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CMBR Power Spectrum and Flow Fluctuations in Relativistic Heavy-Ion Collisions

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Abstract There is a deep interconnection between the physics of flow anisotropies in relativistic heavy-ion collision experiments (RHICE) and the anisotropies observed in cosmic microwave background radiation (CMBR). This is due to the presence of superhorizon fluctuations in both cases which, for CMBR case, have origin in the inflationary phase of the universe. We discuss the basic physics of this interconnection, and present recent simulation results for the power spectrum of flow fluctuation which confirm this prediction showing exactly the same features as present in the CMBR power spectrum. These results, being useful for the study of the QGP system in RHICE, also allow us to probe some aspects of the early inverse physics under laboratory conditions, e.g.horizon entering of density fluctuations for inflation. We also show that initial strong magnetic field in RHICE can significantly enhance elliptic flow which can possibly accommodate larger η/S than the AdS/CFT bound.

1 Introduction

Quantum chromodynamics predicts that in extreme conditions of high density and/or temperature there should be a deconfinement of quarks and gluons, and hadrons should undergo a phase transition to a quark-gluon plasma (QGP). QGP phase is expected from the asymptotic freedom of QCD. The coupling constant becomes small at high energies/small length scales. So, if nuclear matter is in a state in which the nucleon density and/or the energy density become high, then deconfinement may occur. In the Bag model, or string model of quark confinement this happens when quark separation becomes smaller than the typical size ($\sim$ 1 fm). Clearly, from such considerations one would expect that resulting QGP should be a weakly interacting plasma of quarks and gluons. In the early hot stages of the universe, it is believed that the temperature was so high that no bound structures could survive. Indeed, QGP is expected to occur in the early Universe up to the time when the age of the universe was about few micro seconds. QGP is also expected to occur inside neutron stars due to very high baryon density leading to overlapping of hadrons. Direct search for QGP is being carried out by ultra-relativistic heavy-ion collision experiments where heavy nuclei (e.g. lead, gold) are collided at ultrarelativisitc energies. Very high density of partons is expected to be produced in resulting collisions of nucleons which are expected to thermalize and give rise to the QGP phase of QCD. Many signatures have been proposed for detecting the transient phase of QGP in these experiments.

One of the most important results from these experiments has been the observation of the elliptic flow [1–4]. This gives the strongest evidence for the thermalization of the system showing the collective behavior of the partonic matter produced in RHICE [5–7]. (We use RHICE to denote general class of relativistic i heavy-ion collision experiments, to distinguish from the Relativistic Heavy-Ion Collider, RHIC, at Brookhaven). Much work has been done to extract physical information about the system from the behavior of the elliptic flow,

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e.g., equation of state, thermalization time etc. The measured value of the elliptic flow and comparison with hydrodynamical simulations has led to very interesting results. It is found that thermalization has to be reached early, within about 1 fm/c time from the initial overlap of the colliding nuclei. This is the most direct evidence of an early thermalization of QGP in RHICE. Perhaps the biggest surprise from these experiments regarding the nature of QGP came from the magnitude of the observed elliptic flow. We mentioned above that the initial idea of the QGP phase of QCD was motivated from the asymptotic freedom of QCD which implied that QGP should consist of a weakly interacting gas of partons. Such a gas would have a large viscosity. In complete contrast, the measured value of elliptic flow could only be reconciled with hydrodynamical simulations if QGP was assumed to have very low viscosity, much lower than that known for any liquid. QGP in RHICE, therefore is not like an ideal gas, it is almost a perfect fluid, usually termed as sQGP (strongly coupled QGP). In fact, the measured value of the viscosity is close to the so called AdS/CFT bound obtained from string theory.

Elliptic flow results from the spatial anisotropy of the thermalized region at the initial stage in a given event with nonzero impact parameter. Anisotropic pressure gradients then lead to anisotropic fluid velocity which results in anisotropic momentum distribution of particle momenta. Elliptic flow measures the second Fourier coefficient of the angular distribution of the particle momenta in the transverse plane. It has also been noticed that even in central collisions, due to initial state fluctuations, one can get non-zero anisotropies in particle distribution (and hence in final particle momenta) in a given event, though these will be typically much smaller in comparison to the non-central collisions. These will average out to zero when large number of central events are considered.

