit to the 0-40\% charged particles elliptic flow data is obtained with QGP viscosity $\eta/s=0.08$ $((\chi^2/N)_{min}=6.7)$. In the NPT scenario, the best fit is obtained with HRG with viscosity $\eta/s=0.24$, minimum $(\chi^2/N)_{min}$ =11.1. Note that exactly, at these values of

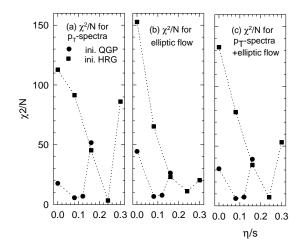


FIG. 3: The filled circles and squares are χ^2/N for (a) p_T spectra, (b) elliptic flow and (c) p_T spectra+elliptic flow, in 0-40% Au+Au collisions, in PT (initial QGP) and NPT (initial HRG) scenarios.

viscosity, p_T spectra are also best explained. However, as opposed to the p_T spectra, elliptic flow is better explained with QGP in the initial state rather than with initial HRG. If both the spectra and elliptic flows are analysed together, minimum χ^2 is similar in both the scenarios, $\chi^2_{min} \approx 6.1$ in the PT scenario and ≈ 7.2 in the NPT scenario (see Fig.3c). It can not be claimed that experimental data are better explained with QGP in the initial state. Quantitatively, both the scenarios give nearly identical description to the data. Hydrodynamical evolution of initial QGP fluid with viscosity to entropy ratio $\eta/s=0.08$, thermalised in the time scale $\tau_i=0.6$ fm to central energy density $\varepsilon_0 = 29.1 \; GeV/fm^3$ and that of HRG with $\eta/s=0.24$, thermalised in the time scale $\tau_i=1$ fm to central energy density $\varepsilon_0 = 5.1 \, GeV/fm^3$ give nearly equivalent description to the PHENIX data for charged particles p_T spectra and elliptic flow in 0-40% Au+Au collisions. We have not explored all possible initial conditions in PT/NPT scenario. However, as the minimum χ^2/N value in NPT/PT scenarios is reasonably small, it is unlikely that with a different initial condition, data could be much better explained in the PT scenario, as long as HRG at central temperature $T_i=220 \text{ MeV}$ is physical.

One may argue that whether or not QGP is produced do not depend only on the p_T spectra and elliptic flow. Jet quenching, high p_T suppression etc. do give additional support to the claim of QGP formation at RHIC energy collisions. However, high p_T suppression or jet quenching phenomena samples only a restricted phase space, as they are associated with high p_T trigger. Bulk of the matter are at low p_T . To claim that QGP is produced in bulk, it is essential that charged particles p_T spectra and elliptic flow are explained in a hydrodynamic model.

The present result that if HRG is physical at T=220 MeV, NPT and PT scenario give equivalent description

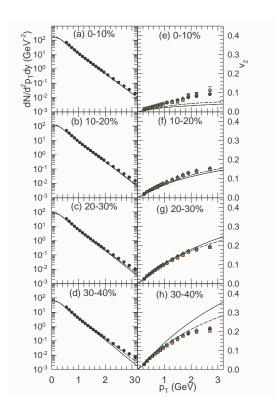


FIG. 4: (color online) In left panels (a)-(d) charged particles p_T spectra in 0-40% Au+Au collisions are compared with hydrodynamical simulations with initial HRG and initial QGP. The solid and dashed lines corresponds to evolution of HRG with viscosity to entropy ratio η/s =0.5, thermalised at τ_i =3 fm, and QGP with viscosity to entropy ratio η/s =0.08, thermalised as τ_i =0.6 fm. In panels (e)-(h) results for elliptic flow are shown.

to RHIC data on p_T spectra and elliptic flow will however be changed if hadronic resonance gas is physical only at a lower temperature $T \leq 200$ MeV. Even with large viscosity, $\eta/s=0.5$, hydrodynamical evolution of HRG, initialised at central temperature $T_i=200 \text{ MeV}$, do not produce comparable number of hadrons as in experiment, unless initial or the thermalisation time is large $\tau_i \geq 3$ fm. In Fig.4, the solid lines are simulation results for charged particles p_T spectra and elliptic flow with viscous $(\eta/s=0.5)$ HRG with central temperature $T_i=200$ MeV, thermalised at the time scale $\tau_i = 3$ fm. For comparison, we have also shown in the simulations results with minimally viscous ($\eta/s=0.08$) QGP at the initial state (the dashed lines). One note that in 0-10% and 10-20% collisions, HRG with central temperature $T_i=200$ MeV, thermalised in the time scale $\tau_i=3$ fm, give comparable description to the experimental charged particles p_T spectra, as obtained with QGP in the initial state. In 20-30% and 30-40% collisions however, data are better explained with QGP in the initial state. Similarly for the elliptic flow also. χ^2 analysis also indicate that charged particles p_T spectra and elliptic flow in 0-40% Au+Au collisions are better expalined with initial QGP

than with initial HRG with central temperature T_i =200 MeV. $\chi^2/N \approx 22$ with HRG at the initial state, factor of ~ 3 larger than that the value obtained with minimally viscous QGP in the initial state. Apparently, if HRG is physical only at temperature $T \leq 200$ MeV, PHENIX data are better explained with initial QGP state than initial HRG state. Large thermalisation time τ_i =3 fm, also raises the issue of non-equilibrium contribution to the particle production. Note that in dissipative hydrodynamics, τ_i is the time required by the system to achieve near equilibration. Large τ_i imply that for a substantial time, system remain in a highly non-equilibrium state, which can not be modeled theoretically, and contribution to particle production from this non-equilibrium

state, though possibly can not be neglected, can not be estimated either. The highly non-equilibrium state, with unknown contribution to particle production make the HRG model with limiting temperature $T_i{=}200$ MeV, untenable. One can possibly exclude initial HRG if HRG is physical only at temperature $T\leq 200$ MeV. Though, present lattice simulations indicate that HRG is physical only at ≤ 200 MeV, as discussed earlier, simulations are not precise enough to exclude HRG at $T\approx 220$ MeV. For confirmatory identification of matter produced in RHIC Au+Au collisions with QGP, it is essential to exclude the HRG scenario. Lattice simulations with realistic boundary conditions, preferably with Wilson fermion actions, are urgently needed to exclude possible HRG scenario.

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