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 by 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 recently years it has been argued that electrically charged spectators, present in non-central heavy ion collisions, are responsible for creating a strong magnetic field (about $10^{19} G$) 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 (b) as shown in Fig. 1. If such a strong field lasts enough time, it is expect to influence some aspects of the QCD phase transition, such as the location of the critical point. Estimations of the duration of the field in the collision are shown in Fig. 2 considering as background the vacuum (blue line) and a electric conducting medium (representing a more realistic description) characterized by electric conductivity $\sigma = 5.8\,\mathrm{MeV}$ (red line) and $\sigma = 16\,\mathrm{MeV}$ (brown line)[1]. We can see that the relaxation time of the magnetic field is considerably longer in the conducting medium.

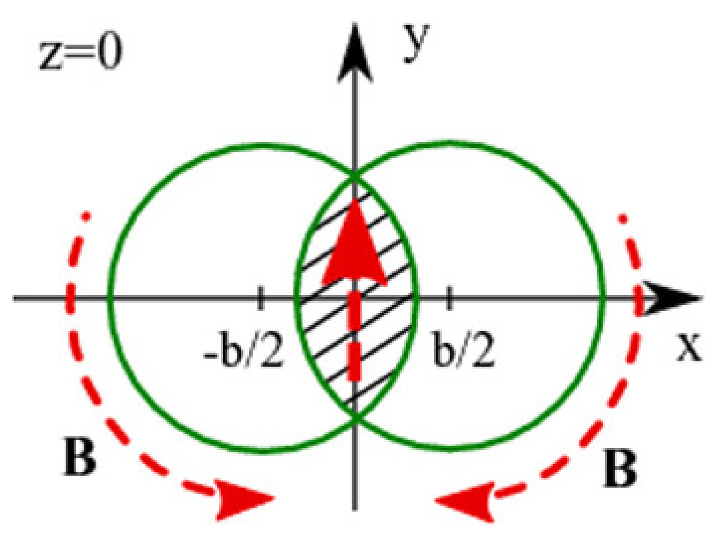

Figure 1: A strong magnetic field can arise in a non-central heavy ion collision.

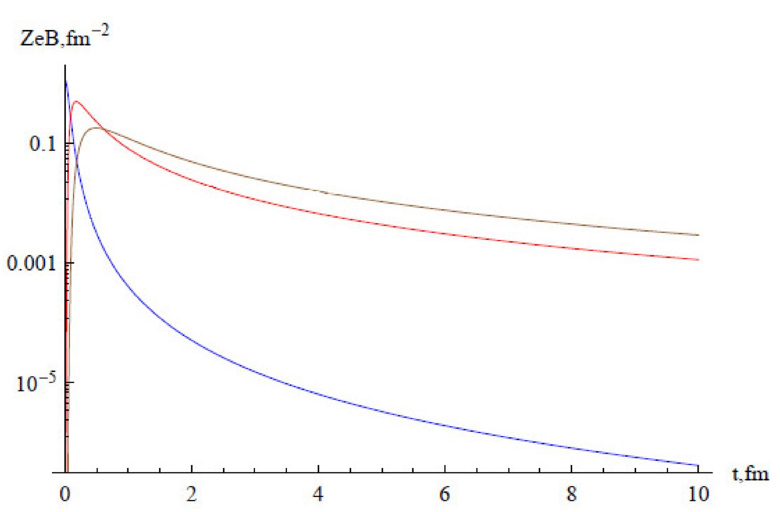

Figure 2: Magnetic field as a function of the proper time in vacuum (blue line) and in a conducting medium (red and brown lines) for $Au-Au$ collision with $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$. Adapted from Ref. [1].

Other components of the electromagnetic field (including electric field components) may appear in single events as shown in Fig. 3 but, on average, the only non-vanishing component of the field is B_y [2].

