Thermodynamic, magnetic and transport properties of hot QCD matter in a strong magnetic field

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Introduction

At high temperatures and/or baryon densities, the nuclear matter transits to a matter consisting of deconfined quarks and gluons, called as quark-gluon plasma (QGP). Such extreme conditions are realized in ultrarelativistic heavy ion collisions at terrestrial laboratories, *e.g.* Alternating Gradient Synchrotron (AGS) at BNL, Super Proton Synchrotron (SPS) at CERN, Relativistic Heavy Ion Collider (RHIC) at BNL, Large Hadron Collider (LHC) at CERN, and are expected to be produced with the dense quark matter in Compressed Baryonic Matter (CBM) experiment at Facility for Antiproton and Ion Research (FAIR) and Nuclotron-based Ion Collider fAcility (NICA) at Joint Institute for Nuclear Research (JINR) in fixed target experiments. The interaction among the constituents of the QGP medium can be explored by the quantum chromodynamics (QCD), the theory of strong interactions. The studies on various properties of the hot QCD matter using different theories were previously done for the simplest possible phenomenological setting with fully central collisions, where the symmetric configuration of the nuclei does not yield any magnetic field. However, in noncentral events of heavy ion collisions, extremely strong magnetic fields are produced, whose magnitudes could vary between m_π^2 ($\simeq 10^{18}$ Gauss) at RHIC to 15 m_π^2 at LHC. The initially produced strong magnetic field has short lifetime, however, depending on the electrical conductivity of the medium, the lifetime of magnetic field may be significantly extended. Since the strong magnetic field breaks the rotational symmetry of the system, various properties of the hot QCD matter might be affected by the strong magnetic field. Thus, in this thesis, we have studied how the thermodynamic, magnetic and transport properties of the hot QCD matter get modified in the presence of a strong magnetic field. We have then extended our study to the finite chemical potential case to observe the effect of the baryon density on different transport coefficients of the hot and magnetized QCD matter.

Results and discussions

We studied the effect of the strong magnetic field on the thermodynamic and magnetic properties of hot QCD matter by calculating various thermodynamic observables within the framework of perturbative QCD, *viz.* the pressure, the entropy density, the energy density, the square of the speed of sound, the magnetization and the magnetic susceptibility in the presence of a strong magnetic field [1, 2]. We observed that the pressure becomes larger in a strong magnetic field as compared to that in the absence of magnetic field. Since the magnetic field is strong, the dependence of pressure on the temperature becomes less steep. The entropy density also gets decreased, which supports the fact that the strong magnetic field restricts the dynamics of quarks to (1+1)-dimensions, hence, the phase space becomes squeezed and results in the reduction of the number of microstates. The strong magnetic field also reduces the energy density, whereas it enhances the square of the speed of sound of hot QCD matter. These observations on the energy density and the speed of sound could affect the expansion dynamics of the medium produced in ultrarelativistic heavy ion collisions. The magnetization and the magnetic susceptibility are found to increase with the magnetic field and remain positive throughout their variations with temperature, thus implying the paramagnetic nature of hot QCD matter in a strong magnetic field. Then, we studied the longitudinal expansion of matter with the paramagnetic equation of state as an input and observed that the energy density evolves faster than that in the absence of magnetic field. So, the cooling becomes faster, which is an artefact of the increase of the speed of sound in a strong magnetic field. This observation could have implications on dilepton and photon productions at the early stages of ultrarelativistic heavy ion collisions.

Then, we studied the effect of the strong magnetic field on the charge and heat transport properties of hot QCD matter [3]. So, we observed the electrical ($\sigma_{\rm el}$) and thermal (κ) conductivities in a thermal

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QCD medium in the presence of weak-momentum anisotropy arising due to the strong magnetic field. To distinguish the effect of strong magnetic field, we also compared the conductivities with those in expansion-driven anisotropy. From this study, we understood the longevity of strong magnetic field, the Lorenz number in the Wiedemann-Franz law, and the validity of local equilibrium by the Knudsen number. In calculating the conductivities we used the relativistic Boltzmann transport equation in the relaxation time approximation, where the interactions are incorporated through the distribution function within the quasiparticle model at finite temperature and strong magnetic field. Compared to the isotropic medium, both $\sigma_{\rm el}$ and κ get enhanced in B-driven anisotropy, whereas they get reduced in expansion-driven anisotropy. Thus, $\sigma_{\rm el}$ and κ may distinguish the origins of anisotropies. We also extended our calculations on the charge and heat transports in a strong magnetic field to the finite chemical potential case to observe the effect of the baryon density [4]. The differences in the behaviors of conductivities in both the anisotropies are due to the differences in the distribution functions, the relaxation times and the dispersion relations. We observed that, for an electrically conducting medium, the lifetime of the strong magnetic field gets increased. The Knudsen number (Ω) is smaller in expansion-driven anisotropy and is larger in B-driven anisotropy in comparison to the isotropic one, but its value remains less than one, thus, the medium can still be in local equilibrium. The ratio, $\kappa/\sigma_{\rm el}$ in the Wiedemann-Franz law in a strong magnetic field has magnitude smaller than that in expansion-driven anisotropy. Thus, the Lorenz number is different for different anisotropies.

We also studied the momentum transport properties of hot QCD matter in the presence of a strong magnetic field [5]. So, we observed the shear (η) and bulk (ζ) viscosities in the strong magnetic field-driven anisotropy. To distinguish the effect of strong magnetic field, we also compared the viscosities with those in the expansion-driven anisotropy. This study helps to understand the fluidity and the location of the transition point of matter through the ratios η/s and ζ/s, respectively, the sound attenuation through the Prandtl number (Pl), the nature of the flow through the Reynolds number (Rl), and the competition between momentum and charge diffusions through the ratio $(\eta/s)/(\sigma_{\rm el}/T)$. We calculated the viscosities by solving the relativistic Boltzmann transport equation in the relaxation time approximation, and used the quasiparticle model of partons at finite temperature and strong magnetic field. We also extended our calculations on the momentum transport for a magnetized QCD medium to the finite chemical potential case to observe the effect of the baryon density [6]. Upon comparing with the results in the isotropic medium we found that, both η and ζ get increased in magnetic field-driven anisotropy, contrary to the decrease in expansion-driven anisotropy. Thus, η and ζ could distinguish the aforesaid anisotropies. We also observed that, η/s gets enhanced in the former case, but gets decreased in the latter case as compared to the isotropic one. Similarly ζ/s gets amplified, but decreases faster with temperature in a strong magnetic field. The B-induced anisotropy increases the Prandtl number, whereas the expansion-induced anisotropy decreases it as compared to the isotropic case. But, Pl remains larger than 1, thus the sound attenuation is governed by the momentum diffusion. In B-driven anisotropy, the Reynolds number becomes smaller than 1, whereas in expansion-driven anisotropy it is larger than 1, so the hot QCD matter is more viscous in a strong magnetic field. The ratio $(\eta/s)/(\sigma_{\rm el}/T)$ gets enhanced in magnetic field-driven anisotropy and gets reduced in expansion-driven anisotropy, but it always remains larger than unity, thus explaining the dominance of momentum diffusion over charge diffusion for a hot QCD matter.

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