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Charge and heat transport coefficients of a hot and dense QCD matter in the presence of a weak magnetic field

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We have explored the effect of weak magnetic field on the transport of charge and heat in hot and dense QCD matter by calculating their response functions, such as electrical conductivity, Hall conductivity, thermal conductivity and Hall-type thermal conductivity in kinetic theory approach. It is found that the electrical and thermal conductivities decrease, and the Hall and Hall-type thermal conductivities increase with the magnetic field in the weak magnetic field regime, whereas the emergence of finite chemical potential enhances these transport coefficients. The effects of weak magnetic field and finite chemical potential on aforesaid transport coefficients are more noticeable at low temperatures, but high temperature suppresses these effects. As a result, some observables associated with the aforesaid transport coefficients such as the Knudsen number, the elliptic flow etc. are most likely to be affected by the magnetic field.

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PoS(LHCP2022)252

1. Introduction

High energetic heavy ion collisions at Relativistic Heavy Ion Collider (RHIC) and Large Hadron Collider (LHC) provide suitable conditions of high temperature and/or high density for the production of quark-gluon plasma (QGP). Noncentral collisions also generate strong magnetic fields with strengths varying between $eB = m_\pi^2$ ($\simeq 10^{18}$ Gauss) at RHIC and $eB = 15\, m_\pi^2$ at LHC. There exist two limits of magnetic field, such as the strong magnetic field limit ($eB \gg T^2$) and the weak magnetic field limit ($T^2 \gg eB$). The lifetimes of such magnetic fields can be extended in an electrically conducting medium [1, 2]. The emergence of magnetic field splits the charge and heat transport coefficients into multicomponent structures [3], *e.g.* electrical ($\sigma_{\rm el}$), Hall ($\sigma_{\rm H}$), thermal (κ) and Hall-type thermal ($\kappa_{\rm H}$) conductivities, which are studied using the relaxation time approximation of kinetic theory. Present analysis uses the thermal masses of particles, which encode the interactions among the medium constituents. In previous works, thermal mass of quark determined in the strong magnetic field limit had been used in studying various transport coefficients [2, 4]. In weak magnetic field limit, the phase space and single particle energies are not affected by the magnetic field through Landau quantization [5] and the magnetic field dependence is mainly attributed by the cyclotron frequency.

2. Electrical, Hall, thermal and Hall-type thermal conductivities

Due to the action of an external electric field, the system gets infinitesimally shifted from equilibrium, which induces an electric current density as

$$J^i = \sum_f g_f \int \frac{d^3{\rm p}}{(2\pi)^3} \frac{p^i}{\omega_f} \left[q\delta f_f(x,p) + \bar{q}\delta \bar{f}_f(x,p)\right] , \tag{1}$$

where g_f is the degeneracy factor of quark with flavor f. If magnetic and electric fields are perpendicular to each other, then J^i in Ohm's law is given by

$$J^i = \left(\sigma_{\rm el}\delta^{ij} + \sigma_{\rm H}\epsilon^{ij}\right) E_j , \tag{2}$$

where $\sigma_{\rm el}$ is electrical conductivity and $\sigma_{\rm H}$ is Hall conductivity. To calculate δf_f, we use the relativistic Boltzmann transport (RBT) equation in the relaxation time approximation,

$$p^\mu \frac{\partial f_f(x,p)}{\partial x^\mu} + \mathcal{F}^\mu \frac{\partial f_f(x,p)}{\partial p^\mu} = -\frac{p_\nu u^\nu}{\tau_f}\delta f_f(x,p) . \tag{3}$$

Here $f_f = \delta f_f + f_f^0$, $\mathcal{F}^\mu = qF^{\mu\nu}p_\nu = (p^0\mathbf{v}\cdot\mathbf{F}, p^0\mathbf{F})$, $\mathbf{F} = q(\mathbf{E} + \mathbf{v}\times\mathbf{B})$ and $F^{\mu\nu}$ is the electromagnetic field strength tensor. The relaxation time for quark (antiquark), τ_f ($\tau_{\bar{f}}$) can be expressed [6] as $\tau_{f(\bar{f})} = 1/\left[5.1T\alpha_s^2\log(1/\alpha_s)\left\{1 + 0.12(2N_f+1)\right\}\right]$. Utilizing an ansatz: $f_f = f_f^0 - \tau_f q\mathbf{E}\cdot\frac{\partial f_f^0}{\partial \mathbf{p}} - \mathbf{\Gamma}\cdot\frac{\partial f_f^0}{\partial \mathbf{p}}$, where $\mathbf{\Gamma}$ depends on magnetic field, and taking $\mathbf{E} = E\hat{x}$ and $\mathbf{B} = B\hat{z}$, one can solve eq. (3) to obtain δf_f and $\delta \bar{f}_f$. Then, by substituting them in eq. (1) and comparing

