PROCEEDINGS OF SCIENCE

Neutron star as a signal for Quark-Gluon Plasma formation

Anisha Khatri[a,*] **and S. Somorendro Singh**[a]

[a] *Department of Physics and Astrophysics, University of Delhi, New Delhi- 110007, India*

E-mail: khatri.anisha20@physics.du.ac.in, sssingh@physics.du.ac.in

Studying neutron stars can help us understand the early formation of the universe. To understand and describe neutron stars, an appropriate equation of state that satisfies bulk nuclear matter properties is necessary. This study explores the quark matter equation of state by applying the Density Dependent Quark Mass model which is an extension of the MIT Bag model. The equation of state such as pressure, energy density, entropy, specific heat and speed of sound are calculated for a range of temperatures. The model results provide QGP equation of state, and the velocity of sound is shown in comparison to the Lattice QCD result.

QCD at the Extremes,
Sep 1-5, 2025

*Speaker

ISSN 1824-8039. Published by SISSA Medialab. https://pos.sissa.it/

PoS(QCDEX2025)019

1. Introduction

Compact stars such as white dwarfs, neutron stars, and the possible existence of quark stars or hybrid stars provide an essential link between nuclear physics and astrophysical observables [1–3]. Neutron stars, in particular, serve as natural laboratories for matter at densities far exceeding those reached in terrestrial experiments. The equation of state (EoS), which specifies the relationship between pressure and energy density, plays a central role in determining their masses, radii, and stability. While the EoS is reasonably well constrained between neutron drip density and about 3×10^{14} g cm^{-3}, where matter consists of nuclei, free neutrons, protons, and electrons, its form at supranuclear densities remains highly uncertain.

It has long been proposed that at sufficiently high densities, hadronic matter undergoes a phase transition to a deconfined state of quarks and gluons [4, 5]. This quark-gluon plasma, containing approximately equal numbers of u, d, and s quarks together with electrons for charge neutrality, has been suggested as the true ground state of matter. The resulting "strange matter hypothesis" implies that neutron stars could convert into strange stars [6], compact objects whose global properties closely resemble those of neutron stars.

Theoretical descriptions of strange quark matter (SQM) are often based on the MIT bag model, sometimes incorporating corrections from the QCD coupling constant [5, 7–9]. An alternative framework is the density-dependent quark mass (DDQM) model [10, 11], where confinement is introduced through a baryon density dependence of quark masses. Unlike the bag model, the DDQM approach endows even the light u and d quarks with appreciable masses at low densities, effectively accounting for first-order QCD corrections while remaining computationally simpler.

Since observed pulsars may be hybrid stars or even pure quark stars, neutron stars themselves offer a potential astrophysical signal of quark-gluon plasma formation. Moreover, the presence of intense magnetic fields on the order of 10^{17}–10^{18} G can substantially alter the EoS of these objects [12]. Motivated by these considerations, this work examines neutron stars as possible indicators of quark-gluon plasma formation, with particular attention to the predictions of the DDQM model under strong magnetic fields.

2. Density Dependent Quark Mass Model

In this model, we have assumed SQM as a free Fermi gas. We study the general properties of strange quark matter in the framework of a new equation of state in which the quark masses are parametrized as functions of the baryon density n_B as follows [13]:

$$m_u = m_d = \frac{c}{3n_B}, \quad m_s = m_{s0} + \frac{c}{3n_B}. \tag{1}$$

Here, m_{s0} is the strange quark current mass and c is a constant. The range of both these parameters is to be constrained by a stability argument. It has to be noted that in the bag model, confinement is independent of density. Here, we have not treated the change of masses of quarks as a phase transition.

