Magnetized QCD phase diagram: net-baryon susceptibilities

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Employing the Polyakov extended Nambu–Jona-Lasinio model, we determine the net-baryon number fluctuations of magnetized three-flavor quark matter. We show that the magnetic field changes the nature of the strange quark transition from crossover to first-order at low temperatures. In fact, the strange quark undergoes multiple first-order phase transitions and several critical end points emerge in the phase diagram.

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1. Introduction

The existence of a chiral critical end point (CEP) in the QCD phase diagram is still an open question. Its possible existence and location are important goals of the heavy ion collision (HIC) programs. The effect of external magnetic fields on different regions of the phase diagram is very important, e.g., for heavy-ion collisions at very high energies, the early stages of the Universe and magnetized neutron stars.

The fluctuations of conserved quantities, such as baryon, electric, and strangeness charges number, play a major role in the experimental search for the CEP in HIC. Experimental measurements of cumulants of net-proton (proxy for net-baryon) are expected to carry information about the medium created by the collision [1]. The cumulants of the net-baryon number are particularly relevant as they diverge at the CEP [2]. We will study how cumulants of the net-baryon number are affected by the presence of magnetic fields with its consequences for the location of the CEP.

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2. Model

The Lagrangian density of the PNJL model in the presence of an external magnetic field reads

\[ \mathcal{L} = \bar{q} [i\gamma_\mu D^\mu - m_f] q + G_s \sum_{a=0}^{8} \left[ (\bar{q} \lambda_a q)^2 + (\bar{q} i\gamma_5 \lambda_a q)^2 \right] - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} \]

\[- K \left\{ \text{det} [\bar{q}(1 + \gamma_5)q] + \text{det} [\bar{q}(1 - \gamma_5)q] \right\} + \mathcal{U}(\Phi, \overline{\Phi}; T). \]

The quark field \( q = (u, d, s)^T \) is the three flavor quark field with corresponding (current) mass matrix \( \hat{m}_f = \text{diag}(m_u, m_d, m_s) \). The (electro)magnetic tensor is given by \( F_{\mu\nu} = \partial_\mu A^\mu_{EM} - \partial_\nu A^\mu_{EM} \), and the covariant derivative \( D^\mu = \partial^\mu - iq_f A^\mu_{EM} \) couples the quarks to both the magnetic field \( B \), via \( A^\mu_{EM} \), and to the effective gluon field, via \( A^\mu(x) = g A^\mu_a(x) \frac{\lambda_a}{2} \), where \( \mathcal{A}_a^\mu \) is the SUc(3) gauge field and \( q_f \) is the quark electric charge \( q_d = q_s = -q_u/2 = -e/3 \). A static and constant magnetic field in the \( z \) direction is considered, \( A^\mu_{EM} = \delta_{\mu2} x_1 B \). The logarithmic effective potential \( \mathcal{U}(\Phi, \overline{\Phi}; T) \) is used, fitted to reproduce lattice calculations \( (T_0 = 210 \text{ MeV}) \). The divergent ultraviolet sea quark integrals are regularized by a sharp cutoff \( \Lambda \) in three-momentum space.

The model parameters used are: \( \Lambda = 602.3 \text{ MeV}, m_u = m_d = 5.5 \text{ MeV}, m_s = 140.7 \text{ MeV}, G_s^0 \Lambda^2 = 1.835, \text{ and } KA^5 = 12.36 \) [4]. Besides, two model variants with distinct scalar interaction coupling are analyzed: a constant coupling, \( G_s = G_s^0 \), and a magnetic field dependent coupling \( G_s = G_s(eB) \) [3, 6]. The magnetic field coupling dependence, \( G_s = G_s(eB) \), reproduces the decrease of the chiral pseudo-critical temperature as a function of \( B \) obtained in LQCD calculations [7].

Fluctuations of conserved charges, such as the net-baryon number, provide important information on the effective degrees of freedom and on critical phenomena. The \( n \)th-order net-baryon susceptibility is given by

\[ \chi_B^n(T, \mu_B) = \frac{\partial^n (P(T, \mu_B)/T^4)}{\partial(\mu_B/T)^n}. \]  

(1)

Symmetric quark matter is considered \( \mu_u = \mu_d = \mu_s = \mu_q = \mu_B/3 \) in the present work.

3. Results

The quark condensates \( \langle q\overline{q}(T, \mu_B)/\langle|q\overline{q}|(0, 0) \) in the absence of an external magnetic field are shown in Fig. [1]. While the chiral condensate (left panel) shows a crossover transition at high temperatures \( (T > T_{\text{CEP}}) \), it undergoes a first-order phase transition at lower temperatures \( (T < T_{\text{CEP}}) \). The
first-order phase transition boundary ends up in a CEP (dot) at \((T_{\text{CEP}} = 133 \text{ MeV}, \mu_{\text{CEP}} = 862 \text{ MeV})\). Despite the strange quark condensate being discontinuous at the first-order chiral phase transition, its value suffers only a slight change and is still high (far from being approximately restored). The decrease of the strange quark condensate, and thus the approximately restored phase, is attained through a crossover transition. Nevertheless, an

![Fig. 1. The (vacuum normalized) light-quark (left panel) and strange-quark (right panel) condensates \(\langle q\bar{q}(T,\mu_B) \rangle / \langle q\bar{q}(0,0) \rangle\). The chiral first-order phase transition (solid line), the CEP (black dot), and both the chiral (dashed line) and deconfinement (dotted line) crossover boundaries are shown.](image1)

![Fig. 2. The \(\chi^3_B\) (left panel) and \(\chi^4_B\) (right panel) net-baryon number susceptibilities. The chiral first-order phase transition (solid line), the CEP (black dot), and both the chiral (dashed line) and deconfinement (dotted line) crossover boundaries are shown.](image2)
Fig. 3. The (vacuum normalized) strange-quark condensate (top panel), the $\chi_3^B$ (middle panel) and $\chi_4^B$ (bottom panel) net-baryon number susceptibilities for $G_s(eB)$ (left) and $G_0^s$ (right) models at $eB = 0.3\text{ GeV}^2$. The chiral first-order phase transition (solid line), the CEP (black dot), and both the chiral (dashed line) and deconfinement (dotted line) crossover boundaries are shown.

An interesting feature is seen when we look at the $\chi_3^B$ and $\chi_4^B$ net-baryon number susceptibilities in Fig. 2. Just as the non-monotonic dependence of the susceptibilities near the CEP, which signals critical phenomena, a similar structure is seen at low $T$ and $\mu_B \approx 1500\text{ MeV}$. This indicates that a slight change on the model parametrization (e.g., a stronger scalar coupling)
might induce a first-order phase transition for the strange quark. A strong external magnetic field has exactly this effect [9]. The strange quark condensate and the net-baryon number susceptibilities for both $G_s(eB)$ (right panel) and $G_0^s$ (left panel) models at $eB = 0.3 \text{ GeV}^2$ are in Fig. 3. We see that both models predict a first-order phase transition for the strange quark and the existence of a CEP related with the strange quark sector. Depending on the magnetic field strength, multiple phase transitions occur for both light and strange quarks [10][11]. The behavior of $\chi^3_B$ and $\chi^4_B$ shows the emergence of several CEPs through the characteristic non-monotonic dependence, which signals the presence of critical behavior.

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