Magnetization of hot QCD matter in a strong and homogeneous magnetic field

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Introduction

The noncentral events of ultrarelativistic heavy ion collisions (URHIC) might produce extremely strong magnetic field, which, depending on the transport properties of the medium, may be still strong and homogeneous during the lifetime of partonic medium [1, 2]. Therefore, the strong magnetic field could have affected the properties of QCD medium, hence the effect of magnetic field may be probed via the hydrodynamic expansion of the medium by calculating the equation of state. However, we intend to study the magnetic property also, such as magnetization, which determines the response of produced QCD matter in URHIC to the strong magnetic field. The free energy in general embraces all the informations about the magnetic properties of a system. Very recently, we have calculated the free energy of QCD matter in the presence of strong magnetic field [3], so we wish to analyse the response of the QCD matter to the strong magnetic field by calculating the magnetization of hot QCD matter.

Magnetization

The magnetization is obtained by the partial derivative of the free energy ($\mathcal{F}$) with respect to the magnetic field at constant temperature i.e.

$$\mathcal{M} = -\left.\frac{\partial \mathcal{F}}{\partial |q_f B|}\right|_T . \quad (1)$$

The free energy due to N_f quarks with N_c colours is the sum of the free energies due to quark and gluonic contributions ($\mathcal{F} = \mathcal{F}_q + \mathcal{F}_g$), which are calculated perturbatively as

$$\mathcal{F}_q = N_c N_f \int \frac{d^4P}{(2\pi)^4} \ln\left[\det\left(S(P)\right)\right], \quad (2)$$

$$\begin{aligned}\mathcal{F}_g &= (N_c^2-1)\left[2\mathcal{F}_g^T + \mathcal{F}_g^L\right] \\ &= -\left(N_c^2-1\right)\left[\int \frac{d^4P}{(2\pi)^4}\ln\left[-\Delta_T(P)\right] \right. \\ &\quad \left. +\frac{1}{2}\int \frac{d^4P}{(2\pi)^4}\ln\left[\Delta_L(P)\right]\right], \quad (3)\end{aligned}$$

where $S(P)$, $\Delta_T(P)$ and $\Delta_L(P)$ represent the effective quark propagator, gluon propagator for transverse and longitudinal modes, respectively. These effective propagators are obtained from quark and gluon self energies through the Schwinger-Dyson equation and they have the following forms.

$$S(P) = \frac{1}{\gamma^\mu \cdot P_\mu - m_f - \Sigma(P)} , \quad (4)$$

$$\Delta_T(P) = \frac{-1}{P^2 + \Pi_T(P)} , \quad (5)$$

$$\Delta_L(P) = \frac{1}{p^2 + \Pi_L(P)} . \quad (6)$$

Recently we have calculated both the quark and gluonic contributions to free energy up to one loop perturbatively [3] in strong magnetic field limit ($|q_f B| \gg T^2$, $|q_f B| \gg m_f^2$, where $|q_f|$ and m_f are the absolute charge and the mass of the quark with flavour f, respectively), where we have observed that the ambience of strong magnetic field enhances the thermal pressure of QCD medium but the rate of increase with the temperature becomes slower. As a result, the entropy density gets decreased due to the presence of strong magnetic field. The above observations in thermodynamic observables will facilitate to understand the response of thermal (QCD) medium

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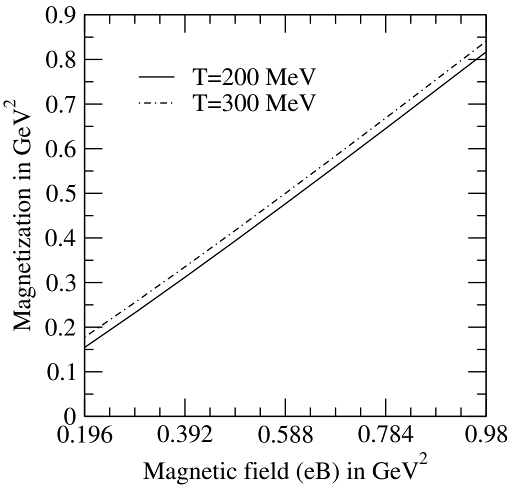

FIG. 1: The variation of magnetization as a function of magnetic field at different temperatures.

to the strong magnetic field. Thus we will study how the magnetization of the medium varies with the strong magnetic field.

The magnetization ($\mathcal{M}$) is thus obtained from eq. (1) and is found to depend on both temperature and magnetic field. For example, the magnetization of thermal QCD medium is found to increase linearly with the strong magnetic field and the above increase will be relatively higher for a hotter medium (in figure 1). On the other hand the magnetization increases very slowly with the temperature at a fixed magnetic field (in figure 2) which can be understood by the fact that, as the temperature increases the magnetic dipoles will be more randomized causing lesser alignment in the magnetic field direction.

Thus the magnetization is always positive, which is due to the decrease of free energy of the hot QCD matter in a magnetic field, so it behaves as a paramagnetic medium. In brief, due to the ambient strong magnetic field, the free energy gets minimized and induces a force, which causes a change in the shape of the QCD matter in the transverse plane of a noncentral heavy ion collision, known as paramagnetic squeezing. In several lattice calculations [4–6], it is also confirmed that the

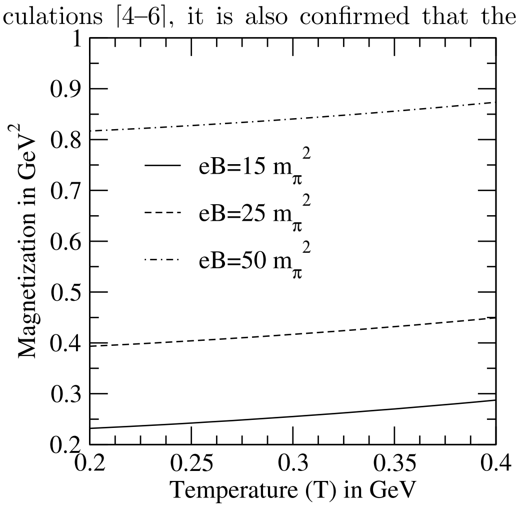

FIG. 2: The variation of magnetization as a function of temperature at different magnetic fields.

QCD medium in a magnetic field behaves like a paramagnet.

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