The system is in the presence of a magnetic field B which is directed along the z-axis. The energy of the charged particle of mass m_i and charge q_i in the presence of the magnetic field is given by [14]

$$\epsilon_i^{\pm} = \left[m_i^2 + p_{z,i}^2 + 2q_iBn\right]^{1/2} \tag{2}$$

where +(-) refers to spin-up(-down) states of the particles, p_z is the momentum along the z-axis and n represents the Landau level. The thermodynamic potential is [12, 13]

$$\Omega = \sum_i \Omega_i - \frac{8}{45}\pi^2 T^4 \tag{3}$$

where the second term is contribution due to gluons. The general expression for the thermodynamic potential Ω_i in the presence of magnetic field is

$$\Omega_i = -T\frac{g_i q_i}{2\pi^2}B\sum_i(2-\delta_{n0})\int dp_z \ \ln\left[1-e^{-\beta(\epsilon_i-\mu_i)}\right] \tag{4}$$

where i = (u, d, s, e), g_i is the degeneracy factor ($g_i = 2 \times 3 = 6$ for quarks, $g_i = 2$ for electrons).

The thermodynamic parameters like pressure, energy density, entropy density, and specific heat of the system can be calculated from eqs. (3) and (4) using the standard thermodynamics relations. The pressure can be written as a function of temperature and finite baryon chemical potential [15, 16].

$$P(T,\mu) = -\Omega(T,\mu) \tag{5}$$

The energy density is calculated using the following expression,

$$\epsilon(T,\mu) = -T^2\left[\frac{\partial}{\partial T}\left(\frac{\Omega(T,\mu)}{T}\right)\right] \tag{6}$$

Thus, we obtain the energy density at a finite baryon chemical potential within a finite magnetic field. This allows for the calculation of the properties of the DDQM model of 2 + 1 flavor quarks at finite baryon chemical potential. Following the same approach, the entropy density of the system is studied to determine the equilibrium and disordered states of the system. The entropy density indicates the order of a phase transition, as reflected in first and second order derivatives. It is calculated from the partial derivative with respect to temperature and expressed as a function of temperature and chemical potential, as shown in the following relation.

$$s(T,\mu) = -\frac{4}{3}T\left[\frac{\partial}{\partial T}\left(\frac{\Omega(T,\mu)}{T}\right)\right] \tag{7}$$

The specific heat of the system is

$$C_v(T,\mu) = T\left[\frac{\partial s}{\partial T}\right] \tag{8}$$

We further calculate the speed of sound of SQM using the standard ratio of entropy density to specific heat. This ratio, as established by previous studies [17, 18] is

$$C_s^2 = \frac{s}{C_v} \tag{9}$$

Since the SQM system is in beta equilibrium it follows that,

$$\mu_d = \mu_s \tag{10}$$

and assuming that neutrinos or antineutrinos produced stream out freely i.e. $\mu_\nu = 0$

$$\mu_d = \mu_u + \mu_e \tag{11}$$

The charge neutrality condition gives

$$2n_u - n_d - n_s - 3n_e = 0 \tag{12}$$

The baryon number density of the system is

$$n_B = \frac{(n_u + n_d + n_s)}{3} \tag{13}$$

Thus, for a given value of n_B equations (10)-(13) can be solved for μ_u, μ_d, μ_s, μ_e. The quantities of physical interest, viz., P, ϵ, s, C_v, C_s^2 provide us the equation of state of the system, i.e, $P = P(\epsilon)$.

3. Results

The values of the parameters c and m_{s0} are constrained by requiring that

$$\begin{aligned} &\frac{\epsilon}{n_B} < 930\,\text{MeV} \quad \text{for SQM,} \\ &\frac{\epsilon}{n_B} > 930\,\text{MeV} \quad \text{for two-flavor quark matter.} \end{aligned} \tag{14}$$

From the stability window of SQM [11], the range for c is from 70 to 110 MeV fm^{-3} and for m_{s0} is within 50-180 MeV. In our study, we have considered $c = 75$ MeV fm^{-3}, $m_{s0} = 140$ MeV fm^{-3} and $eB = 1 \times 10^4$ MeV^2. At finite temperature, the chemical potential of the electron μ_e varies between 6 and 50 MeV [12]. We have taken it to be 7 MeV.

