The Influence of Strong Magnetic Fields in the QCD Transition

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Abstract

A widely studied subject within the context of strong interactions in high energy physics is that of the QCD phase transition. After it became clear that hadrons are composed of confined quarks and gluons it was suggested that they might undergo a phase transition at high temperature or density, becoming a deconfined plasma, the so-called “quark-gluon plasma”. This transition has significant experimental implications (some of them being tested in modern accelerators such as the LHC, RHIC, etc), not to mention the description of the early stages of the universe and the matter inside neutron stars.

In the recent years it has been argued that electrically charged spectacles, present in non-central heavy ion collisions, are responsible for creating a strong magnetic field (about $10^15$ G) that could play an important role in the QCD phase transition influencing, e.g., the eventual location of the critical end point. At low temperatures one also expects that these strong magnetic fields influence the equation of state for quark matter which is of utmost importance for the physics of compact stellar objects. In this work we present some recent results for magnetized quark matter using an effective theory described by the Nambu-Jona-Lasinio model (NJL).

Introduction

Strong magnetic fields can be created in peripheral heavy ion collision at RHIC and LHC with non vanishing impact parameter ($\lambda$) as shown in Fig. 1. If such a strong field lasts enough time, it is expected that these strong magnetic fields influence the equation of state for quark matter which is of utmost importance for the physics of compact stellar objects. In this work we present some recent results for magnetized quark matter using an effective theory described by the Nambu-Jona-Lasinio model (NJL).

Magnetized Quark Matter

We use the Nambu-Jona-Lasinio model [1] in the SU(2) version in order to study the chiral transition in quark matter with three color degrees of freedom. Therefore, we introduce the lagrangian

$$\mathcal{L} = \overline{q}(\gamma_\mu D^\mu - m) + G (\overline{q} \gamma^5 q + \overline{q} \gamma^5 \gamma^\sigma q)^2 + \frac{1}{2} F_{\mu\nu} F^{\mu\nu}, \quad (1)$$

where $q$ represents the fermion field, $G$ is the quark electric charge, $m$ is the quark bare mass (assumed to be equal for both up and down quarks), $G$ is the coupling constant and $\mathbb{I}$ the Pauli matrices. The first term in the right hand side of eq (1) is the free part, the second term is the scalar channel while the third is the pseudo-scalar channel. The effective potential in the mean field approximation can be written as follows[4]

$$F = \frac{1}{2} \overline{q} \gamma^\mu \gamma_{\mu\nu} + F_{\mu\nu} + F_{\text{ext}}$$

where

$$F_{\mu\nu} = -2N_F \Lambda \int \frac{dp}{2\pi^3} E_\mu E_\nu$$

$$F_{\text{ext}} = -\sum_F N_F \langle |\psi_F|^2 \rangle \int \frac{dp}{2\pi^3} \{ \xi (-1, \xi) \frac{1}{\sqrt{1 - \xi^2}} - \xi |\psi_F|^2 \}$$

are the vacuum, magnetic and medium contributions, respectively. We use $\Lambda$ to represent the Landau levels and $\omega_0 = 2\omega_0$ takes into account the degeneracy of the non-zero levels. In eq (3) $N_1 = 1$ and $N_2 = 2$ are the color and flavor degrees of freedom, respectively, and the integral is carried out up to $\Lambda = 590\text{ MeV}$ (the cutoff).

In eq (4) $\xi = M_F^2 / 2T_B$ and (1) $-\xi$ are related to $\langle \mathcal{O} \rangle$ with $\mathcal{O}$ being the Riemann-Hurwitz function. We also fix the coupling constant as $G = 2.41$. Finally, in eq (5) we have $F_{\text{ext}} = \sqrt{2} \frac{\omega_0}{\Lambda} = \frac{\omega_0}{\Lambda}$. Equations (2)-(5) allow us to study the chiral transition in quark matter at finite $T$ and $\mu$ under the influence of an external magnetic field $B$.

Results

The effect of the magnetic field on the normalized quark condensate, at $\theta = 0$ and $\rho = 0$, is shown in figure 4. The magnetic field enhances chiral symmetry breaking in a effect known as magnetic catalysis.

Conclusions

We have discussed the effects of a strong magnetic field in the chiral transition using an effective model for QCD, the two flavor Nambu-Jona-Lasinio model. We found that the transition is of first order at low temperature and high chemical potential and a crossover at high temperature and low chemical potential, as in the case with null magnetic field, although the critical end point is shifted as $B$ increases. We also found that the crossover pseudo-temperature at $\rho = 0$ always increases with $B$. This is in contrast with recent QCD-lattice calculations, that suggest that the crossover pseudo-temperature may actually decrease with $B$. However, based on the QCD asymptotic freedom, a very recent investigation [6] has considered the possibility that the NJL coupling runs with $B$, in this case the pseudo-critical temperature decreases with $B$ like in the lattice case. The coexistence diagram in the $T - \rho_{\mu}$ plane show [5] that for low $T$ the coexistence lines in the higher density branch for $B > 0$ oscillates around the $B = 0$ line which is due to the filling of the Landau levels as discussed in Ref. [5].

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References