EVOLUTION OF TEMPERATURE FLUCTUATION IN A THERMAL BATH AND ITS IMPLICATIONS IN HADRONIC AND HEAVY-ION COLLISIONS*

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The evolution equation for inhomogeneous and anisotropic temperature fluctuations inside a medium is derived within the ambit of Boltzmann Transport Equation. Also, taking some existing realistic inputs, we have analysed the Fourier space variation of temperature fluctuation for the medium created after heavy-ion collisions. The effect of viscosity on the variation of fluctuations is investigated. Further, possible implications in hadronic and heavy-ion collisions are explored.

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1. Introduction

Fluctuations are commonly discussed for wide range of systems leading to various different phenomena. Density fluctuations at all length scales in the second order phase transition, the event-by-event fluctuation of conserved numbers in heavy-ion collisions, which are important to explore the phase diagram of quantum chromodynamics (QCD), are some of such examples. Much in the same way as number of particles in a certain region of a system fluctuates, the everyday examples teach us that the temperature for physical systems can also fluctuate. The dynamics of the evolving system dictates the temperature fluctuation until the system comes to equilibrium and, therefore, it may vary with time and space during evolution.

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Figure 1 shows a system with radially varying temperature zones. We model the system to consist of several non-interacting zones, for which temperatures remain constant within a pre-determined time scale. Howerver, after that given time, the temperatures vary. So, the average value as well as the temperature fluctuation are the quantities which vary with time.

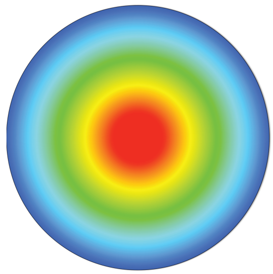

Fig. 1. Radially varying temperature profile in a medium [1].

In the present work, the evolution of fluctuation in inverse temperature ($\beta = 1/T$) is discussed for a system resembling with the system formed in heavy-ion collisions using Boltzmann Transport Equation (BTE) in Relaxation Time Approximation (RTA). It is assumed that the observation time is much less than the relaxation time of the thermal bath. Further, we extend this study for an arbitrary observation time.

2. Method

In order to study the evolution of temperature fluctuation, we consider the following Ansatz for the particle distribution function

$$f = e^{-\beta p(1+\Delta\beta)} \,. \tag{1}$$

Here, we consider a medium with Boltzmann distribution of massless particles with average inverse temperature $\beta(t)$, at some time slice. To include anisotropic and inhomogeneous fluctuation, we add a function $\Delta\beta(\vec{r}, \hat{p}; t)$, where $\hat{p}$ is an unit vector along the direction of motion of particle. We use the BTE to calculate the temporal evolution of β. Following is the generic form of BTE

$$\frac{\mathrm{d}f}{\mathrm{d}t} = \frac{\partial f}{\partial t} + \vec{v} \cdot \vec{\nabla} f + \vec{F} \cdot \vec{\nabla}_p f = \mathcal{C}[f] \,. \tag{2}$$

Here, $\vec{v}$ is particle velocity, $\vec{F}$ is any external force, $C[f]$ is the collision term to take care of the interaction and $\vec{\nabla}_p$ is the momentum-space gradient operator. For present study, we assume that the system experiences no external force, and hence $\vec{F} = 0$. However, the inhomogeneity in $\Delta\beta$ still exists.

By assuming an isotropic fluctuation profile and averaging over the whole solid angle Ω subtended by $\hat{p}$ the average fluctuations are derived as follows:

$$\begin{aligned}\Delta\beta_{\rm av}\left(\vec{k};t\right) &= \Delta\beta\left(\vec{k};t^0\right)e^{-\frac{t-t^0}{t_{\rm R}}}\frac{1}{4\pi}\int\limits_{\Omega} e^{-ik\mu\left(t-t^0\right)}{\rm d}\Omega \\ &= \Delta\beta\left(\vec{k};t^0\right)e^{-\frac{t-t^0}{t_{\rm R}}}\frac{1}{4\pi}\int\limits_{-1}^{1}{\rm d}\mu e^{-ik\mu\left(t-t^0\right)}\int\limits_{0}^{2\pi}{\rm d}\phi\,, \\ \Delta\beta_{\rm rel}\left(\vec{k};t\right) &= \frac{\Delta\beta_{av}\left(\vec{k};t\right)}{\Delta\beta\left(\vec{k};t^0\right)} = e^{-\frac{t-t^0}{t_{\rm R}}}\frac{\sin k\left(t-t^0\right)}{k\left(t-t^0\right)}\,. \end{aligned} \qquad (3)$$

Here, $\vec{k}$ is a constant vector directed along the z-axis. Figure 2 shows the parametric Fourier space variation of $\Delta\beta_{\rm rel}(\vec{k};t)$ with time $(t-t^0)$ and relaxation time $(t_{\rm R})$, respectively. It is observed that the relative fluctuations die down with time. Additionally, the fluctuations at larger distances towards the periphery of the medium are large. Further, we observe no modification of fluctuation with increasing $t_{\rm R}$ when $(t-t_0) \ll t_{\rm R}$.