It is important to realize that the QGP phase is a transient stage in lab, lasting for about 10^{-22} s. Finally only hadrons are detected carrying information of the system at freezeout stages (chemical and/or thermal freezeout). One often says, that the situation is quite like cosmic microwave background radiation (CMBR) in the universe which carries the information at the surface of last scattering in the universe. Just like for CMBR, one has to deduce information about the earlier stages from this information contained in hadrons coming from the freezeout surface. In a series of works we have demonstrated that this apparent correspondence with CMBR is in fact very rigorous [8,9]. There are strong similarities in the nature of density fluctuations in the two cases (despite the obvious difference due to the absence of gravity effects for relativistic heavy-ion collision experiments). It was shown in these works that there are deep interconnections between the evolution of flow anisotropies in relativistic heavy-ion collision experiments and the physics of inflationary density fluctuations observed as CMBR anisotropies. It was pointed out in Ref. [8,9] that instead of focusing on first few flow coefficients in the conventional approach to flow analysis for RHICE (which were primarily only even flow coefficients v_2, v_4, v_6) one should plot the entire power spectrum of all flow coefficients including the odd coefficients. Flow coefficients v_n are defined in terms of Fourier expansion of the azimuthal particle momentum distribution, $P(\phi) = \sum_n v_n e^{-in\phi}$. The reason for departure from the conventional focus on only first few even flow coefficients was due to the recognition that initial state fluctuations contribute to all flow coefficients (including the odd ones). Thus even for a central collisions one expects non-zero flow coefficients.

2 Initial State Fluctuations and Flow Anisotropies

It was proposed in Ref. [8,9] that instead of focusing on the average values of the flow coefficients v_n, one should calculate root-mean square values of the flow coefficients v_n^{rms}, just as one focuses on the power spectrum for CMBR fluctuations. We denote the flow coefficients, defined with respect to the lab fixed frame, as v_n and its root mean square value as v_n^{rms}. Thus, $v_n^{rms} = \sqrt{\langle v_n^2 \rangle}$. It was further emphasized that these calculations should be performed in a lab fixed frame, thereby eliminating difficulties associated with determination of event plane for conventional elliptic flow analysis. One of the most important aspects of the density fluctuations in the universe is the coherence effect which eventually results in the remarkable acoustic peaks in the power spectrum of CMBR anisotropies. The source of this lies in the inflationary origin of the density fluctuations leading to production of super-horizon density fluctuations. These fluctuations eventually re-enter the horizon around the decoupling stage and leave imprints on CMBR anisotropies. It was argued in [8,9] that quite similarly, super-horizon fluctuations are present in RHICE as well. However, here they will result in non-zero flow coefficients as spatial anisotropies lead to anisotropic pressure gradients. The anisotropies in the momentum distributions of the particles, especially at large orders of the Fourier coefficients, will capture information about the nature of initial spatial anisotropies, their evolution, and freezeout.

As we mentioned above, initial state inhomogeneities are necessarily present in RHICE. These result from fluctuations in positions of initial nucleons as well as fluctuations in the process of initial particle production.

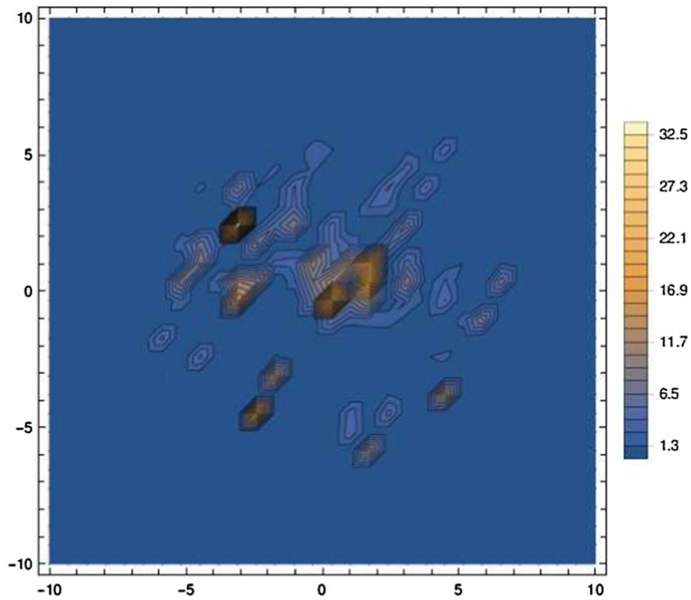

Fig. 1 Contour plot of the initial transverse energy density distribution in the central rapidity region from HIJING for a given Au–Au collision central event at 200 GeV/A center of mass energy. X–Y axes are in units of fm and transverse energy density is in units of GeV/fm^2