This enables us to numerically compute the thermodynamic parameters for a range of temperatures at baryonic chemical potential $\mu = 300$ MeV, which are then demonstrated in the figures.

In Fig 1, we first plot the pressure with respect to temperature at finite chemical potential μ and finite magnetic field in the DDQM model. There is a rapid rise in pressure at the initial stage of temperature and there is a constancy of P/T^4 with the increase of temperature beyond $T \approx 250$ MeV. In the second plot, the energy density rises sharply around the critical temperature and reaches a saturation value. Beyond the critical temperature, it remains essentially constant, indicating that the system's energy density stabilizes at high temperatures.

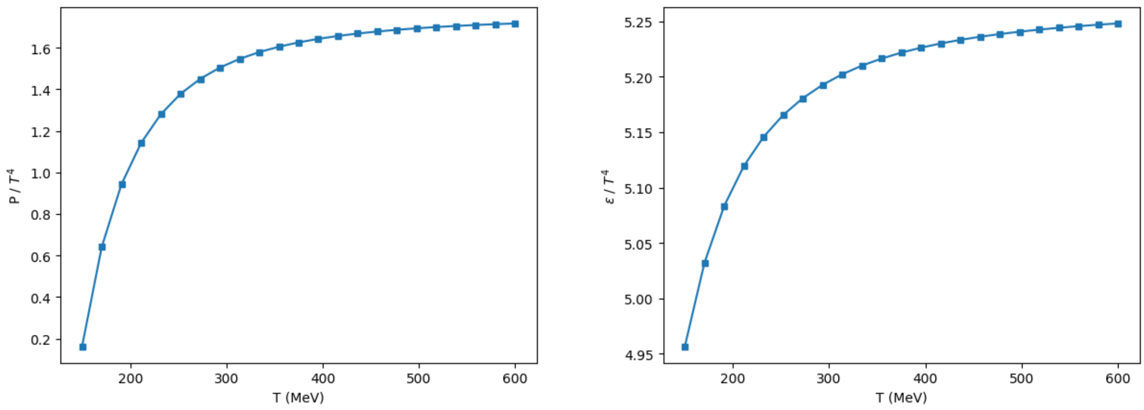

Figure 1: Variation of pressure (P/T^4, left) and energy density (ϵ/T^4, right) with temperature T (MeV).

Fig. 2 shows the plot of the variation of entropy density and specific heat with temperature at fixed chemical potential and magnetic field. The entropy density increases rapidly with temperature up to $T \approx 250$ MeV, beyond which it approaches a nearly constant behavior. The specific heat C_v, which is a second-order derivative of the thermodynamic potential, exhibits a similar smooth behavior and does not show any discontinuity in the transition region. The smooth rise and subsequent saturation of the entropy density indicate a continuous second order transition from the confined hadronic phase to the deconfined phase of quarks and gluons.

Fig. 3 shows the variation of the interaction term, defined as ϵ - 3P with temperature. The plot indicates that as the temperature increases, the interaction term gradually decreases towards zero. When the interaction term approaches zero, it signifies that the potential governing interactions between quarks and gluons become negligible, and the quarks and gluons behave as a "quasi-free" system. In this asymptotically free regime, they approximately obey the relation $P \approx \frac{1}{3}\epsilon$.