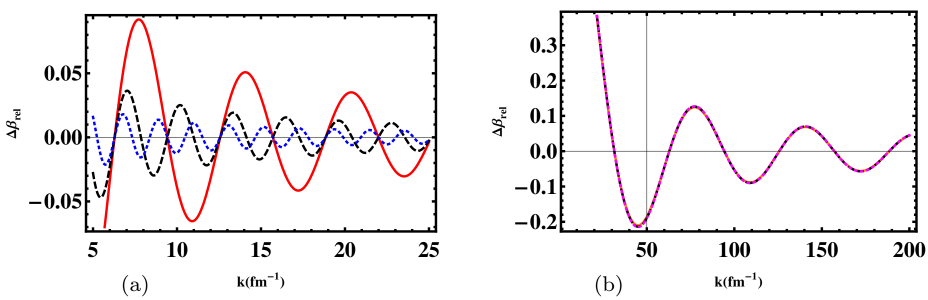

Fig. 2. (Colour on-line) Variation of $\Delta\beta_{\rm rel}(\vec{k};t)$ with k. (a) Solid (red): $(t-t^0) =$ 1 fm, dashed (black): $(t-t^0) = 2$ fm, dotted (blue): $(t-t^0) = 3$ fm for $t_{\rm R} = 3$ fm. (b) Solid (orange): $t_{\rm R} = 3$ fm, dashed (black): $t_{\rm R} = 6$ fm, dotted (magenta): $t_{\rm R} = 9$ fm for $(t-t^0) = 0.1$ fm [1].

To study a more realistic situation, we consider the temperature profiles [1] of an evolving medium at different stages of the evolution of Quark–Gluon Plasma [2] created in central collisions. Given the profile, we get a set of temperatures, their average value and the temperature fluctuation on top of the average value. We can find out the variation of the inverse temperature fluctuation at different stages (for more details, see [1]).

3. Results and discussion

Figure 3 (a) shows that the soft modes of β-fluctuation become dominant at large system radius and Fig. 3 (b) shows the variation of fluctuation for different viscosities of the medium. As intuitively expected, higher viscosity favours lower fluctuations. Within any arbitrary choice of radius shell, the relative fluctuations die down with time. For demonstration, we have chosen the shell ranging between the radii of 14 fm to 15 fm. Observation remains unaltered for any other shell.

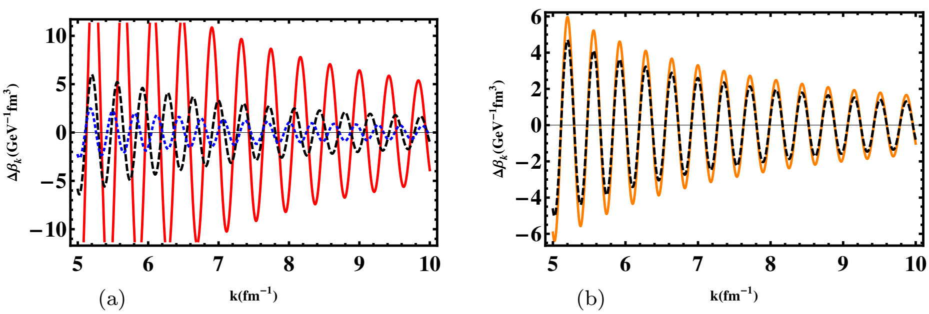

Fig. 3. (Colour on-line) Variation of inverse temperature fluctuation in a viscous medium with k. (a) Solid (red): $\tau = 2.2$ fm/c, dashed (black): $\tau = 5.1$ fm/c, dotted (blue): $\tau = 9.1$ fm/c. $\eta/s = 0.08$ for all the figures. (b) Solid (orange): $\eta/s = 0.08$, dashed (black): $\eta/s = 0.3$. at $\tau = 5.1$ fm/c [1].

In view of the connection between the relative temperature fluctuation and the Tsallis q parameter, as shown in Ref. [3], we can compute the relative temperature fluctuation in QGP produced in a single event existing even after a long time. The relative temperature fluctuation at the boundary is seen to be close to the experimentally obtained value 0.018 ± 0.005 for 0–10% central HICs at RHIC with $\sqrt{s_{NN}} = 200$ GeV [4].

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