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Effect of Magnetic Field on QGP Equation of State

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The equation of state (EoS) of quark-gluon plasma (QGP) using a phenomenological model is studied with the effect of magnetic field. The calculations are performed with the effective mass of quark in the presence of magnetic field. The results presented using thermodynamic variables are significantly affected in the presence of magnetic field. The model results provide EoS of QGP which are in good agreement with Lattice QCD results and also enhance appreciably as comparison to the other work.

KEYWORDS: Quark-Gluon Plasma, Equation of State

1. Introduction

The ongoing experiments at Relativistic Heavy Ion Collision (RHIC) and Large Hadron Collider (LHC) may provide us possibilities of production of huge magnetic field for non- central collision [1, 2]. Such an intense magnetic field strength appears in heavy-ion collisions only on limited distances and exists for a very short time [3]. When two nuclei at relativistic speed collide with a non-zero impact parameter, a huge magnetic field is produced in the collision region, 10^{19} G at the RHIC energies and 10^{20} G at the LHC energies [4]. Such a huge magnetic field may also exists in the early Universe [5].

Lattice QCD simulations [6] have explored the effects of background magnetic fields on the EoS by computing the thermodynamic variables like as pressures, entropy, speed of sound and energy density etc. In this, the thermodynamic quantities increases well with the magnetic field [6]. It is very interesting to know the dependence of the transition temperature and the nature of the transition on the magnetic field.

The above study motivates us to work on EoS of QGP in the presence of a magnetic field. We develop a phenomenological model to check the behaviour of thermodynamic observables like the pressure, the energy density, the entropy, the speed of sound etc. with the different values of magnetic fields i.e. up to $eB = 0.4\ GeV^2$ and for a wide range of temperatures $110MeV < T < 300$ MeV and compared results with the zero magnetic field. The current study is based on our earlier model where it has been shown that how the temperature dependent quark mass affects the EoS of QGP in heavy-ion collisions. Now in this current work, we study the QGP EoS with the effective quark mass and with the effect of zero and finite value of magnetic field.

Thus, the paper is presented as: In Section II, we briefly discuss the theoretical model. In Section III, we explain the equation of state of QGP with magnetic field. The results are presented in Section IV. Finally, we conclude in Section V.

2. Description of a theoretical model

Based on earlier model [7, 8], the effective quark mass is suitably modified using magnetic field. Therefore, the effective quark mass in the presence of magnetic field is called magnetized effective quark mass (MEQM) [9].

In the presence of a constant magnetic field (along the z-axis), the single particle energy eigen value is given by [10],

$$E^{B\dagger} = \left[k^2 + M^B_{eff}\right]^{1/2} , \tag{1}$$

$$M^B_{eff} = M^2_{eff} + eB(2n + s + 1) , \tag{2}$$

M^B_{eff} is the MEQM. M^2_{eff} is the effective quark mass and it is defined as [8, 11],

$$M^2_{eff} = \mathrm{m}_c{}^2 + \sqrt{2}\mathrm{m}_c m_q + m_q{}^2 . \tag{3}$$

Where m_c and m_q are current and thermal mass of quark [8, 12]. The values $n = 0, 1, 2, ...$, are the principle quantum numbers for allowed Landau levels, $s = \pm 1$ refers to spin up (+) or down (−) states, and k is the component of particle momentum along the direction of the external magnetic field.

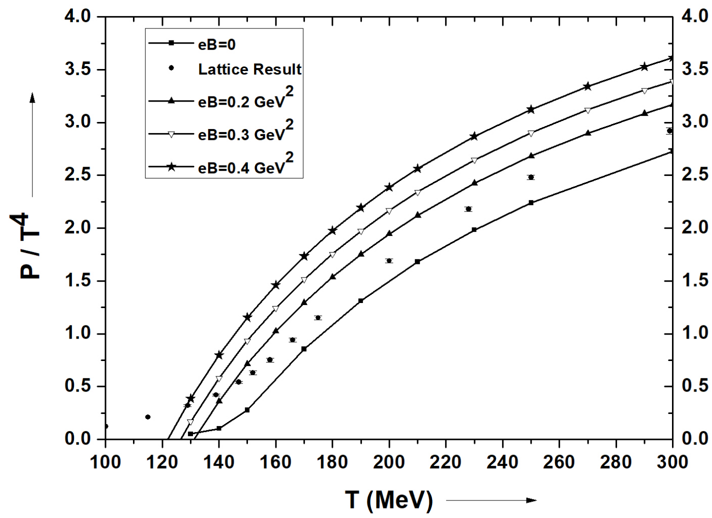

Fig. 1. The pressure (P/T^4) with respect to temperature (T) is shown with the effective mass of quark in the presence of magnetic field.