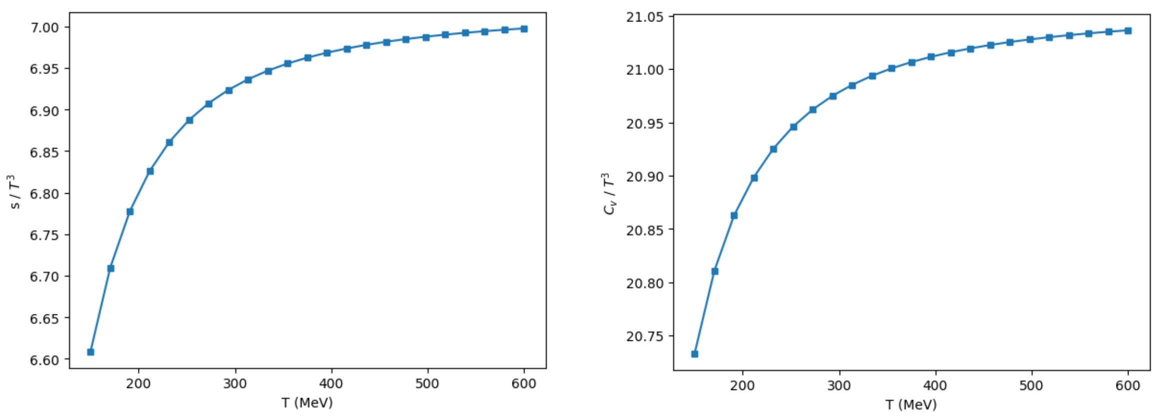

Figure 2: Variation of entropy density (s/T^3, left) and specific heat (C_v/T^3, right) with temperature T (MeV).

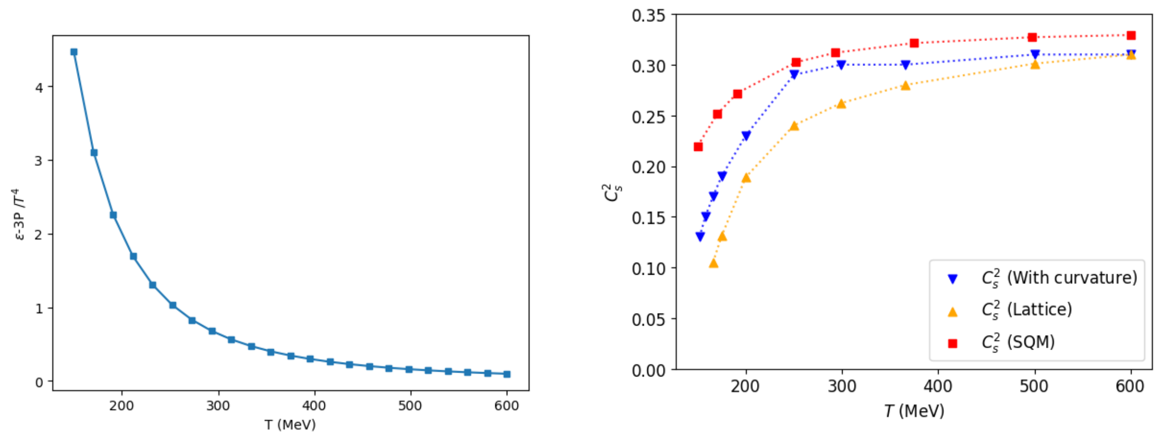

Figure 3: Variation of Interaction ($(\epsilon - 3P)/T^4$, left) and speed of sound (C_s^2, right) with temperature T (MeV).

A critical temperature around $T \approx 250$ MeV can be identified, corresponding to the transition of hadronic matter into the deconfined state.

The behavior of the speed of sound, obtained from the ratio of entropy to specific heat, is also well defined. When compared with both lattice and curvature data, it exhibits a similar trend at higher temperatures. Lattice QCD calculations indicate that at small baryonic chemical potential, the confinement-deconfinement transition is not of first order [19]. At temperatures below and well above the critical point, the speed of sound for strange quark matter takes values larger than those predicted by lattice QCD. However, the results remain significant for capturing the qualitative features of the speed of sound under extreme conditions of temperature and density.

4. Conclusion

We investigated strange quark matter (SQM), potentially present in neutron star cores, using the phenomenological DDQM model. The influence of a strong magnetic field ($eB = 1 \times 10^4$ MeV^2) on the second order quark-hadron phase transition was analyzed. Key thermodynamic quantities were computed to obtain the equation of state (EoS), and the speed of sound was compared with lattice and curvature data, showing similar trends at high temperatures. The DDQM model predictions are consistent with the lattice QCD calculations, also suggesting a continuous, second order transition under these conditions.