PoS(LHCP2022)252

with eq. (2), we get $\sigma_{\rm el}$ and $\sigma_{\rm H}$ respectively [7] as

$$\sigma_{\rm el}=\frac{\beta}{3\pi^2}\sum_f g_f q_f^2\int d{\rm p}\frac{{\rm p}^4}{\omega_f^2}\left[\frac{\tau_f f_f^0\left(1-f_f^0\right)}{1+\omega_c^2\tau_f^2}+\frac{\tau_{\bar{f}}\bar{f}_f^0\left(1-\bar{f}_f^0\right)}{1+\omega_c^2\tau_{\bar{f}}^2}\right], \tag{4}$$

$$\sigma_{\rm H}=\frac{\beta}{3\pi^2}\sum_f g_f q_f^2\int d{\rm p}\frac{{\rm p}^4}{\omega_f^2}\left[\frac{\omega_c\tau_f^2 f_f^0\left(1-f_f^0\right)}{1+\omega_c^2\tau_f^2}+\frac{\omega_c\tau_{\bar{f}}^2\bar{f}_f^0\left(1-\bar{f}_f^0\right)}{1+\omega_c^2\tau_{\bar{f}}^2}\right], \tag{5}$$

where $\omega_c=\frac{qB}{\omega_f}$ represents the cyclotron frequency.

The heat flow four-vector is defined by the difference between the energy diffusion and the enthalpy diffusion, *i.e.* $Q_\mu=\Delta_{\mu\alpha}T^{\alpha\beta}u_\beta-h\Delta_{\mu\alpha}N^\alpha$, where $\Delta_{\mu\alpha}=g_{\mu\alpha}-u_\mu u_\alpha$ and the enthalpy per particle $h=(\varepsilon+P)/n$ with the particle number density $n=N^\alpha u_\alpha$, the energy density $\varepsilon=u_\alpha T^{\alpha\beta}u_\beta$ and the pressure $P=-\Delta_{\alpha\beta}T^{\alpha\beta}/3$. Spatial component of the heat flow is written as

$$Q^i=\sum_f g_f\int\frac{d^3{\rm p}}{(2\pi)^3}\frac{p^i}{\omega_f}\left[(\omega_f-h_f)\delta f_f(x,p)+(\omega_f-\bar{h}_f)\delta\bar{f}_f(x,p)\right]. \tag{6}$$

In the Navier-Stokes equation at finite magnetic field, if gradients of temperature and pressure are perpendicular to magnetic field, then we have

$$Q^i=-\left(\kappa\delta^{ij}+\kappa_{\rm H}\epsilon^{ij}\right)\left[\partial_j T-\frac{T}{\varepsilon+P}\partial_j P\right], \tag{7}$$

where κ is thermal conductivity and $\kappa_{\rm H}$ is Hall-type thermal conductivity. Using the ansatz in eq. (3), we get δf_f and $\delta\bar{f}_f$. Substituting them in eq. (6) and then comparing with eq. (7), we calculate κ and $\kappa_{\rm H}$ respectively [7] as

$$\kappa=\frac{\beta^2}{6\pi^2}\sum_f g_f\int d{\rm p}\frac{{\rm p}^4}{\omega_f^2}\left[\frac{\tau_f\left(\omega_f-h_f\right)^2 f_f^0\left(1-f_f^0\right)}{1+\omega_c^2\tau_f^2}+\frac{\tau_{\bar{f}}\left(\omega_f-\bar{h}_f\right)^2\bar{f}_f^0\left(1-\bar{f}_f^0\right)}{1+\omega_c^2\tau_{\bar{f}}^2}\right], \tag{8}$$

$$\kappa_{\rm H}=\frac{\beta^2}{6\pi^2}\sum_f g_f\int d{\rm p}\frac{{\rm p}^4}{\omega_f^2}\left[\frac{\omega_c\tau_f^2\left(\omega_f-h_f\right)^2 f_f^0\left(1-f_f^0\right)}{1+\omega_c^2\tau_f^2}+\frac{\omega_c\tau_{\bar{f}}^2\left(\omega_f-\bar{h}_f\right)^2\bar{f}_f^0\left(1-\bar{f}_f^0\right)}{1+\omega_c^2\tau_{\bar{f}}^2}\right]. \tag{9}$$

