First order dissipative hydrodynamics from an effective fugacity model

Samapan Bhadury[1],* Manu Kurian[2], Vinod Chandra[2], and Amaresh Jaiswal[1]
[1]School of Physical Sciences, National Institute of Science Education and Research, HBNI, Jatni-752050, India and
[2]Indian Institute of Technology Gandhinagar, Gandhinagar-382355, Gujarat, India

Production of Quark-Gluon-Plasma (QGP) state in Heavy-Ion-Collision (HIC) is now an unambiguous phenomenon. Here we use relativistic dissipative hydrodynamics to describe the space-time evolution of hot and dense QCD matter created in HIC as it has been used successfully in several previous works. Hydrodynamics uses macroscopic variables whereas QCD is a microscopic phenomena. Thus we relate them using kinetic theory.

We briefly explain the effective fugacity model (EQPM) and derive a causal theory of relativistic hydrodynamics which is thermodynamically consistent with a realistic equation of state (EoS)in the kinetic theory framework. The transport coefficients are evaluated and their relative significance is studied to get an idea of the dominating mechanism that drives the evolution. EQPM is found to be showing very promising results in the high temperature regime. We have used a relaxation time approximation (RTA) type of collision kernel in the Relativistic Boltzmann equation we extract the transport coefficients for massive particles with finite chemical potential.

Formalism

This work is inspired from the covariant kinetic theory for hot QCD medium as developed by Chandra and Mitra [1] employing EQPM [2, 3]. We have extended their analysis for non-zero quark (antiquark) chemical potential and finite quark (antiquark) masses to study the effect on transport properties of the hot QCD systems.

*Electronic address: samapan.bhadury@niser.ac.in

We have considered the $(2 + 1)$flavor lattice QCD EoS to provide an effective description of QGP. The EQPM energy-momentum tensor and the net baryon four-flow are defined in terms of dressed momenta $\vec{\tilde{p}}_k$ for the k-th particle species as [1]:

$$T^{\mu\nu}(x) = \sum_{k=1}^{N} g_k \int d\tilde{P}_k\, \tilde{p}_k^\mu\, \tilde{p}_k^\nu\, f_k^0(x,\tilde{p}_k) + \sum_{k=1}^{N} \delta\omega_k\, g_k \int d\tilde{P}_k\, \frac{\langle \tilde{p}_k^\mu\, \tilde{p}_k^\nu \rangle}{E_k}\, f_k^0(x,\tilde{p}_k), \quad (1)$$

$$N^\mu(x) = g_q \int d\tilde{P}_q\, \tilde{p}_q^\mu \left[f_q^0 - f_{\bar{q}}^0\right] + \delta\omega_q\, g_q \int d\tilde{P}_q\, \frac{\langle \tilde{p}_q^\mu \rangle}{E_q} \left[f_q^0 - f_{\bar{q}}^0\right], \quad (2)$$

where, N is the total number of species. The distribution functions under EQPM are modified by a temperature dependent fugacity factor and are defined as:

$$f_q^0 = \frac{z_q \exp\left[-\beta(u^\mu p_\mu - \mu_q)\right]}{1 + z_q \exp\left[-\beta(u^\mu p_\mu - \mu_q)\right]}, \quad (3)$$

$$f_{\bar{q}}^0 = \frac{z_q \exp\left[-\beta(u^\mu p_\mu + \mu_q)\right]}{1 + z_q \exp\left[-\beta(u^\mu p_\mu + \mu_q)\right]}, \quad (4)$$

$$f_g^0 = \frac{z_g \exp\left[-\beta(u^\mu p_\mu)\right]}{1 - z_g \exp\left[-\beta(u^\mu p_\mu)\right]} \quad (5)$$

where the dispersion relation relates the quasiparticle (dressed) four-momenta $\tilde{p}_k^\mu$ and the bare particle four-momenta p_k^μ as:

$$\tilde{p_k}^\mu = p_k^\mu + \delta\omega_k\, u^\mu, \quad \delta\omega_k = T^2\, \partial_T \ln(z_k). \quad (6)$$

The relativistic Boltzmann equation determines the change of phase space distribution function through the collision kernel $C[f_k]$, (which has been taken to be given by, relaxation time approximation (RTA) [4]) and has the following form for the particle species k,

$$\frac{1}{\omega_k}\tilde{p}_k^{\mu}\partial_{\mu}f_k^0(x,\tilde{p}_k) + F_k^{\mu}\partial_{\mu}^{(p)}f_k^0 = -\frac{\delta f_k}{\tau_R}. \quad (7)$$

where, the force term, $F_k^{\mu} = -\partial_{\nu}(\delta\omega_k u^{\nu}u^{\mu})$ is defined from the conservation of energy momentum and particle flow [1]. We solve the relativistic Boltzmann equation with RTA for δf_k, using the Chapman-Enskog (CE) expansion where we assumed $\delta f_k \ll f_k$. Once, δf_k is found, we can evaluate the transport coefficients using the definition of shear viscosity, bulk viscosity and baryon diffusion current:

$$\pi^{\mu\nu} = \sum_{k=1}^{N} g_k\Delta_{\alpha\beta}^{\mu\nu}\int d\tilde{P}_k\ \tilde{p}_k^{\alpha}\tilde{p}_k^{\beta}\delta f_k + \sum_{k=1}^{N}\delta\omega_k g_k\Delta_{\alpha\beta}^{\mu\nu}\int d\tilde{P}_k\ \tilde{p}_k^{\alpha}\tilde{p}_k^{\beta}\frac{1}{E_k}\delta f_k, \quad (8)$$

$$\Pi = -\frac{1}{3}\sum_{k=1}^{N} g_k\Delta_{\alpha\beta}\int d\tilde{P}_k\ \tilde{p}_k^{\alpha}\tilde{p}_k^{\beta}\delta f_k - \frac{1}{3}\sum_{k=1}^{N}\delta\omega_k g_k\Delta_{\alpha\beta}\int d\tilde{P}_k\ \tilde{p}_k^{\alpha}\tilde{p}_k^{\beta}\frac{1}{E_k}\delta f_k, \quad (9)$$

$$n^{\mu} = g_q\Delta_{\alpha}^{\mu}\int d\tilde{P}_q\ \tilde{p}_q^{\alpha}(\delta f_q - \delta f_{\bar{q}}) - \delta\omega_q g_q\Delta_{\alpha}^{\mu}\int d\tilde{P}_q\ \tilde{p}_q^{\alpha}\frac{1}{E_q}(\delta f_q - \delta f_{\bar{q}}). \quad (10)$$

Dissipative evolution equation

For simplicity we considered the thermal relaxation time τ_R to be independent of four-momenta. Keeping terms up to first-order in gradients, we find the transport coefficients can be obtained from Navier-Stokes like equations via:

$$\pi^{\mu\nu} = 2\,\tau_R\,\beta_{\pi}\,\sigma^{\mu\nu}, \quad \Pi = -\tau_R\,\beta_{\Pi}\,\theta, \quad n^{\mu} = \tau_R\,\beta_n\,\nabla^{\mu}\alpha, \quad (11)$$

The definitions of the transport coefficients β_{π}, β_{Π} and β_n can be found in [8].

Results and Discussions

In Fig. 1, we provide the temperature dependence of the ratio of the transport coefficients of the bulk to shear i.e. $\frac{\beta_{\Pi}}{\beta_{\pi}}$ for $\mu_q = 0.1$

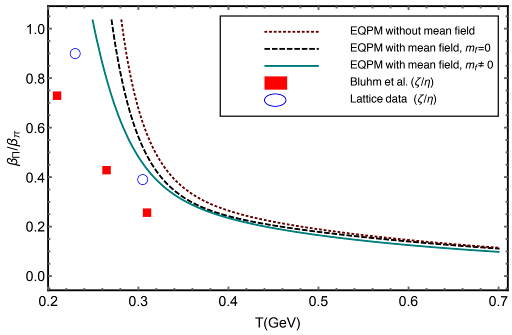

FIG. 1: The ratio $\frac{\beta_{\Pi}}{\beta_{\pi}}$ as a function of temperature and compared the results with [5–7]

GeV. Under RTA, the ratio, $\frac{\beta_{\Pi}}{\beta_{\pi}} = \frac{\zeta}{\eta}$, where ζ is the bulk viscosity of the hot QGP medium. We observe that with increasing temperature, the ratio $\frac{\beta_{\Pi}}{\beta_{\pi}}$ decreases. We also note that the modifications due to finite quark mass mean field are more visible in the low temperature regime close to the transition temperature T_c. Furthermore, comparison of the results with other parallel work and the lattice results have also been presented.

References

[1] S. Mitra and V. Chandra, Phys. Rev. D **97**, no. 3, 034032 (2018) [arXiv:1801.01700 [nucl-th]].

[2] V. Chandra and V. Ravishankar, Phys. Rev. D **84**, 074013 (2011) [arXiv:1103.0091 [nucl-th]].

[3] V. Chandra, R. Kumar and V. Ravishankar, Phys. Rev. C **76**, 054909 (2007) [arXiv:0705.2690 [nucl-th]].

[4] J. L. Anderson and H. R. Witting Physica **74**, 466 (1974).

[5] M. Bluhm, B. Kampfer and K. Redlich, Phys. Lett. B **709**, 77 (2012), [arXiv:1101.3072 [hep-ph]].

[6] H. B. Meyer, Phys. Rev. D **76**, 101701 (2007) [arXiv:0704.1801 [hep-lat]].

[7] H. B. Meyer, Phys. Rev. Lett. **100**, 162001 (2008) [arXiv:0710.3717 [hep-lat]].

[8] S. Bhadury, M. Kurian, V. Chandra and A. Jaiswal, arXiv:1902.05285 [hep-ph].