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Quark-Gluon Plasma Fireball Formation in the Environment of Strong Magnetic Field

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Abstract

Using a theoretical model based on quasi-particle, we calculated the free energy evolution of quark-gluon plasma (QGP) in the presence of strong magnetic field generated in the high energy heavy ion collisions. The finite quark mass is used under the assumption of vanishing chemical potential. We found that the size of QGP fireball enhanced and more stable in the presence of strong magnetic field. This indicates that magnetic field plays an important role to describe the dynamics of QGP fireball under suitable conditions. Current results are useful in order to create a finite size of large QGP droplet. We noticed that the current results are also improved as compared to our earlier work where the contribution of magnetic field was neglected at RHIC and LHC. Thus, our results with quasi-particle model are of relevance in connection with the relativistic heavy ion collisions as well as for cosmological quark-hadron phase transition. In near future, experimentalists may provide the data for the existence of QGP fireball at RHIC, LHC and FAIR experiments.

Keywords: Quark-gluon plasma; Quantum chromodynamics; Heavy ion collision.

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1. Introduction

The creation of QGP fireball is assumed to exist for a short period of time. Due to which, it is very difficult to deal with such a complicated system in order to detect a QGP signal. The ongoing experiments at Relativistic Heavy Ion Collider (RHIC) situated at Brookhaven National Laboratory (BNL) and at the Large Hadron Collider (LHC) situated at CERN have attracted a great interest in the early phase of big bang where the critical temperature is $T_c \approx 170$ MeV and also in the core of neutron star where nuclear density is 5-10 times of standard nuclear density [1]. In the early phase of big bang, the system of QGP assume to be too hot and later it cools down on expansion. The facilities at RHIC and LHC help us in the various sectors; to study the detection and the formation of QGP, early phase transition and also to explore quantum chromodynamics (QCD) phase

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structure at very high nuclear density. Since the direct detection of QGP is not possible, so there are many indirect possibilities available in order to understand the behavior of QGP.

For the formation of QGP fireball and also to claim the order of phase transition, the dynamical parameters have been used in the density of state of relativistic quarks and gluons. This density of state for relativistic particles are used in computing the free energy of a system. However, one can obtain various size of QGP droplets using free energy evolution that depend strongly on flow parameters. The formation of QGP droplet also help us to predict the order of phase transition in different region of temperature and / or chemical potential.

Recently, it is reported that a strong magnetic field plays an essential role in the study of the evolution of early phase of universe [2], in neutron star and strange quark matter physics [3-11]. Such a strong magnetic field may also affect the thermodynamic observables in case of non-central collisions of heavy ions [12]. It is also indicated that a very strong magnetic field $\approx 10^{19} - 10^{20}$ Gauss might be generated in heavy-ion colliders [13-18]. It was suggested that such strong magnetic field exists only for a short period of time [19]. Some works have been done in the study of equation of state (EoS) of QGP in the presence of magnetic field. Moreover, the properties of QGP showed the significant change with the effect of magnetic field and also reported by Lattice QCD simulations [20]. Several authors [21-24] found that the transition temperature comes down with the effect of magnetic field. Apart from these studies, it is also noticed that the phase diagram of hadronic matter [25,26] also affects in the presence of magnetic field using low energy effective theories. However, it is very interesting to know that how the system of QGP behaves in the environment of strong magnetic field which is created during the collisions of heavy ion beams of giant accelerators situated at BNL and CERN. The above interesting studies motivated us to work on the QGP fireball formation under the influence of strong magnetic field.

The structure of our paper is as follows: In section 2, we give a brief description of model. In section 3 we calculate total free energies for quarks, gluons, pions and interface term in the environment of magnetic field. In section 4 results are presented for the evolution of free energy of QGP. At last, in section 5 we give the main conclusion.

2. A Brief Model Description

The formation of QGP fireball plays a vital role in the field of high energy physics. Many authors have reported that QGP is composed of quasi-particles (quarks and gluons) and mass of these particle have dominance on temperature so they are considered as thermal quark mass which depends strongly on temperature [27-29]. Bannur *et al.* have modified the calculations of quark mass under the consideration of chemical potential [30]. Our earlier calculations have been performed at zero quark mass. Now in order to see the QGP fireball formation, we extend our previous work in the environment of huge magnetic field. However, the finite quark mass is used under the assumption of vanishing chemical potential. Thus, it is defined as [31-33]

$$m_q^2(T,\mu=0)=\gamma_q\frac{N}{\ln\left(1+\frac{k^2}{\Lambda^2}\right)}\left[T^2+\frac{\mu^2}{\pi^2}\right] \tag{1}$$

In this equation, the value of chemical potential is taken as zero. The parameter,

$$k=\left[\frac{\gamma N^{\frac{1}{3}}T^2\Lambda^2}{2}\right]^{\frac{1}{4}} \tag{2}$$

is known as momentum with N=16π/ (33-2N_f) and N_f=3 is the number of quark flavours. The parameterization factor $\gamma^2=2[(1/\gamma_q^2)+(1/\gamma_g^2)]$ with γ_q=1/6 and γ_g=6 γ_q is taken from Refs. [31,33] and Λ is the QCD parameter.