3. Equation of state of QGP with magnetic field

The modified free energy for quarks is defined in the presence of magnetic field along z-axis using Ref. [8, 12]. It is defined as:

$$F^{B\dagger} = F^0_q + F^B_q = F^0_q - eBM , \tag{4}$$

where M is the magnetization. Here F^0_q is the free energy for fermions (quarks) in the limit of zero magnetic field [8, 12] and F^B_q is the quark free energy shift induced by magnetic field. It is defined as in Ref. [13],

$$F^B_q = -Tg_q eB \int \rho_q(k) \ln[1 + e^{-E^{B\dagger}/T}]dk. \tag{5}$$

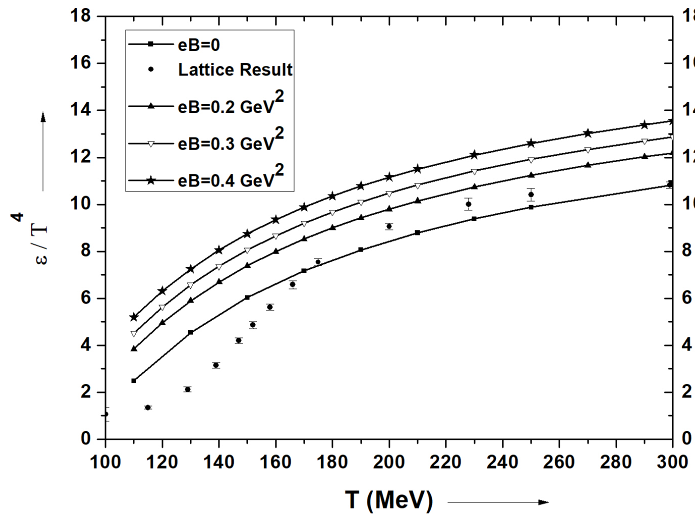

Fig. 2. The energy density (ε/T^4) with respect to temperature (T) is shown with the effective mass of quark in the presence of magnetic field.

It is the fact that gluon can interact with a magnetic field through a quark loop, which is expected to be large when the magnetic field is strong enough. Thus, free energy for gluons may exist, but is not included in this current analysis. So, in the same manner, we can define the free energy equation for bosons (gluons) by fixing zero magnetic field which is given as,

$$F_g = T g_g \int \rho_g(k) \ln[1 - e^{-E/T}] dk. \tag{6}$$

The density of state for quarks and gluons is represented as $\rho_q(k)$ and $\rho_g(k)$ [7]. The $g_{q,g}$ is quarks and gluons degeneracy factor. In the framework of the same model, the interfacial free energy is introduced [8, 12]. Finally, we calculate the total free energy which includes the terms like magnetic quark free energy, gluon free energy and interface free energy. This total modified free energy can be useful to describe the evolution of QGP. In this work, we compute pressure and energy density using total free energy with and without the magnetic field. It is expressed as:

$$P = -\left(\frac{dF_{total}}{dv}\right) . \tag{7}$$

The total pressure P is composed of different terms like quarks, gluons and interface mentioned above. Then, energy density can also be computed with the help of total pressure,

$$\varepsilon = T\frac{dP}{dT} - P . \tag{8}$$

Before calculating the thermodynamic observables, we should be careful in choosing the range of temperatures and magnetic fields, which should be compatible to the strong magnetic field limit. However, we have studied the variations of the thermodynamic observables with either the magnetic field or with the temperature in GeV. Thus applicable in studying the equation of state of quark-gluon plasma using effective mass of quark and in the presence of magnetic field.

4. Results

In Figure [1] and [2], we plot thermodynamic variables such as pressure (P/T^4) and energy density (ε/T^4) with temperature (T) in the presence of magnetic field. As we know that the thermodynamic observables are affected in the presence of the magnetic field, so we expect that the equation of state may also be affected in the presence of a strong magnetic field. We noticed that the effective value of quark mass does not deviate much from the finite value of quark mass. The impact of this effective quark mass is very much less and hence produce almost same output in the absence of magnetic field. So, the equation of state of QGP are almost consistent with earlier work, although there is a small decrement. Above all, it is verified that the effective quark mass fits nicely in the calculation to produce better results of equation of state of QGP. Further we computed all thermodynamic observable of a hot medium in the presence of the external magnetic field. It is found that the pressure and energy density increases with the magnetic fields. Results are compared with [12, 14].

Finally, a simple phenomenological model of the effective quark mass in the presence of magnetic field enhance output appreciably as compared to our previous results [12]. The prediction of EoS of QGP by using other models are also consistent with recent Lattice QCD results [14]. Results were presented for a variety of thermodynamic observables, indicating that the EoS is significantly affected by the magnetic field, even at moderate values of B. The results are confronted to recent Lattice QCD simulations. The agreement is fairly good.

5. Conclusion

In this work, we have explored how the thermodynamic observables of a hot medium affected in the presence of a very strong magnetic field, which may be produced in the non-central events of ultra-relativistic heavy ion collisions. It is noticed that the pressure for non-interacting quarks in a strongly magnetized thermal medium gets enhanced and an overall increase in the total pressure of the QCD matter is observed compared to a thermal medium in the absence of an external magnetic field. Finally we conclude that our model results with the help of effective quark mass and in the presence of magnetic field shows significant output. The model results can be successfully applied to the description of the properties of QGP created in the collisions of two massive nuclei at RHIC and LHC. The results are also important to produce EoS of QGP and significant in heavy-ion nuclear collisions.

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