Typically, one finds initial state fluctuations of all wavelengths as sown in Fig. 1. In the figure the contours plot of energy density in the transverse plane in the central rapidity region (bin width of unit rapidity) is shown, showing large inhomogeneities to be present initially. X–Y axes are in units of fm and transverse energy density is in units of GeV/fm^2. As we mentioned above that one expects thermalization to be achieved in RHICE very quickly, within 1 fm/c time (or even shorter). Thus, we conclude that inhomogeneities, especially anisotropies with wavelengths larger than the thermalization time scale should be necessarily present at the thermalization stage when the hydrodynamic description is expected to become applicable. This is what gives the most important correspondence between the universe and the RHICE. It is the presence of fluctuations with superhorizon wavelengths.

In the universe, density fluctuations with wavelengths of superhorizon scale have their origin in the inflationary period where quantum fluctuations of sub-horizon scale were stretched to superhorizon scales during the inflationary regime. Initial state density fluctuations in Fig. 1 show that superhorizon fluctuations should be present in RHICE at the initial equilibration stage itself. The reason these are superhorizon is that the causal horizon is given by the sound horizon, $H_s \sim c_s \tau$ where c_s is the sound speed, as we are interested in the flow arising from pressure gradients. At the stage of equilibration, $c_s \tau_{eq}$ is at most 1 fm. Thus every fluctuation of wavelength larger than H_s^{eq} is superhorizon. The famous acoustic peaks of CMBR power spectrum arise from the existence of super-horizon fluctuations resulting from the inflationary stage. As we have super-horizon fluctuations in RHICE as well, we expect acoustic peaks in the power spectrum of flow fluctuations.

In [8,9], plots of v_n^{rms} using model estimates based on initial energy density anisotropies from HIJING event generator were given for large range of values of n (with n ranging from 1 to 30) for central collisions. It was argued that such plots can yield important information about the nature of initial state anisotropies and their evolution for RHICE. These plots were obtained by modeling the physics of acoustic oscillations in a power spectrum of flow coefficients obtained using HIJING, and were not obtained using a hydrodynamical simulations. Such hydrodynamical simulations were later carried out in [10] and results from the simulations confirmed the model based predictions of [8,9], such as that the location of first peak in the flow power spectrum can give information about the freezeout surface. This is shown in Fig. 2. It is important to realize that these results, being useful for the study of the QGP system in RHICE, also allow us to probe some aspects of the early inverse physics under laboratory conditions, e.g.horizon entering of density fluctuations for inflation. These involve aspects of hydrodynamical evolution of fluctuations which have superhorizon wavelength. Clearly, large wavelength fluctuations in QGP are of same nature and their experimental study can shed light on these calculations for inflationary fluctuations.

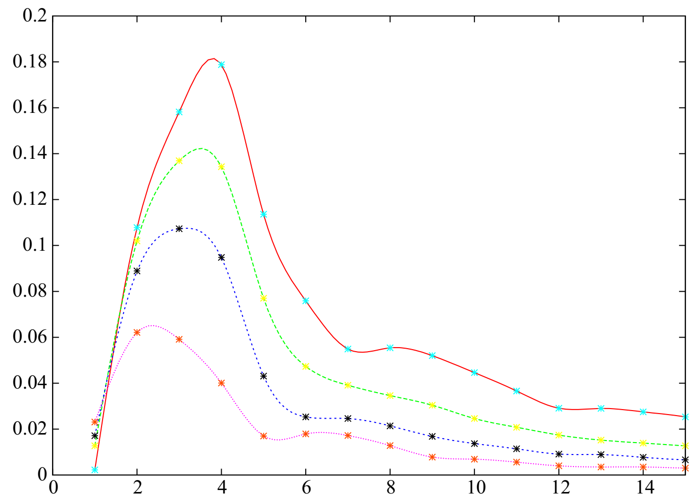

Fig. 2 Plots of v_n^{rms} w.r.t n are shown here at different times τ (in fm) for one specific simulation. Plots from top to bottom correspond to values of $\tau = 0.93, 1.98, 2.40, 3.24$ respectively. Note consistent shift of the location of first peak towards lower values of n as time increases