3. Evolution of Quark-Gluon Plasma

The free energy for quarks, gluons and hadrons can be achieved through the canonical ensemble of thermodynamic system. We define partition function of the system as [34]:

$$Z(T,\mu,V)=Tr\left[\exp\{-\beta(\overset{\Lambda}{H}-\mu\overset{\Lambda}{N})\}\right], \tag{3}$$

where, the parameter μ is chemical potential of the system, $N^\wedge$ is quark number and β = 1/T. This partition function is used to correlate the free energy of a system through the density of state. The free energy has been evaluated by the authors [35-37] and taken as:

$$F_i=T\ln Z(T,\mu,V). \tag{4}$$

Earlier, we have worked on the evolution of free energy of quark-gluon plasma using the curvature term having dynamical quark mass and by fixing zero chemical potential. In the present work, modification has been done in earlier calculation given in Ref. [31,32] with the effect of strong magnetic field. Thus, the modified free energy for quarks, F_q, using finite quark mass is defined as:

$$F_q=\mp Tg_q\int dk\rho(k)\ln\left(1\pm e^{\frac{-(E-\mu)}{T}}\right). \tag{5}$$

We have substituted zero chemical potential i.e. μ=0 in the above equation 5. Similarly, free energy for gluons, F_g is taken from Ref. [31,32]. ρ(k) is the density of state of quarks and gluons and g_q is the degeneracy factor for quark. The interface and pion free energy of a system are defined in Ref. [31,32].

Now as Sethy *et al.* [38] have assumed that a constant magnetic field produced along z-axis of central collisions of massive ion beam at RHIC and LHC, the energy eigen value for a single particle is taken into the consideration with finite value of magnetic field under suitable condition. It is defined in Ref. [39,40] as:

$$E=\left[k^2+m_q^2+2B\right]^{1/2}. \tag{6}$$

The parameters involved in the above equation are suitably defined in Ref. [39,40]. The value of energy in equation 5 can now be replaced by equation 6. So, we have modified the free energy for quark under the influence of strong magnetic field involving various initial conditions.

Finally, the total free energy F_{total} is modified and calculated with the contribution of all above free energies in the suitable environment of strong magnetic field and it is given as,

$$F_{Total} = F_q + F_{gluon} + F_{\pi} + F_{\mathrm{int}erface} \tag{7}$$

The total free energy is therefore helpful to describe the physical picture of QGP in the presence of magnetic field by considering zero-chemical potential.

4. Results

In order to discuss the free energy evolution, we showed the modified results of free energy by considering the strong magnetic field at RHIC and LHC. Our model calculations have been performed in the limit of zero chemical potential. The reason is due to the particular relevance in the investigations of cosmological quark-hadron phase transition and also in the ultra-relativistic nuclear collisions at RHIC and LHC [41-43]. Unfortunately, the "sign problem" of lattice QCD do not provide relevant data with finite value of chemical potential [44,45]. Since the lattice QCD results successfully describe QGP as well as hadronic phase, it provides best output at large value of temperature and at zero chemical potential. Therefore, under the assumption of zero chemical potential, our model results are significant in order to describe the properties of QGP and also to determine the phase diagram of QCD.

In Fig. 1, we have plotted total free energy with respect to droplet radius by varying the temperature range T=150-250 MeV at zero magnetic field, also assuming zero chemical potential. We noticed that the free energy goes on increasing as we increase the size of droplets nearly up to 5 fm, afterwards it falls down and become zero and on further increasing size of droplet, it turns down towards the negative values of free energy. The smooth cut at phase boundary indicates the stability of QGP fireball. However, we obtained a stable QGP fireball. The picture of stable QGP fireball is taken with the suitable choice of the parametrization factor such as γ_q=1/6 and γ_g=6γ_q. These are the particular value of parametrization factors at which we found a stable QGP fireball formation. Below and above this value of γ_g, there is no stable QGP fireball formation. The particular choice of this flow value is due to the high stability in the formation of QGP droplet. Interestingly, we further pointed out that the bunching of curves at a particular point gives the more realistic picture for the stability of QGP droplet as shown by arrowhead. In this, the size of QGP droplet is formed around 9 fm as clearly shown in the Fig. 1. Also, the higher amplitude (barrier height) indicates that the free energy inclined toward more stability. The decrease in the critical size of QGP droplet with increasing temperature have also been observed.

