Analytical attractors and thermal particle spectra from quark-gluon plasma

Lakshmi J. Naik[1],* Sunil Jaiswal[2], K. Sreelakshmi[1], Amaresh Jaiswal[3], and V. Sreekanth[1]
[1]*Department of Sciences, Amrita School of Engineering Coimbatore, Amrita Vishwa Vidyapeetham, India*
[2]*Department of Nuclear and Atomic Physics, Tata Institute of Fundamental Research, Mumbai 400005, India and*
[3]*School of Physical Sciences, National Institute of Science Education and Research, HBNI, Jatni 752050, Odisha, India*

Relativistic hydrodynamics has been applied successfully to describe the dynamics of Quark Gluon Plasma (QGP) created in high energy nucleus-nucleus collisions. The causal description of this matter, with extreme low value of viscosity (η/s) has generated a lot of interest and has led to the development of various dissipative hydrodynamic theories. In the present work, we intend to study an important feature of boost invariant causal dissipative hydrodynamics - "hydrodynamic attractor" [1] through thermal particle production. We consider the recently obtained analytical solutions of higher-order causal viscous hydrodynamic theories under longitudinal boost invariance [2] to study thermal particle spectra from QGP. Thermal dileptons and photons, which are emitted during the entire evolution of QGP, contain information about different stages of evolution and hence can be considered as most useful tool to study the hydrodynamic attractor. We calculate the dilepton and photon yields in the presence of Chapman-Enskog like viscous corrections to the distribution function and study the particle spectra under Björken expansion by employing the analytical solutions, including the attractor solution, of higher order viscous fluid dynamics [3].

Considering the boost invariant expansion of Björken, with Milne coordinates $x^\mu = (\tau, r, \varphi, \eta_s)$, the evolution equations for energy density, ϵ and normalized shear stress $\bar{\pi}$ are obtained as [2, 3]

$$\frac{1}{\epsilon}\frac{d\epsilon}{d\bar{\tau}} = -\frac{4}{\bar{\tau}}\left(\frac{1-\bar{\pi}}{\bar{\pi}+2}\right) \quad (1)$$

$$\left(\frac{\bar{\pi}+2}{3}\right)\frac{d\bar{\pi}}{d\bar{\tau}} = -\bar{\pi} + \frac{1}{\bar{\tau}}\left(a - \lambda\,\bar{\pi} - \gamma\,\bar{\pi}^2\right) \quad (2)$$

where $\bar{\pi} = \pi/4P$. We consider the coefficients, a, λ and γ corresponding to the third-order theory developed in Ref [4]. These coupled equations can be solved analytically for certain approximations of relaxation time τ_π. We note that for a conformal system, we have $T\tau_\pi = 5(\eta/s) =$ const. The equations are solved analytically for three cases of $\tau_\pi \sim 1/T$, where T is either a constant or follows the ideal of Navier-Stokes evolution. The analytical solutions thus obtained correspond to different values of integration constant α, with $\alpha = 0, \infty$ denoting the attractor and repulsor respectively. Also, using the analytic solutions, we constrain the values of α to lie between $\alpha = 0$ and ∞ [3]. Next, we study the particle spectra by employing the attractor solution.

Within relativistic kinetic theory, the rate of dilepton emission from $q\bar{q}$ annihilation process, $q\bar{q} \to \gamma^* \to l^+l^-$ is given by

$$\frac{dN}{d^4x d^4p} = g^2 \int \frac{d^3\mathbf{p_1}}{(2\pi)^3}\frac{d^3\mathbf{p_2}}{(2\pi)^3} f(E_1,T) f(E_2,T) \times v_{rel}\sigma(M^2)\delta^4(p-p_1-p_2), \quad (3)$$

where M^2 represent the invariant mass of virtual photon and p is the dilepton

*Electronic address: jn_lakshmi@cb.students.amrita.edu

4−momentum. $\sigma(M^2)$ denote the cross-section for this process in Born approximation and $f(E_{1,2},T)$ is the modified quark (anti-quark) distribution function in the presence of viscous correction *i.e.*, $f = f_0 + \delta f$. Keeping the terms upto quadratic in momenta, we write the total dilepton emission rate in the Maxwell-Boltzmann limit as sum of ideal and viscous contributions [3]

$$\frac{dN^0}{d^4xd^4p} = \frac{1}{2}\frac{M^2g^2\sigma\left(M^2\right)}{(2\pi)^5}e^{-E/T},$$
$$\frac{dN^\pi}{d^4xd^4p} = \frac{dN^0}{d^4xd^4p}\frac{\beta}{2\beta_\pi|\mathbf{p}|^5}\left[\frac{E|\mathbf{p}|}{2}\left(2|\mathbf{p}|^2-3M^2\right) + \frac{3}{4}M^4\ln\left(\frac{E+|\mathbf{p}|}{E-|\mathbf{p}|}\right)\right]p^\alpha p^\beta\pi_{\alpha\beta}. \quad (4)$$

