Calculation of Early Universe Expansion of Quark Gluon Plasma with Chemical Potential

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Introduction

It is proposed that in the initial moments of our universe, matter existed in form of a Quark-Gluon Plasma (QGP). To understand the time evolution of QGP, we must consider the effects of a finite chemical potential [1]. We have used a simple quasi-particle model [2] in which we consider a thermal (temperature dependent) quark mass and a term involving the chemical potential μ.

To calculate the time evolution of thermodynamic observables such as energy density ϵ and temperature T, we attempt to solve the time evolution equation, i.e. $\frac{d\epsilon}{dt}$ and $\frac{dT}{dt}$ obtained from the Friedmann equation [3].

Considering the effects of chemical potential is an important to have a better understanding of the equation of state (EOS) of QGP in the early universe. Experiments at RHIC and LHC have not currently obtained an exact measure of this small chemical potential, but efforts to better understand the nature of this complex system continues.

Model Description

We employ a simple quasi-particle model in which we consider the effect of temperature on the quark mass. Along with thermal quark mass, we also consider the effect of a finite chemical potential. Taking into account both of these effects, we obtain the expression of the mass of a quark [4]:

$$m_{j=q}^2(T,\mu) = \gamma_q(g^2(p))[T^2 + \frac{\mu^2}{\pi^2}] \quad (1)$$

Here, γ_q and $g(p)$ are characterizing parameters of QGP flow and running couple constant of QCD. p and μ are momentum and chemical potential terms as usual.

The free energy of quarks and gluon can be described by the following equation [4, 5]:

$$F_j = \mp T g_j \int \rho_j(p) \ln(1 \pm e^{-\sqrt{[(m_j)^2+p^2]}/T+\mu/T}) dp \quad (2)$$

g_j is the spin and color degeneracy factor used as 8 (gluons) and 6 (quarks). $\rho_j(p)$ is the state density for a quark and a gluon and other variables have their usual meanings. g(p) is already defined in Ref. [4, 5].

We also add the interface term here, which separates hadronic and QGP phase [4, 5]:

$$F_{int} = \frac{1}{4}\gamma r^2 T^3 \quad (3)$$

in which, r is the QGP droplet radius and:

$$\gamma = (\sqrt{2})\sqrt{\frac{1}{\gamma_g^2} + \frac{1}{\gamma_q^2}} \quad (4)$$

is the effective RMS value of the quark and gluon flow parameter.

The total pressure as a sum of the individual pressure terms contributed by the total free energy term which can be defined as [6]:

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$$P = -(\frac{dF_j}{dV}) \tag{5}$$

We also have the energy density time evolution equation from the Friedmann equations as [7]:

$$\frac{d\epsilon}{dt} = -\sqrt{\frac{8\pi G}{3}}(3\sqrt{\varepsilon}(\varepsilon + P)) \tag{6}$$

The pressure obtained in eqn. (6) is connected with energy density by the expression [6]:

$$\epsilon = T\frac{dP}{dT} - P \tag{7}$$

And by the simple application of chain rule, we can finally derive the time evolution of temperature as [7]:

$$\frac{dT}{dt} = \frac{d\epsilon}{dt} \times \frac{1}{(\frac{d\epsilon}{dT})} \tag{8}$$

Solving for $\epsilon(t)$ and $T(t)$ provide us the EOS of QGP with the finite chemical potential effects which account for the time evolution of early universe.

Results

In this current work, we have solved for the expressions of $\epsilon(t)$ and $T(t)$ and the time evolution of these equations. The study is motivated by the work of Sanches et al. [7] and Kumar [8] who have determined the QGP EoS of early universe in the limit of zero chemical potential. In our earlier work [8], we have showed the variation of energy density and temperature with respect to time. The temperature of phase transition we have predicted around 150 MeV at zero chemical potential although no definite conclusion was given to claim the order of phase transition. The current work may provide us some new insights at some finite values of chemical potential where the transiiton temperature and order of phase transition accurately determine. The work is still under progess

Conclusions

It is expected that this study will give some important clue about the evolution of our universe and about the nature of QGP at finite chemical potential. The asymmetry between quarks and antiquarks gives rise to a small finite chemical potential, the effects of which should be considered while computing the EOS of QGP. It is important to consider the predictions of theoretical models in this case such that theoretician and experimentalists can further attempt to confirm these predictions on the basis of probing methods such as heavy-ion collisions. Relentless efforts are ongoing to understand this exotic stage of matter but, so far, we still know very little about this phase. Besides, we must also appreciate the significance of these studies in the context of cosmology, since a better understanding of QGP and its evolution would help us better understand the initial conditions of the universe and validate the prevailing models such as the Big Bang model of the inception of our universe.

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