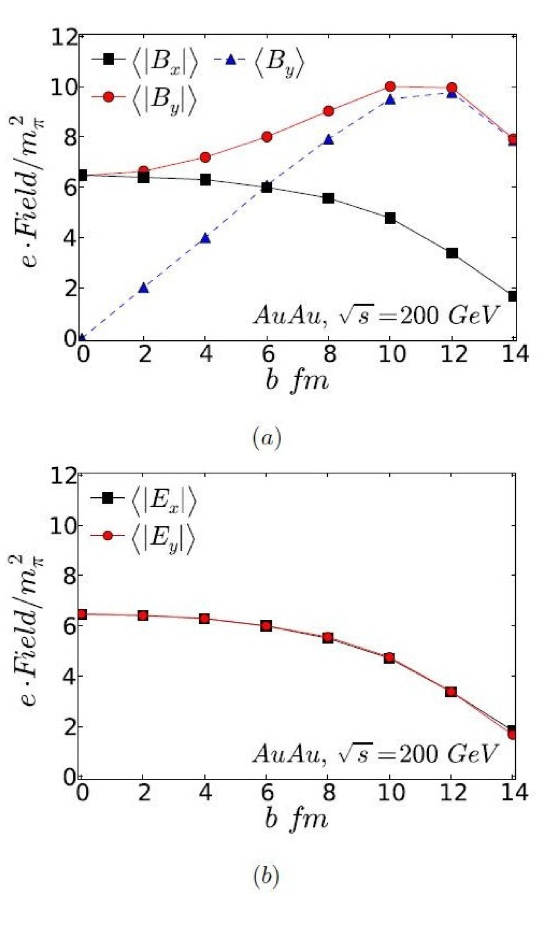

Figure 3: Components of the electromagnetic field as a function of the impact parameter.

Magnetized Quark Matter

We use de Nambu-Jona-Lasinio model [3] 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

$$\mathcal{L} = \bar{\psi}\left(i\,\partial\!\!\!/ - q\gamma_\mu A^\mu - m\right)\psi + G\left[(\bar{\psi}\psi)^2 + (\bar{\psi}i\gamma_5\vec{\tau}\psi)^2\right] - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}\,, \quad (1)$$

where ψ represents the fermion field, q 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 $\vec{\tau}$ 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]:

$$\mathcal{F} = \frac{(M-m)^2}{4G} + \mathcal{F}_{vac} + \mathcal{F}_{mag} + \mathcal{F}_{med} \quad (2)$$

where

$$\mathcal{F}_{vac} = -2N_c N_f \int \frac{d^3p}{(2\pi)^3} E_p \quad (3)$$

$$\mathcal{F}_{mag} = -\sum_{f=u}^{d} \frac{N_c(|q_f|B)^2}{2\pi^2}\left\{\zeta'[-1, x_f] - \frac{1}{2}[x_f^2 - x_f]\ln(x_f) + \frac{x_f^2}{4}\right\} \quad (4)$$

$$\mathcal{F}_{med} = -\frac{N_c}{2\pi}\sum_{f=u}^{d}\sum_{k=0}^{\infty}\alpha_k(|q_f|B)\int_{-\infty}^{\infty}\frac{dp_z}{2\pi}\left\{T\ln[1+e^{-[E_{p,k}(B)+\mu]/T}] + T\ln[1+e^{-[E_{p,k}(B)-\mu]/T}]\right\} \quad (5)$$

are the vacuum, magnetic and medium contributions, respectively. We use k to represent the Landau levels and $\alpha_k = 2-\delta_{0k}$ takes into account the degeneracy of the non-zero levels. In eq (3) $N_c = 3$ and $N_f = 2$ are the color and flavor degrees of freedom, respectively, and the integral is carried out up to $\Lambda = 590\mathrm{MeV}$ (the cutoff).

In eq (4) $x_f = M^2/(2|q_f|B)$ and $\zeta'[-1, x_f] = d\zeta(z, x_f)/dz|_{z=-1}$ with $\zeta(z, x_f)$ being the Riemann-Hurwitz function. We also fix the coupling constant as $G = 2.44/\Lambda^2$. Finally, in eq (5) we have $E_{p,k}(B) = \sqrt{p_z^2 + 2k|q_f|B + M^2}$. Equations (2)-(5) allow us to study the chiral transition in quark matter at finite T and μ under the influence of an external magnetic field B.