Similarly, photon emission rate for Compton scattering, $q(\bar{q})g \to q(\bar{q})\gamma$ and $q\bar{q}$ annihilation, $q\bar{q} \to g\gamma$ is obtained as sum of ideal and viscous parts [3]

$$E\frac{dN^0}{d^4xd^3p} = \frac{5}{9}\frac{\alpha_e\alpha_s}{2\pi^2}T^2e^{-E/T}\ln\left(\frac{3.7388E}{g^2T}\right),$$
$$E\frac{dN^\pi}{d^4xd^3p} = E\frac{dN^0_\gamma}{d^4xd^3p}\left\{\frac{\beta}{\beta_\pi}\frac{p^\alpha p^\beta\pi_{\alpha\beta}}{2E}\right\}. \quad (5)$$

Next, we determine the dilepton and photon yields by integrating the above expressions over space-time evolution of QGP along with the temperature and $\bar{\pi}$ profiles. We choose the evolution of T and $\bar{\pi}$ corresponding to ideal τ_π approximation. In Fig. 1, we plot the ratio of viscous to ideal dilepton yield, $R_{l^+l^-}$ as a function of transverse momentum of the dileptons produced by varying the parameter α. The solid curve represents the attractor solution and dotdashed curve denotes the repulsor. The ideal case ($\delta f = 0$) is represented using dotted line and the dashed lines correspond to ratios for different values of α ranging from 10 to 5000. It is found that the particle yields are maximum for the attractor and minimum for repulsor. Yields corresponding to various α values lie between both these curves. As α increases the suppression to the yield increases and the curves approach the repulsor. Fig. 2 shows the strength of viscous to ideal photon spectra for $\tau_\pi \sim 1/T_{id}$. We conclude from this study that maximum increment in yield is observed for attractor and maximum suppression is for repulsor.

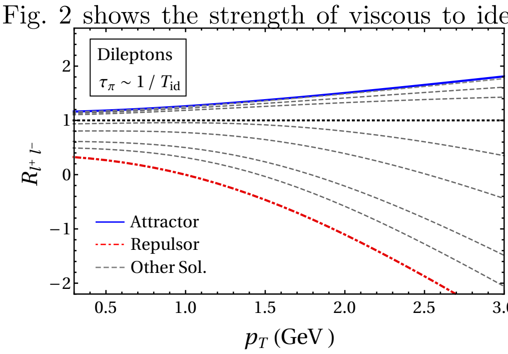

FIG. 1: Ratio of viscous to ideal dilepton yield for $\tau_\pi \sim 1/T_{id}$ approximation.

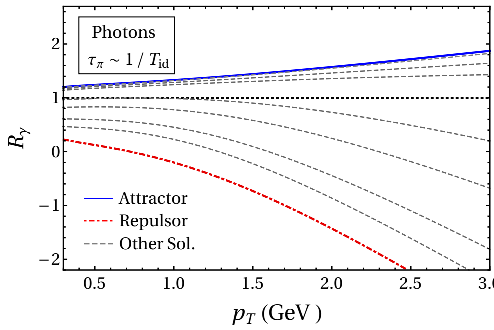

FIG. 2: Ratio of viscous to ideal photon spectra for $\tau_\pi \sim 1/T_{id}$ approximation.

References

[1] M. P. Heller and M. Spalinski, Phys. Rev. Lett. **115**, no.7, 072501 (2015).
[2] S. Jaiswal, C. Chattopadhyay, A. Jaiswal, S. Pal and U. Heinz, Phys. Rev. C **100**, no.3, 034901 (2019).
[3] L. J. Naik, S. Jaiswal, K. Sreelakshmi, A. Jaiswal and V. Sreekanth, [arXiv:2107.08791 [hep-ph]].
[4] A. Jaiswal, Phys. Rev. C **88**, 021903 (2013).