Equation of state in magnetized quark matter

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Introduction

Strange quark matter (SQM) is formed with up (u), down (d), and strange (s) quarks under β-equilibrium and electric charge neutrality [1]. After Witten's statement about the stability of SQM, the study of strongly interacting matter became an important topic of nuclear, astrophysics, and cosmology. The SQM exists in the core of neutron stars [2] or may be produced in relativistic heavy-ion collision experiments [3]. The stability of SQM is also affected by strong magnetic field. The EoS generates the mass-radius relation of compact stars using Tolman-Oppenheimer-Volkov (TOV) equations. Recently, heavy pulsars such as PSR J0348+0432, PSR J2215+5135, PSR J0740+6620, and gravitation wave events GW170817 and GW190814 were discovered and put strong constraint on EoS and mass-radius relation. In literature, magnetized quark matter was studied by many authors, and observed a significant effect on EoS [4]. Furthermore, Felipe *et. al.* [6] investigated the magnetized strangelets for finite temperature. The chiral SU(3) quark mean field (CQMF) model based on quark degree of freedom was used to study the SQM and strange quark stars (SQSs) [7, 8]. In the present work, we explored the longitudinal and transverse EoS of SQM in presence of a magnetic field using the CQMF model at zero temperature.

Methodology

To study the magnetized strange quark matter (MSQM) under β-equilibrium, the thermodynamical potential density of chiral SU(3) quark mean field (CQMF) model are written as

$$\Omega = -\mathcal{L}_{\rm M} - \mathcal{V}_{\rm vac} - \sum_{i=q,l}\sum_{k=0}^{k_{i,max}} \alpha_k \frac{|q_i|BN_c}{4\pi^2} \Big[\mu_i\sqrt{\mu_i^2 - M_i^*(k,B)^2} - M_i^*(k,B)^2 \times \ln\left(\frac{\mu_i+\sqrt{\mu_i^2-M_i^*(k,B)^2}}{M_i^*(k,B)}\right)\Big]. \quad (1)$$

In above equation, the term $\mathcal{L}_{\rm M} = \mathcal{L}_{\Sigma\Sigma} + \mathcal{L}_{\rm VV} + \mathcal{L}_{\rm SB}$ defines the meson interactions. Also, the vacuum energy term, $\mathcal{V}_{\rm vac}$, is subtracted to attain zero vacuum energy. Moreover, the color degree of freedom, $N_c = 3$ for quarks, whereas 1 for leptons, B is the magnetic field, q_i is the electric charge of each quark, $\alpha_0 = 1$, $\alpha_{k>0} = 2$ and $M_i^*(k,B) = \sqrt{m_i^{*2} + 2|q_i|Bk}$.

The scalar density, ρ_i^s, and vector density, ρ_i, of quarks can be defined as

$$\rho_i^s = \sum_{k=0}^{k_{i,max}} \alpha_k \frac{N_c|q_i|Bm_i{}^*}{2\pi^2} \ln\left(\frac{k_{F,i}+\mu_i}{s_i^*(k,B)}\right), \quad (2)$$

$$\rho_i = \sum_{k=0}^{k_{i,max}} \alpha_k \frac{N_c|q_i|B}{4\pi^2} k_{F,i}\ , \quad (3)$$

where, $k_{F,i} = \sqrt{\mu_i^2 - s_i^*(k,B)^2}$ represents the fermi momenta of quarks.

To explain the EoS of MSQM, we need to introduce the $\beta-$equilibrium and charge neutrality condition of quarks and leptons via relations [4]

$$\mu_d = \mu_s = \mu_u + \mu_e - \mu_{\nu_e} \quad \text{and} \quad \mu_\mu = \mu_e, \quad (4)$$

and

$$2\rho_u = \rho_d + \rho_s + 3(\rho_e + \rho_\mu). \quad (5)$$

We can calculate the energy density, ϵ, longitudinal pressure $P_\parallel$ and transverse pressure, $P_\perp$ using

$$P_\parallel = -\Omega, \quad (6)$$

$$P_\perp = -\Omega + MB, \quad (7)$$

$$\epsilon = \Omega + \sum_{i=q,l} \mu_i\rho_i, \quad (8)$$

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where $M = \sum_{i=q,l} M_i$ is the magnetization of system.

Results and Discussion

This section investigates the longitudinal and transverse EoS using the CQMF model. The parameters used in the present work are provided in Ref.[7].

In Figs.1 and 2, we have shown the variation of longitudinal pressure, $P_{\|}$, and transverse pressure, $P_{\perp}$ with energy density, ϵ at $B = 10^{17}$, 10^{18} and $5{\times}10^{18}$ G for $g_v = 0$ and 3. The longitudinal and transverse pressure increase smoothly with energy density at a finite magnetic field. An increase in the value of B, increase the stiffness in the longitudinal EoS of MSQM; whereas transverse EoS get softer at moderate energy density, and no measurable change is observed at high and low energy density. In this case, the anisotropy of pressure is very small due to the absence of direct contribution from the magnetic field in pressure. On the other hand, both transverse and longitudinal EoS becomes stiffer by increasing the value of vector interaction. The effect of matter contribution on pressure anisotropy with/without field contribution in MSQM has also been studied in Ref.[5, 6].

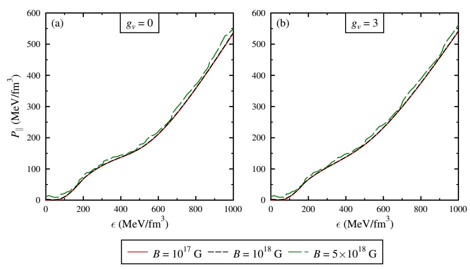

FIG. 1: The longitudinal pressure as a function of energy density at $B = 10^{17}$, 10^{18} and $5{\times}10^{18}$ G for $g_v = 0$ and 3 are plotted in above figure.

Summary

We have studied the EoS of magnetized quark matter under β-equilibrium using the CQMF model. It was observed that the magnetic field increases the stiffness of longitudinal EoS. The inclusion of vector interaction further increases the stiffness of EoS. Further, the EoS can be used to calculate the mass-radius of magnetized quark stars. In future, the effect of B-term in longitudinal and transverse pressure will be studied.

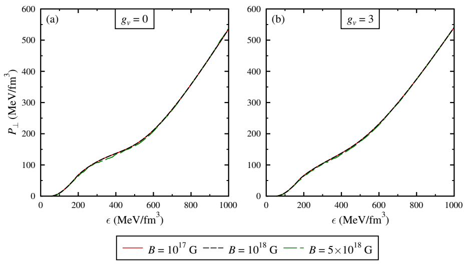

FIG. 2: The transverse pressure as a function of energy density at $B = 10^{17}$, 10^{18} and $5{\times}10^{18}$ G for $g_v = 0$ and 3 are plotted in above figure.

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