Induced electromagnetic field in an evolving quark-gluon plasma due to thermoelectric effects

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Introduction

Heavy-ion collision experiments are capable of creating the state of deconfined and locally thermalized medium of quarks and gluons, known as quark-gluon plasma (QGP). The space-time evolution of the created QGP medium can be understood by using dissipative hydrodynamics [1]. The hydrodynamical expansion of the medium affects its transport properties [2]. Being made of electrically charged particles (quarks), it exhibits thermoelectric properties throughout its evolution.

In this work, for the very first time, we have calculated the electric field produced in QGP due to the thermoelectric effect. The Seebeck coefficient (S) is essential in determining the induced field. The Seebeck coefficient of any medium is a measure of the magnitude of an induced electric potential in response to a temperature gradient present in the medium. In baryonic QGP, the net heat flow is governed by the baryon current carried by the constituent quarks. As the quarks are electrically charged, a net non-zero electric potential will appear, giving rise to a non-zero electric field. We have also estimated the effect of QGP cooling in the calculation of thermoelectric coefficients using Bjorken and Gubser hydrodynamics.

Formalism

In kinetic theory, electric current density for such a system can be expressed as [3]

$$\vec{j} = \sum_i q_i g_i \int \frac{d^3|\vec{k_i}|}{(2\pi)^3} \frac{\vec{k_i}}{\omega_i} \delta f_i \ . \qquad (1)$$

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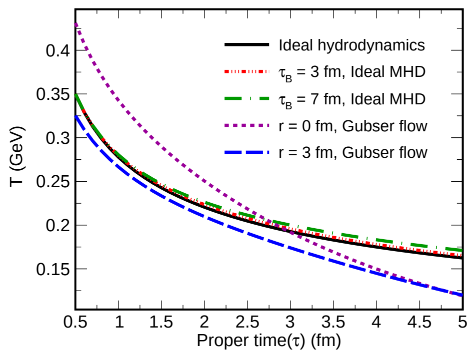

FIG. 1: Temperature (T) as a function of proper time (τ) for different hydrodynamical theories [4]

Here, q_i is the electric charge, and g_i is the degeneracy of the i$^{\text{th}}$ species particles. The ansatz chosen for $\delta f_i = (\vec{k_i} \cdot \vec{\Omega}) \frac{\partial f_i^0}{\partial \omega_i}$. Where the vector $\vec{\Omega} = \alpha_1 \vec{E} + \alpha_2 \vec{\nabla} T + \alpha_3 \vec{\nabla} \dot{T}$. Using the expressions of δf_i in Eq. (1), we get

$$j^l = \sum_i \frac{q_i g_i}{3} \int \frac{d^3|\vec{k_i}|}{(2\pi)^3} v_i^2 \tau_R^i \Big[-q_i E^l + \frac{(\omega_i - \mathrm{b}_i h)}{T} \Big\{ \frac{\partial T}{\partial x^l} - \tau_R^i \frac{\partial \dot{T}}{\partial x^l} \Big\} \Big] \frac{\partial f_i^0}{\partial \omega_i}. \qquad (2)$$

In above Eq., by setting $j_x = j_y = j_z$=0, we can get E_x, E_y and E_z in terms of temperature gradients $\frac{dT}{dx}$, $\frac{dT}{dy}$ and $\frac{dT}{dz}$. Further detail can be found in Ref. [4]. The cooling rates obtained using different hydrodynamical theories are shown in fig 1.

Results and Discussion

In head-on collisions, the magnetic field is not produced during the collision. In Fig. (2), we have shown the vector plot of the induced electric field in the transverse plane for head-on collisions. Due to symmetry consideration,

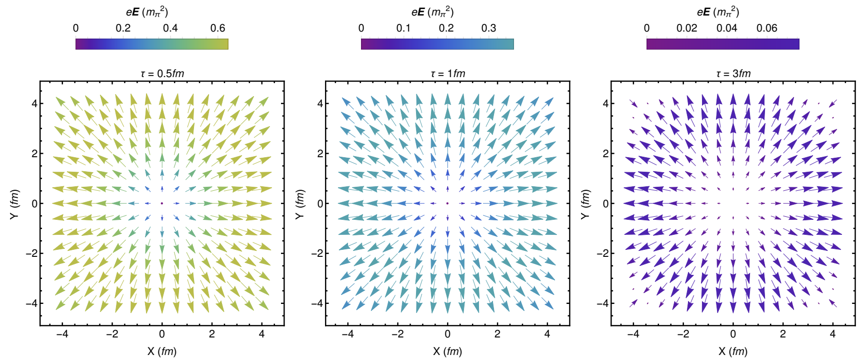

FIG. 2: Electric field induced in the QGP in head-on nuclear collisions [4].

T and its gradient are symmetric in the transverse ($x-y$) plane. Moreover, because of boost invariant symmetry along z axis, $\frac{\partial T}{\partial z} = 0$. Therefore, only x and y components of the electric field survive, and $\vec{E}$ is symmetric in the transverse plane. Time evolution of $\vec{E}$ is shown by three panels in the Fig. (2), from left to right $\tau = 0.5,\ 1,\ 3$ fm. The direction and magnitude of $\vec{E}$ are represented in the figures by the arrow tip and its length, respectively. Magnitude is also colored for clarity; the color bar on the top of the figures is given for magnitude in the unit of m_π^2. $\vec{E}$ is zero at the center (as $\vec{\nabla}T$ vanishes) and directed radially outward with increasing magnitude. At $\tau = 0.5$ fm, the induced field is as high as $eE = 0.6\ m_\pi^2$, and its strength decreases as the medium evolves in time. The direction of $\vec{E}$ can be understood from Eqs. $E_x = S\frac{dT}{dx}$, $E_y = S\frac{dT}{dy}$. The S is negative at the early time [4]. $\vec{\nabla}T$ is also negative, as T decreases as we go away from the center ($x = y = 0$, or, $r = 0$). This explains the direction of $\vec{E}$. The value of S, $\vec{\nabla}T$, and hence $\vec{E}$ is sensitive to the cooling rate.

Summary

In summary, for the first time, we estimated the induced electric field in QGP solely using the thermoelectric effect. We employed the kinetic theory-based RTA approach to calculate thermoelectric coefficients and induced electric field. For numerical estimation, we used a quasiparticle model that reproduces the lattice QCD EoS of QGP. Moreover, considering the realistic scenario of the temperature evolution of QGP, we introduced a term containing the time derivative of temperature gradient in the calculation of the total single-particle distribution function in the Boltzmann equation. In this instance, a finite baryon chemical potential is necessary. Otherwise, thermoelectric coefficients diverge up at vanishing baryon density. All results here are presented for the baryon chemical potential $\mu_B = 0.3$ GeV.

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