For future work, additional parameters such as number density, susceptibility, and Taylor coefficients can be computed to further explore the QCD phase structure. Moreover, extensions of the model with quark masses that are both density and temperature dependent could be developed and compared with the DDQM model. Overall, the DDQM model provides a reasonable approximation for describing the EoS of quark-gluon plasma under the high temperature and high density conditions expected in neutron star interiors.

References

[1] Cutler, C., Lindblom, L., & Splinter, R. J, *Damping times for neutron star oscillations* *Astrophys. J.* **363** (1990) 603.

[2] R. F. Sawyer, *Damping of vibrations and of the secular instability in quark stars*, *Phys. Lett. B* **233** (1989) 412.

[3] J. B. Hartle and J. L. Friedman, *Slowly Rotating Relativistic Stars. VIII. Frequencies of the Quasi-Radial Modes of an N = 3/2 Polytrope*, *Astrophys. J.* **196** (1975) 653–660.

[4] E. Witten, *Cosmic separation of phases*, *Phys. Rev. D* **30** (1984) 272–285.

[5] E. Farhi and R. L. Jaffe, *Strange matter*, *Phys. Rev. D* **30** (1984) 2379–2390.

[6] N. K. Glendenning, *Compact Stars: Nuclear Physics, Particle Physics, and General Relativity*, Iowa State University Press, 1997.

[7] B. A. Freedman and L. D. McLerran, *Fermions and gauge vector mesons at finite temperature and density. I. Formal techniques*, *Phys. Rev. D* **16** (1977) 1130–1146.

[8] A. Goyal and J. D. Anand, *Effect of temperature and quark-gluon interaction on strange matter*, *Nucl. Phys. B Proc. Suppl.* **24** (1991) 18–22.

[9] K. S. Cheng, Z. G. Dai, and T. Lu, *Strange stars and related astrophysical phenomena*, *Int. J. Mod. Phys. D* **7** (1998) 139–176.

[10] M. Plümer, S. Raha, and R. M. Weiner, *Effect of confinement on the sound velocity in a quark-gluon plasma*, *Phys. Lett. B* **139** (1984) 198–202.

[11] O. G. Benvenuto and G. Lugones, *The Properties of Strange Stars in the Quark-Density-Dependent Model*, *Int. J. Mod. Phys. D* **7** (1998) 29–48.

[12] J. D. Anand and S. Singh, *On quark matter in a strong magnetic field*, *Pramana* **52** (1999) 127–132.

[13] J. D. Anand, N. Chandrika Devi, V. K. Gupta, and S. Singh, *Radial Oscillations of Quark Stars in Strong Magnetic Fields*, *Astrophys. J.* **538** (2000) 870.

[14] L. D. Landau and E. M. Lifschits, *The Classical Theory of Fields*, Pergamon Press, Oxford, 1975.

[15] G. S. Bali, F. Bruckmann, G. Endrődi, Z. Fodor, S. D. Katz, and A. Schäfer, *QCD quark condensate in external magnetic fields*, *Phys. Rev. D* **86** (2012) 071502.

[16] S. S. Singh, *Thermodynamic equation of state of magnetized PNJL model of 2 + 1 flavor at finite baryonic density*, *Indian Journal of Physics* **99**, 2181–2190 (2025).

[17] R. V. Gavai, S. Gupta, and S. Mukherjee, *Lattice quantum chromodynamics equation of state: A better differential method*, *Pramana* **71** (2008) 487–508.

[18] S. Borsányi, *Thermodynamics of the QCD transition from lattice*, *Nucl. Phys. A* **904–905** (2013) 270c–277c.

[19] S. Borsányi, Z. Fodor, J. N. Guenther, R. Kara, S. D. Katz, P. Parotto, A. Pásztor, C. Ratti, and K. K. Szabó, *QCD Crossover at Finite Chemical Potential from Lattice Simulations*, *Phys. Rev. Lett.* **125** (2020) 052001.