Effect of time-varying electromagnetic field on Wiedemann-Franz law in a hot hadronic matter

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Introduction

Relativistic heavy ion collisions (RHICs) offer insight into the properties of deconfined matter. The observation of collective behavior in the QCD plasma of the primordial particles, called quarks and gluons (QGP) has fascinated the scientific community's interest in relativistic hydrodynamics. The study of dissipative hydrodynamics helps us to understand the expansion and evolution of QGP [1]. According to the laws of electromagnetic theory, peripheral heavy ion collisions can generate a strong magnetic field.

In this work, we have estimated a hadron resonance gas's electrical and thermal conductivity for a time-varying magnetic field, which is also compared with constant and zero magnetic field cases. Considering the exponential decay of electromagnetic fields with time, a kinetic theory framework can provide the microscopic expression of electrical conductivity and thermal conductivity related to baryon current in terms of relaxation and decay times. In the absence of a magnetic field, only a single time scale appears, and in the finite magnetic field case, their expressions carry two time scales - relaxation time and cyclotron time period. Estimating the conductivities for HRG matter in three cases - zero, constant, and time-varying magnetic fields, we have studied the validity of the Wiedemann–Franz law.

Formalism

In the presence of an electromagnetic field, the general form of electric current density can be expressed as

$$\vec{j} = j_e \hat{e} + j_H (\hat{e} \times \hat{b}) \ , \tag{1}$$

where $\hat{e}$, $\hat{b}$ are unit vectors along the direction of electric field ($\vec{E} = E\hat{e}$) and magnetic field ($\vec{B} = B\hat{b}$), respectively. j_e represents the Ohmic current density along the directions of the electric field, and j_H is the Hall current density perpendicular to the electric and magnetic fields. We solve the Boltzmann transport equation (BTE) for a single particle distribution function f_i with the help of relaxation time approximation (RTA). One can see the detailed formalism in Ref. [2]. In the presence of a time-varying magnetic field, heat current in the fluid rest frame can be expressed as

$$\vec{I} = \kappa_0 \vec{\nabla} T + \kappa_H (\vec{\nabla} T \times \hat{b}) \ . \tag{2}$$

κ_0 is the leading component of thermal conductivity along the temperature gradient, and the Hall type component is κ_H.

Results and discussion

For quantitative estimation of conductivities, we used the ideal HRG model, taking into account all the resonances (baryons and mesons) from the particle data group (PDG) having spin $0, 1, 1/2$, and $3/2$. In electrical conductivity, only the charged hadrons contribute. In thermal conductivity, only baryons (charged and neutral) directly contribute, and mesons contribute via the particle's relaxation time and enthalpy of the system. The final expression for the electrical and thermal conductivities in time-varying magnetic field (with $\chi_i = \frac{\tau_R^i}{\tau_B} = \frac{\tau_R^i}{\tau_E}$) are respectively as in Eq. 3. [2]

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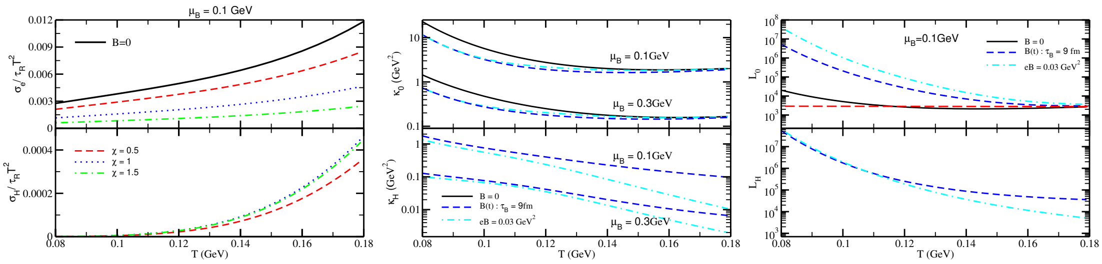

FIG. 1: (Left) Scaled electrical conductivity components (σ_e, $\sigma_H/\tau T^2$), (Middle) Components of thermal conductivity (κ_0, κ_H) and (Right) Lorenz number (L_0, L_H) as a function of temperature (T) [2].

Summary

In summary, we have estimated the thermal and electrical conductivity in a time-varying electromagnetic field in the hadronic matter. We have observed the deviation of WF law in the entire hadronic temperature domain, although, at high temperatures, a possibility of saturation value is noticed. Concerning the saturation value, if we measure the deviation of WF law, then we will find a ranking - constant magnetic field > time-varying magnetic field > zero magnetic field. We have also estimated the Hall-Lorenz number for the HRG matter, which also shows a possible violation of WF law in the presence of a magnetic field. It should be noted here that the WF law for metals and for a hadron resonance gas is different because of different quanta of the systems. For more details see Ref. [2].

$$\sigma_e = \frac{1}{3T}\sum_i g_i(q_i)^2\int\frac{d^3|\vec{k}_i|}{(2\pi)^3}\frac{\vec{k}_i^2}{\omega_i^2}f_i^0(1\mp f_i^0)\tau_R^i\ \frac{2\chi_i^2+2\chi_i+1}{(\chi_i+1)(\chi_i^2+1)(\chi_i^2+\chi_i+1)}\ .$$

$$\sigma_H = \frac{1}{3T}\sum_i g_i(q_i)^2\int\frac{d^3|\vec{k}_i|}{(2\pi)^3}\frac{\vec{k}_i^2}{\omega_i^2}f_i^0(1\mp f_i^0)\tau_R^i\ \frac{\chi_i\left(\chi_i^3+\chi_i^2+2\chi_i+1\right)}{(\chi_i+1)(\chi_i^2+1)(\chi_i^2+\chi_i+1)}\ .$$

$$\kappa_0 = \frac{1}{3T^2}\sum_i g_i\int\frac{d^3|\vec{k}_i|}{(2\pi)^3}\frac{\vec{k}_i^2}{\omega_i^2}(\omega_i-\mathrm{b}_i h)^2 f_i^0(1\mp f_i^0)\tau_R^i\ \frac{1}{(1+\chi_i+\chi_i^2)}\ .$$

$$\kappa_H = \frac{1}{3T^2}\sum_i g_i\int\frac{d^3|\vec{k}_i|}{(2\pi)^3}\frac{\vec{k}_i^2}{\omega_i^2}(\omega_i-\mathrm{b}_i h)^2 f_i^0(1\mp f_i^0)\tau_R^i\ \frac{\chi_i}{(1+\chi_i+\chi_i^2)}\ . \tag{3}$$

Acknowledgments

KS acknowledges the doctoral fellowship from UGC, Government of India. JD and RS gratefully acknowledge the DAE-DST, Govt. of India funding under the mega-science project – "Indian participation in the ALICE experiment at CERN" bearing Project No. SR/MF/PS-02/2021- IITI (E-37123).

References

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