3 Effect of Magnetic Field on Flow

In recent years it has been realized that in relativistic heavy-ion collision experiments extremely high magnetic fields are expected to arise, especially in non-central collisions. During earliest stages, magnetic field in the plasma can be of order 10^{15} Tesla (few m_π^2). This is the largest magnetic field any where in the present universe, several orders of magnitude larger than the magnetic field even in magnetars. This will lead to important effects for QGP, such as the exciting possibility of observing CP violation effects [11,12]. In an earlier work we had shown that an important effect of the presence of magnetic fields in the plasma will be to lead to strongly affect the flow pattern. It was based on the realization that magnetic field will lead to variations in velocities of different types of waves in the plasma, thereby modifying the development of anisotropic flow. In Ref. [13], it was argued that the flow coefficients can be significantly affected by these effects, in particular, magnetic field can lead to enhancement in the elliptic flow coefficient v_2 by almost 30%. It raises the possibility whether a larger value of η/s can be accommodated by the elliptic flow data when these effects are incorporated.

This prediction was confirmed by us in a subsequent magnetohydrodynamical (MHD) simulation [14]. It was found that magnetic field leads to enhancement in the elliptic flow for small impact parameters while it suppresses it for large impact parameters (which may provide a signal for initial stage magnetic field). We have also carried out simulations corresponding to nontrivial magnetic field configurations arising from collision of deformed nuclei and have shown that it can lead to anomalous elliptic flow. Interestingly, deformed nucleus leads to new possibilities for elliptic flow even in the absence of magnetic field. For example, a collision when the impact parameter is along the long axes of nuclei (assuming nuclei to be ellipsoidal and having same orientations) can lead to a QGP region having negative elliptic flow. This is shown in Fig. 3. The presence of magnetic field leads to strong effects, leading to very strong suppression of the elliptic flow at large impact parameters as seen in Fig. 3. We show here results of simulation carried out at a lower value of $\sqrt{s} = 20$ GeV. Relativistic MHD simulation for higher lead to difficulties for our 3+1 dimensional simulation in regions where magnetic field density is large. So at present we show the results for lower values of center of mass energy. The physics underlying the behavior of elliptic flow is hopefully valid for higher collision energy as well. Here B_{time} represents the time after the collisions at which initial profile of magnetic field is calculated in vacuum from Lorentz contracted nuclei. Subsequently, the thermalized conducting medium is supposed to form which traps the initial magnetic field in our ideal MHD approximation. Thus a larger value of B_{time} will give a smaller value of initial magnetic field.

Our results have shown that a power spectrum of flow fluctuations in RHICE can lead to valuable information about the initial state fluctuations in these collisions of heavy nuclei. Further, one can learn about important stages of QGP evolution such as freezeout etc. We have shown that magnetic field can strongly affect the flow pattern and lead to important effects on elliptic flow which can be used to detect presence of initial state

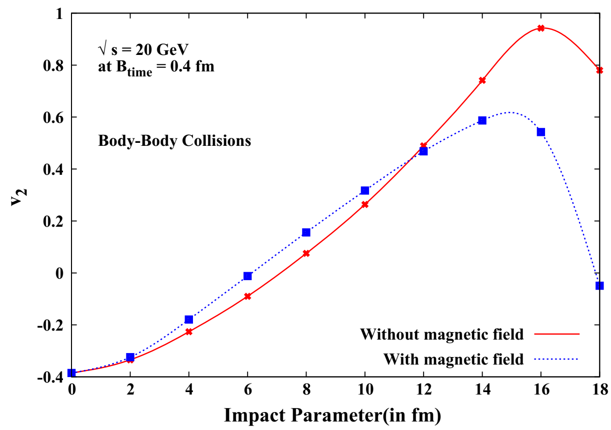

Fig. 3 Collision of deformed nuclei can lead to unconventional geometries of QGP leading to negative elliptic flow. Further, resulting magnetic field can lead to strong suppression of elliptic flow for large impact parameters

magnetic field in the plasma. Collision of deformed nuclei leads to further richness in these effects, for example one gets negative elliptic flow, and a strong suppression of elliptic flow for large impact parameters.

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