Results

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

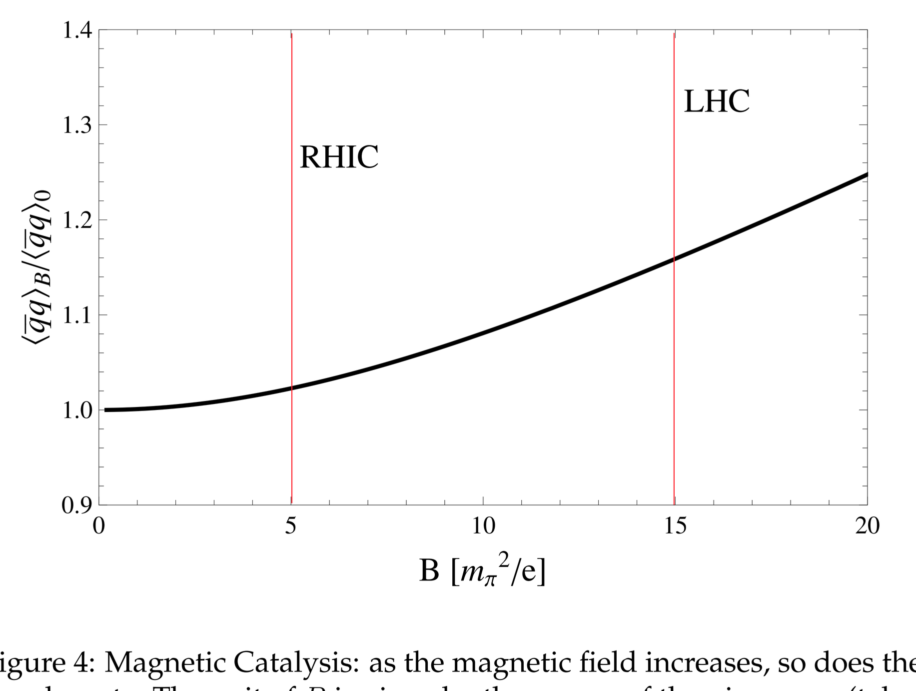

Figure 4: Magnetic Catalysis: as the magnetic field increases, so does the quark condensate. The unit of B is given by the square of the pion mass (taken to be $140.2\mathrm{MeV}$) divided by the elementary charge e ($1/\sqrt{137}$).

The restoration of chiral symmetry takes place at finite temperature and/or chemical potential. The phase diagram is shown in figure 5, where we have plotted the first order phase transition lines and the pseudo-temperature crossover lines for different values of the magnetic field. We observe that the critical point (the point where the first order phase transition line ends) is shifted depending on the value of B and that the crossover pseudo-temperature at $\mu = 0$ always increases with B. Recently QCD lattice results suggests that this may not be the case, leaving the question of whether the magnetic field increases or not the crossover pseudo-temperature open. Recent studies show that one may conciliate the model results with the lattice predictions by imposing that the NJL coupling, G, runs with B and T so as to mimic asymptotic freedom. When this is done the thermal susceptibility, $-d\langle\bar{\psi}\psi\rangle/dT$ shows that the pseudo critical temperature *decreases* with B in agreement with the latest lattice predictions.

