Finite magnetic field effects on properties of quark matter

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Introduction

Phase diagram of quantum chromodynamics (QCD) in presence of external magnetic field have attracted a great deal of attention. This is due to the fact that strong magnetic fields are anticipated to be produced in the early universe, magnetar and heavy-ion collisions. The value of magnetic field produced is likely to be around m_π^2 at Relativistic Heavy Ion Collider (RHIC) and approximately $15m_\pi^2$ at Large Hadron Collider(LHC). Lattice QCD simulations at low values of temperature and outcomes of low energy effective theory calculations have shown a relocation of phase boundary towards the higher value of temperature with the increasing magnetic field, an effect known as "magnetic catalysis". Alongwith experimental endeavors, various theoretical models have also been employed to study the strange quark matter in presence of magnetic field. In the present work, we have studied the impact of magnetic field on the thermodynamic properties of asymmetric quark matter by using (2+1)-flavor Polyakov loop extended quark meson (PQM) model.

Methodology

Polyakov quark meson model is based on chiral symmetry breaking and confinement properties of QCD. The total effective Lagrangian for N_f flavors is written as [1]

$$\mathcal{L} = \bar{\psi} i\gamma^\mu \partial_\mu \psi + \mathrm{Tr}\left(\partial_\mu \varphi^\dagger \partial^\mu \varphi\right) + \mathcal{L}_{qm} - \lambda_1 \left[\mathrm{Tr}\left(\varphi^\dagger\varphi\right)\right]^2 - \lambda_2 \left[Tr\left(\varphi^\dagger\varphi\right)\right]^2 + c\left(\det(\varphi) + \det\left(\varphi^\dagger\right)\right) + \mathrm{Tr}\left[H\left(\varphi+\varphi^\dagger\right)\right] - m^2\,\mathrm{Tr}\left(\varphi^\dagger\varphi\right) - \frac{1}{4}\mathrm{Tr}\left(V_{\mu\nu}V^{\mu\nu}\right) + \frac{m_1^2}{2} V_{a\mu} V_\mu^a. \quad (1)$$

The first term of above equation is kinetic energy term of quarks while the second term represents the kinetic energy of scalar mesons. The terms involving λ_1 and λ_2 are quadratic interaction terms, and $\mathcal{L}_{qm}$ is the quark meson interaction term given as

$$\mathcal{L}_{qm} = g_s\left(\bar{\psi}_L \varphi \psi_R + \bar{\psi}_R \varphi^\dagger \psi_L\right) - g_v\left(\bar{\psi}_L \gamma^\mu L_\mu \psi_L + \bar{\psi}_R \gamma^\mu R_\mu \psi_R\right). \quad (2)$$

The model has been extended by the introduction of vector interaction term and inclusion of isospin chemical potential in order to study asymmetric quark matter. To study the impact the finite magnetic field in PQM model, we have considered an uniform magnetic field along z-direction. Due to the Landau quantization in presence of external magnetic field, the effective energy of quarks is modified as [2]

$$E_i^* = \sqrt{p_z^2 + m_i^{*2} + |q_f|\,(2n+1-\alpha)B}, \quad (3)$$

where α is the spin quantum number. The term $(2n+1-\alpha)$ in eqn. 3 is replaced by a single quantum number, k, termed as Landau level. The quark-antiquark interaction term is hence altered and is given as [3]

$$\Omega_{q\bar{q}} = -\sum_{f=u,d,s} \frac{|q_i|\,BT}{2\pi} \sum_{k=0}^{\infty} \alpha_k \int_{-\infty}^{\infty} \frac{dp_z}{2\pi} \times \left(\ln g_f^+ + \ln g_f^-\right). \quad (4)$$

We obtain the total thermodynamic potential of PQM model in presence of finite magnetic field and minimize it to obtain the field values.

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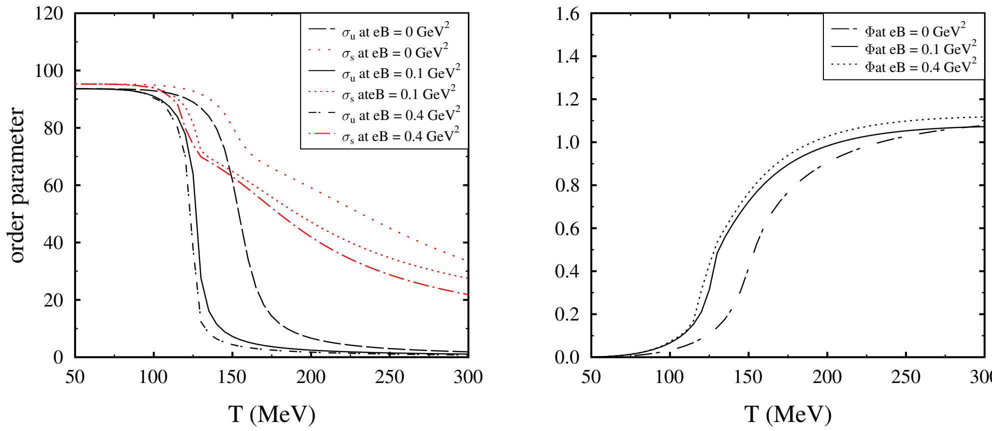

FIG. 1: Order parameters σ_u, σ_s (left panel) and Φ (right panel) as a function of temperature, T at baryon chemical potential, μ_B = 200, strangeness chemical potential, μ_S = 200 MeV and isospin chemical potential is fixed at 80 MeV.

Results and Discussion

In this section, we have discussed the effect of finite magnetic field on the thermodynamics of Polyakov loop extended quark meson model. The value of g_v, the vector interaction coupling constant is considered to be 1.95. In Fig. 1, it is observed that the value of quark condensates, σ_u and σ_s decreases and the value of Polyakov-loop variable, Φ increases with increasing magnetic field at different values of temperature. With rise in value of the magnetic field, the quark condensates are suppressed in regime of phase transition. This trend of quark condensates with increment in external magnetic field is termed as "inverse-catalysis" [4]. The enhancement of quark condensates is attributed to the saturation of valence quark interactions by the sea quarks especially near the transition region. This signifies the shift of pseudo-critical temperature towards lower value with increase in magnetic field. The sudden change in value of Polyakov loop parameter signifies the change in degrees of freedom from confined to deconfined state. As we observe that the value of Φ increases with the rise in magnetic field, which indicates the shift of deconfinement temperature towards a higher value with the increasing magnetic field. In conclusion, the inclusion of finite magnetic field relocates the critical temperature towards lower value of temperature and hence plays a significant role in studying the phase diagram of QCD.

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