QGP Expansion at Early Universe Stage with the Effective Quark Mass

K. Jindal[1], Y. Kumar[1],* A. Gupta[1], P. Jain[2], P. Bangotra[3], and V. Kumar[4]
[1]*Department of Physics, Hansraj College, University of Delhi, Delhi, India*
[2]*Department of Physics, Sri Aurobindo College, University of Delhi, Malviya Nagar, New Delhi-110017, India*
[3]*Department of Physics, Netaji Subhas University of Technology, Dwarka, Delhi, India and*
[4]*Department of Physics, University of Lucknow-226007, Lucknow, U.P., India*

Introduction

In the early universe, highly dense and hot matter is supposed to be existed in a new state of matter called as a Quark-Gluon Plasma (QGP). To accurately model the time evolution of the complex QGP, it is to account for the effects of a finite effective mass of quark. In this study, we calculate the time evolution of energy density by solving the time-dependent equation derived from the Friedmann equation [1]. The inclusion of effective mass of quark plays a significant role in refining our understanding of the QGP's equation of state during these initial phases of the early universe.

Model Description

In the modifed model, we tested a simple theoretical approach that takes into consideration the influence of temperature on effective quark mass using below equation [2]:

$$m_{eff}^2 = m_c^2 + \sqrt{2} m_c m_q + m_q^2 \tag{1}$$

Here m_c is the current value of quark mass and m_q is the quark mass value. Extensively, we used the thermal value of quark mass in the given Ref. [3–5]:

$$m_q^2(T) = \gamma_q (g^2(p)) T^2 \tag{2}$$

The objects used in the above equation are defined in Ref. [3–5].
The free energy of quarks and gluons can be elucidated through the subsequent equation [5, 6]:

$$F_j = \mp T g_j \int \rho_j(p) \ln(1 \pm e^{\frac{-\sqrt{(m_{eff})^2 + p^2}}{T}}) dp \tag{3}$$

In this equation, $\rho_j(p)$ shows the density of states for quarks and gluons particles and other objects represent their conventional meanings [5, 6]. In addition to this, we also have the interface term which is used to separate the QGP phases from hadronic phase [5, 6]:

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

The value of r used in above equation is represented as the QGP droplet radius while γ is the effective RMS value of the quark and gluon flow parameter.
The total pressure is the sum of individual pressure terms contributed by the total free energy term defined in Ref. [7]. Then the energy density time evolution equation from the Friedmann equations can be computed using Ref. [8] and defined as:

$$\frac{d\epsilon}{dt} = -\sqrt{\frac{8\pi G}{3}} (3\sqrt{\varepsilon}(\varepsilon + P)) \tag{5}$$

Results and Conclusion

We use the energy density term, $\epsilon(t)$ with respect to time in the presence of effective quark mass and analyzed the time evolution of the quark-gluon plasma (QGP) in the early

*Electronic address: keshav02jindal@gmail.com

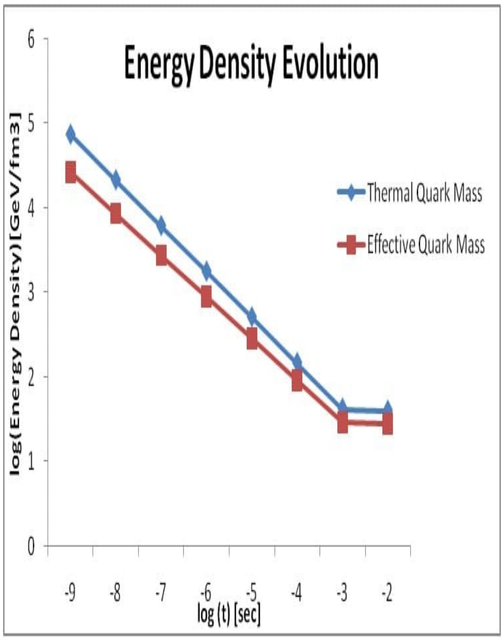

FIG. 1: Energy density evolution with respect to time is shown.

stage of universe. This study is well motivated by the efforts of authors such as Sanches et al. [8] and Kumar [9], who used the equation of state (EoS) of QGP and tested model in the early universe stage.

The plot shows the time evolution of the energy density, where we observe that the curve belongs to thermal mass of quark is ahead of effective quark mass. It indicates that the thermal quark mass is more dominant than effective quark mass. It is also observed that energy density is decreasing with respect to time up to 10^{-3} sec and on further increasing of time, energy density become constant. This may give the signal of phase transition from QGP phase to hadronic phase.

This analysis may provides new insights into the behavior of complex QGP under the effect of finite value of effective quark mass. It is important to consider the predict of phenomenological approaches, permitting both theoreticians and experimentalists to probe these conjecture through probing techniques such as ultra relativistic heavy-ion collisions at RHIC and LHC. Moreover, it is vital to observe the consequences of these inspections in the context of cosmology, heavy ion collisions and astrophysics. Finally, this study could offer a deeper understanding of the plasma's properties in extreme conditions at the early universe.

Acknowledgments

The authors extend their gratitude to the Department of Physics and Electronics, Hansraj College, Malka Ganj, DU, New Delhi for their unwavering support and encouragement in pursuing research in the field of High Energy Physics.

References

[1] A. Friedman, Gen. Rel. and Grav. **31(12)**, 1991 (1999).

[2] Y. Kumar, EPJ Web of Conf. **182**, 02070 (2018).

[3] Y. Kumar, JoP: Conf. Ser. **668**, 012110 (2016).

[4] P. K. Srivastava et al., Phys. Rev. D **82**, 014023 (2010).

[5] Y. Kumar and S. S. Singh, EPJ Web Conf. **137**, 13008 (2017).

[6] Y. Kumar, JoP Conf. Ser. **668**, 012110 (2016).

[7] Y. Kumar, JPS Conf. Proc. **26**, 024028 (2019).

[8] S. M. Sanches et al., Nucl. Phys. A. **937**, 1 (2015).

[9] Y. Kumar et al., J. Phys.: Conf. Ser. **2349**, 012016 (2022).