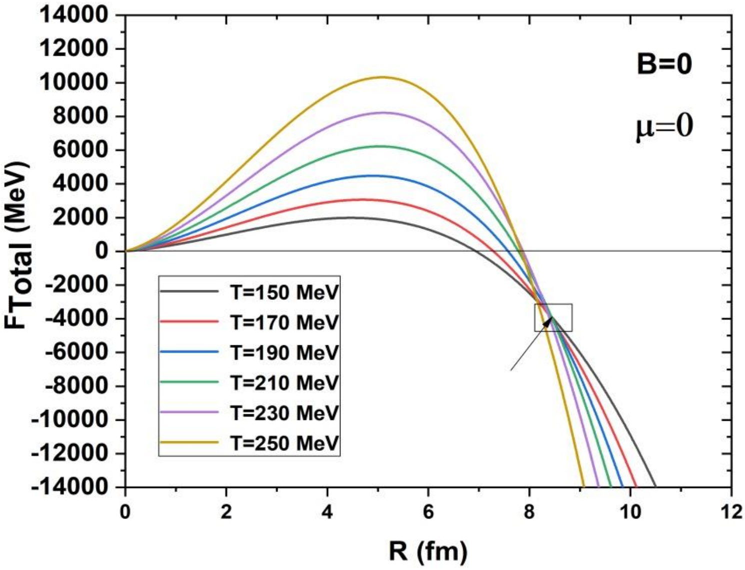

Fig. 1. Free energy with respect to size of droplets is shown by varying temperature at zero magnetic field.

In Fig. 2, although we found almost the same pattern as in Fig. 1, the barrier height as well as the size of QGP droplet show appreciable enhancement. This indicates that the strong magnetic field generated at RHIC and LHC affects the overall energy of QGP system and hence become more dependent in the presence of magnetic field to change the free energy evolution. Here, we have checked the dependence of magnetic field on the evolution of free energy at a particular value of magnetic field i.e. B=0.2 GeV^2. It is found that the critical size of QGP droplet formation appears around 10.3 fm which is much larger than our previous size as shown in Fig. 1. Both figures are taken under the consideration of zero chemical potential. These results are plotted with and without magnetic field using thermal mass of quark. Therefore, our results are very interesting in which enhanced output have been observed in the presence of a strong magnetic field. This information opens a new era for both high energy as well as astrophysics fields in order to detect the QGP signal and to explore the properties of QGP. However, the model results explore the phase diagram of QCD and hence give the clear cut information about the creation of QGP droplet. In both figures, the smooth cut at the phase boundary indicates that there is a phase transition at zero chemical potential with and without magnetic field although the order of phase transition is still an unresolved puzzle. Here, we claimed that the transition from hadronic phase to QGP phase is of first order. Finally, our results provide clear cut connection about quark-hadron phase transition which help us to confirm the existence of QGP.

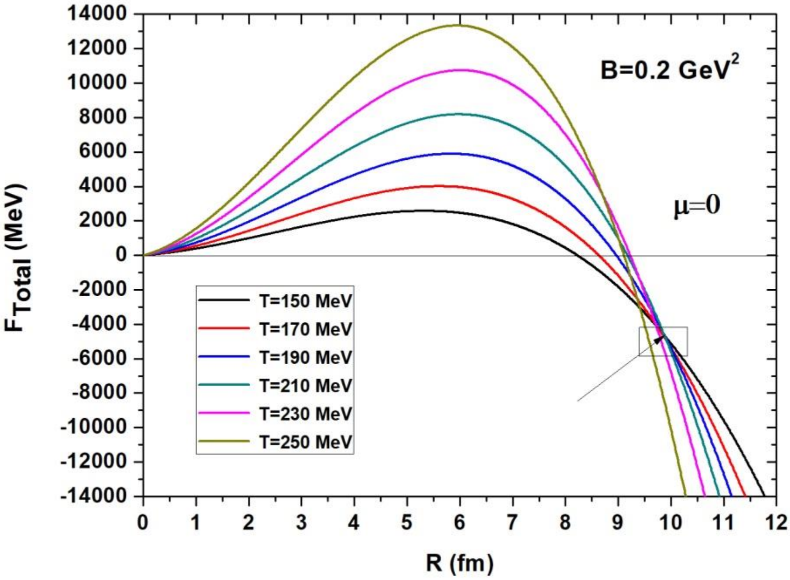

Fig. 2. Free energy with respect to size of droplets is shown by varying temperature at non-zero magnetic field.

5. Conclusion

In this work, we have explored the phase diagram of QCD where our results are appreciably influenced by the presence of very strong magnetic field to create QGP fireball. The results are improved and enhanced in which the contribution of quarks affected strongly by the magnetic field while the gluon part showed negligible change with the same environment. The current study may be of interest in order to see the dynamics of QGP medium produced at RHIC and LHC in the presence of a strong magnetic field. We have created a QGP fireball with large radius and successfully made a comparison between with and without magnetic field with the inclusion of finite quark mass at zero chemical potential. Finally, the output with the help of finite quark mass and in the presence of magnetic field showed enhanced results in comparison to the earlier results. Our results are useful as they develop more interest in the search of quark-gluon plasma.

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