Collective excitations of the hot QCD medium and quark-gluon plasma in relativistic heavy-ion collisions

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Introduction

The fundamental forces of nature play dominant roles based on the size/energy of the system. Their corresponding theories help in investigating various properties of that system. If we probe inside the nucleus of an atom, the degrees of freedom are effective quarks and gluons whose dynamics is governed by the laws of strong interaction theory or Quantum Chromodynamics (QCD). There are two most striking features of the QCD, *viz.*, the confinement at low energy regime in which quarks and gluons are bound within the nucleonic volume and the asymptotic freedom at high energy regime where the quarks and gluons are effectively free to move beyond the nucleonic volume and where the Quark-Gluon-Plasma (QGP) could form. There is a transition from deconfined to the confined phase which is expected to be a crossover.

The prime focus here is to model the hot QGP/QCD medium and understand certain interesting properties of it. We employed the effective semi-classical transport theory and derived the gluon selfenergy (that contains the medium information) considering the isotropic, anisotropic and collisional hot QCD medium. The medium interaction effects employed through the equilibrium momentum distributions for quarks, anti-quarks and gluons. To that end, we worked with the relativistic (interacting) hot QCD Equations of State (EoSs) computed within the effective field theory approach at finite temperature and the lattice QCD EoS with the physical quark masses. Thereafter, we studied the following aspects.

A. Collective modes in the hot QCD medium [1, 2]

To study collective modes, the idea is as follows. Consider a homogeneous and stationary state of the QGP perturbed by either a random fluctuation or external field. As a result, local charges or currents appear in the plasma that generates chromoelectric/chromomagnetic fields. The fields then interact with colored partons. If the wavelength of the perturbation exceeds the typical inter-particle spacing, the plasma undergoes a collective motion involving many partons which are present within the interaction range. We call it collective modes/excitations of the plasma that could be studied in terms of gluon selfenergy in the QGP medium. We found that, in the collisionless isotropic medium, there were only two real-stable modes whereas after considering weak (momentum) anisotropy, three real stable and two unstable modes were realized. The study of unstable modes is comparatively more important in the sense that they help in the fast isotropization of the medium produced in the collision experiments. The results while considering the non-ideal EoSs were found to suppress the numbers but followed the similar patterns.

Later, we generalized this analysis by including collisional effects while employing the BGK collisional kernel. We observed that along with the previous results, there generated extra three modes which were imaginary but stable.

B. Dielectric properties of the hot QCD medium [3]

The dielectric properties of the hot QGP medium have been studied in terms of

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the refractive index while considering the anisotropic aspects of the hot QCD medium. To that end, we have first derived the expression for the dielectric permittivity and permeability in terms of gluon selfenergy. We have observed that there exist a certain frequency range where the QGP possess the negative refraction as well as a frequency region that shows opacity for the chromo-electro magnetic waves. While considering the anisotropy, the degeneracy of the eigenvalues of dielectric permittivity was found to be destroyed and hence, the left-handed and right-handed refractive indices were obtained separately. While incorporating the non-ideal medium effects, the results were found to be contracting the frequency range of negative refraction and the opacity region.

C. Energy loss of heavy quarks moving in the hot QCD medium [4]

The heavy quarks produced in the early stages of the heavy-ion collision pass through the QGP medium as the independent degrees of freedom because of their slower thermalization. They lose their energy while interacting with the medium in several ways such as radiation, collision, *etc*. We studied the energy loss of charm and bottom quarks moving in the collisional isotropic hot QGP medium. We derived the expression of energy loss in terms of the induced electric field, that in turn, depend on the gluon selfenergy. It has been observed that the energy loss increases with the particle momentum initially then saturates. Furthermore, the energy loss also increases with the collisions frequency. The bottom quark is found to lose less energy than the charm quark at fixed collisions frequency and particle momentum. The hot QCD medium effects are seen to suppress energy loss in both cases.

D. Quarkonia dissociation in the hot QCD medium [5]

While passing through the hot QCD medium, the static potential between the quark-antiquark pair of a particular quarkonia state gets modify due to screening and dissipation in the medium. As a consequence, causes the dissociation of these states. To study the dissociation of quarkonia, we first obtained the medium modified complex potential while considering anisotropy in the medium with the anisotropic strength $'\xi'$. The imaginary part of the modified potential gives rise to the thermal widths whereas the real part contributes to the binding energies of these states. Whenever the binding energy overcomes the thermal width of a given quarkonia state in the medium, this particular quarkonium dissociates. TableI, shows the dissociation temperature of various states compared with the lattice results present in the literature [6].

Temperatures are in the unit of T_c				
Anisotropy →	$\xi = -0.3$	$\xi = 0.0$	$\xi = 0.3$	Lattice[6]
1s states ↓				
Υ	2.861	2.964	3.062	2.31
J/ψ	1.487	1.520	1.551	1.10
2s states ↓				
Υ'	1.447	1.478	1.508	1.10
ψ'	1.054	1.066	1.078	0.20

TABLE I: Leading order results for prolate, isotropic and oblate cases.

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