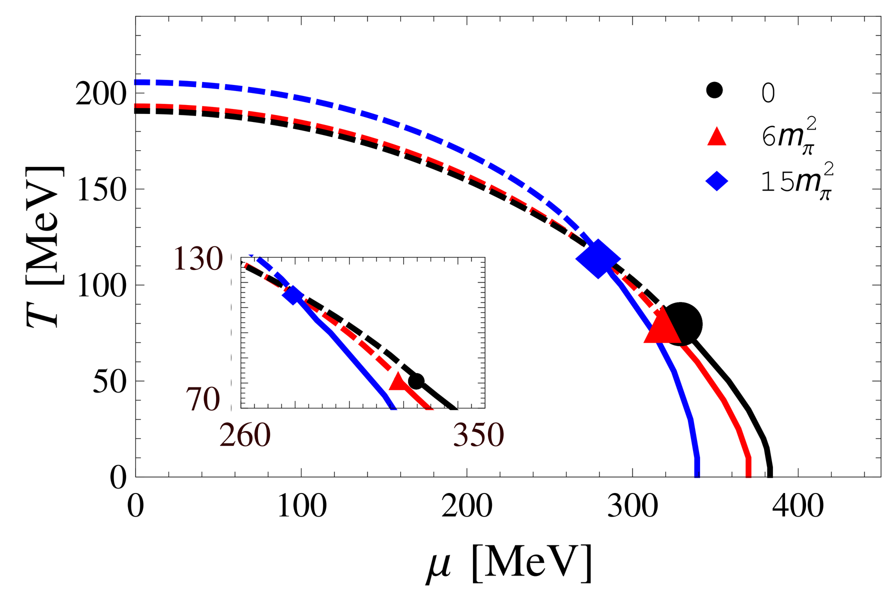

Figure 5: The NJL Phase Diagram.

All of the relevant thermodynamical quantities can be readily obtained by recalling that the free energy, evaluated at the mass value which satisfies the gap equation, gives the negative of the pressure, $\mathcal{F}(M) = -P$. Then, the net quark number density is obtained from $\rho = dP/d\mu$, and the entropy density from $s = dP/dT$ while the energy density is $\varepsilon = -P + Ts + \mu\rho$.

An interesting feature arises when we look at the coexistence diagram in the $T - \rho_B$ plane. For low temperature we see that the higher value of ρ_B for $B \neq 0$ oscillates around the $B = 0$ line which is due to the filling of the Landau levels as discussed in Ref. [5].

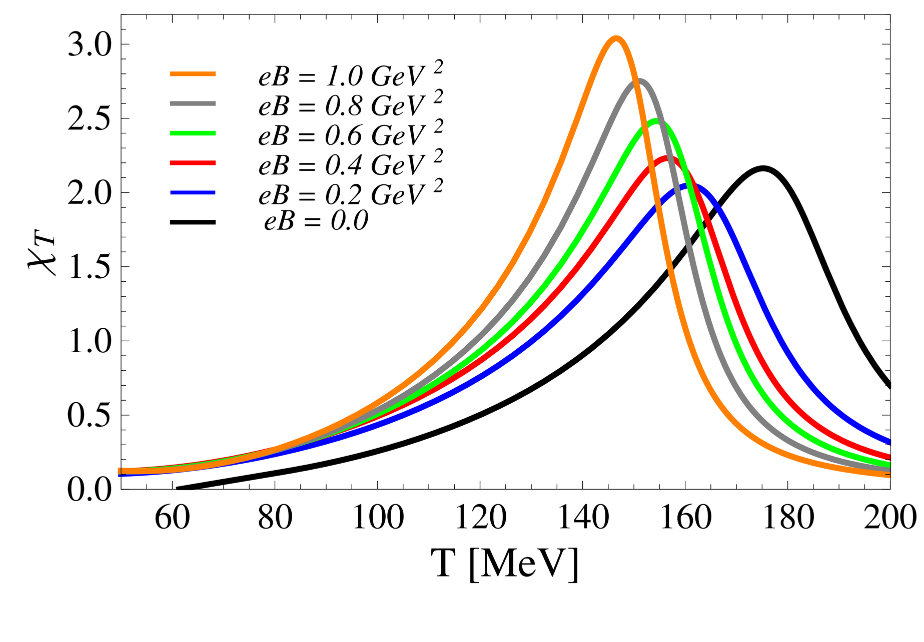

Figure 6: Thermal susceptibility at $\mu = 0$ obatined with a B dependent coupling.

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 $\mu = 0$ always increases with B. This is in contrast with recently 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 $T - \rho_B$ plane show [5] that for low T the coexistence lines in the higher density branch for $B \neq 0$ oscillates around the $B = 0$ curve. This is explained in terms of the filling in the Landau levels at different B.

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