In this study, we use the thermal mass (squared) of quark [8], $m_{fT}^2=\frac{g^2T^2}{6}\left(1+\frac{\mu_f^2}{\pi^2T^2}\right)$. We also assume that the chemical potentials for all flavors are same, *i.e.* $\mu_f=\mu$.

3. Results and discussions

Figure 1a explains the decrease of $\sigma_{\rm el}$ in a weak magnetic field, because the emergence of magnetic field deviates the direction of moving quarks, which causes a reduction of electric current along the direction of electric field, thus $\sigma_{\rm el}$ gets decreased. On the other hand, finite chemical potential increases $\sigma_{\rm el}$, which is attributed to the enhancement of distribution function in the similar

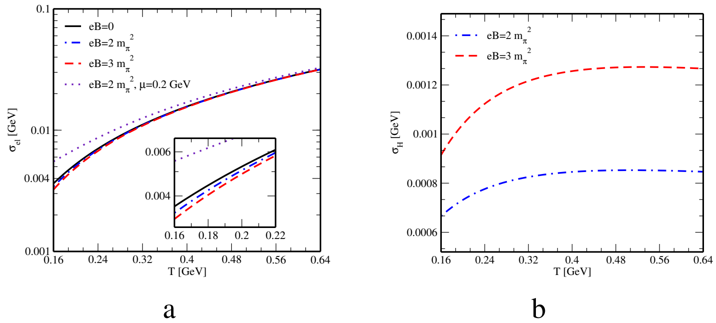

Figure 1: Variations of (a) $\sigma_{\rm el}$ and (b) $\sigma_{\rm H}$ with T for different weak magnetic fields and chemical potentials.

environment. Thus, the charge transport is less in a magnetized QCD medium than that in a dense QCD medium. Figure 1b shows that $\sigma_{\rm H}$ is smaller than $\sigma_{\rm el}$, but with magnetic field it increases even in the weak magnetic field regime, which is mainly due to the increase of cyclotron frequency with magnetic field.

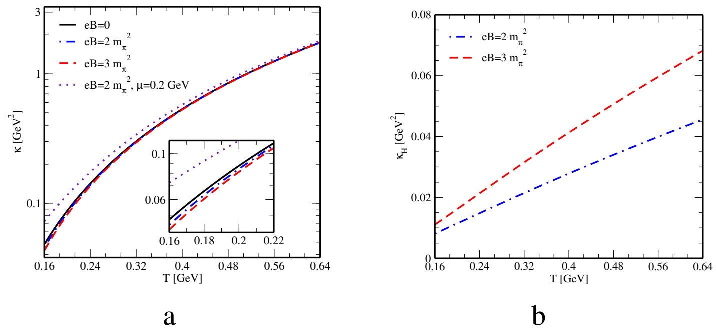

Figure 2: Variations of (a) κ and (b) $\kappa_{\rm H}$ with T for different weak magnetic fields and chemical potentials.

From figure 2a, one can see the reduction of κ in a weak magnetic field and its enhancement at finite chemical potential, thus describing the decrease of heat transport in a magnetized QCD medium and its increase in a dense QCD medium. Although $\kappa_{\rm H}$ in figure 2b is smaller in magnitude than κ, but with the magnetic field it increases due to the same reason as for $\sigma_{\rm H}$. The increase of both κ and $\kappa_{\rm H}$ with temperature is mainly attributed to the increase of both enthalpy per particle and distribution function with temperature.

4. Conclusions

In this work, we studied the effect of weak magnetic field on different charge and heat transport coefficients of hot and dense QCD matter, which were determined by utilizing kinetic theory approach. It was observed that the weak magnetic field decreases the transport of charge and heat in hot QCD matter, whereas the finite chemical potential facilitates these transports. In addition, the Hall components of both charge and heat transports were found to be smaller than the corresponding electrical and thermal conductivities.

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