Free energy droplet formation in ultra-relativistic heavy-ion collision

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Introduction

In ultra-relativistic heavy-ion collisions, quantum chromodynamics (QCD) predicts the phase transition from hadronic phase to the quark-gluon plasma phase. The lattice QCD calculations suggest the phase transition is of first order at a critical temperature around $T \approx 170$ MeV [1]. Such phase transition form a new state of matter, called the quark-gluon plasma (QGP) [2]. The fact is that the order of phase transitions are still unknown.

In ultra-relativistic heavy-ion collisions, free energy droplet formation provide a unique opportunity as one of the promising experimental signature of the quark-gluon plasma. Thus, if transition is a first order then it may proceed with a supercooling quark gluon plasma followed by a nucleation and growth of droplet with the release of latent heat as the transition progress.

So far we have calculated the free energy with effect of curvature using dynamical quark mass. In order to demonstrate the robustness of our numerical results, we now extend the previous work using dynamical quark mass as a finite quark mass to calculate free energy droplet formation in ultra-relativistic heavy-ion collision. The finite quark mass is temperature dependent and created due to the interaction of quarks and/or gluons with matter. It behaves well near or above the critical temperature. The quark mass is defined as [3]:

$$m_q^2(T) = \gamma_q g^2(k) T^2. \quad (1)$$

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Here, $g^2(k) = 4\pi\alpha_s$ with QCD strong coupling constant α_s defined as;

$$\alpha_s = \frac{4}{(33 - 2N_f)\ln(1 + \frac{k^2}{\Lambda^2})}. \quad (2)$$

where, $k = [\frac{\gamma N^{\frac{1}{3}} T^2 \Lambda^2}{2}]^{\frac{1}{4}}$ known as momentum with $N = \frac{16\pi}{[33-2N_f]}$, number of flavor $N_f = 3$ and parametrization factor $\gamma^2 = 2[\frac{1}{\gamma_q^2} + \frac{1}{\gamma_g^2}]$ with $\gamma_q = 1/6$ and $\gamma_g = 6\gamma_q$ [3]. We choose these parametrization factor because they nicely fit into our calculations and also help to enhance free energy evoltuion. The main purpose of the present work is to calculate the total free with the effect of curvature term incorporating the value of finite quark mass. The nucleation of the quark gluon plasma droplets is naturally driven by statistical fluctuations. The results are significantly improved and also enhanced the size of droplet with quark mass.

Free energy droplet formation

In the past decade, the work on free energy QGP droplet formation has well explained in the Ramanathan et al. [4] using simple statistical model. Further authors [5] have studied free energy of a quark gluon plasma with the inclusion of curvature term. In the present work, we modify earlier calculation of Ref.[5] with the effect of finite quark mass for three flavor.

We modify the free energy, F_i for quarks and gluons by modifying the density of states with the inclusion of curvature term with finite quark mass using [5]. The free energies of the constituent particles are dependent on the density of state which set up the fireball.

It is defined as:

$$F_i = \mp T g_i \int dk \rho_i(k) \ln(1 \pm e^{-(\sqrt{m_i^2+k^2})/T}) \ , \quad (3)$$

where $\rho_i(k)$ is the density of states of the particular particle i (quarks, gluons, interface, pions etc.), and g_i is the degeneracy factor and its value is taken from [5]. The interfacial free energy is defined as:

$$F_{interface} = \frac{1}{4} R^2 T^3 \gamma \ . \quad (4)$$

where, R is the radius of the droplet. In a similar manner, the free energy for the pionic enviornment is given as Ref. [4],

$$F_\pi = (3T/2\pi^2)\nu \int_0^\infty k^2 dk \ln(1 - e^{-\sqrt{m_\pi^2+k^2}/T}) \ . \quad (5)$$

We can thus compute the total free energy F_{total} as,

$$F_{total} = F_{q=u,d,s} + F_{gluon} + F_\pi + F_{surface} \ . \quad (6)$$

From above total energies, we can explain free energy evolution of quark gluon plasma in which the curvature term with finite quark mass indicate the propensity of the system for droplet formation.

Results and discussion

In the results and discussion, we present the modified results in order to demonstrate the robustness of numerical results for the evolution of free energy of the plasma at various temperature with the finite value of quark mass for three flavor. The figure describe the physical picture of free energy droplet formation. The calculations are performed in a similar way by modifying the Ramanathan et al. model with inclusion of curvature term incorporating quark mass with a major difference that in present paper, is properly taken into account. The calculation is done for three quark flavor. In figure, the size of QGP droplet formation is large in the presence of quark mass with the effect of curvature term. Also it shows a clear cut information about the stability of the droplet by looking smooth cut at the phase boundary for the various values of temperature. The bunching of curves provide more realistic picture for the stabilty of QGP droplet as shown by arrowhead. The more stability of free energy droplet formation occurs around 10 fm. Above all, there is stable droplet formation of quark-gluon plasma in ultra-relativistic heavy-ion collision with the effect of quark mass. It indicates that the use of finite quark mass with the effect of curvature term enhances the droplet size and make more stability in plasma evolution from earlier work [5].

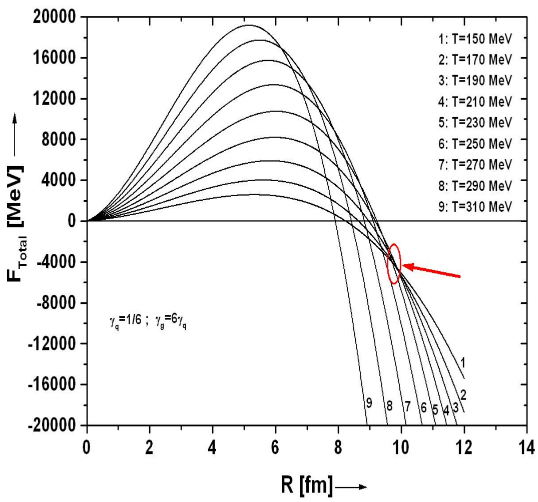

FIG. 1: The free energy F (MeV) of QGP evolution versus droplet size R (fm) for various temperatures with 3 flavors.

References

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