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

$$\mathcal{L} = \bar{q}\left[i\gamma_\mu D^\mu - \hat{m}_f\right]q + G_\mathrm{s}\sum_{a=0}^{8}\left[(\bar{q}\lambda_a q)^2 + (\bar{q}i\gamma_5\lambda_a q)^2\right] - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$
$$-K\left\{\det\left[\bar{q}(1+\gamma_5)q\right] + \det\left[\bar{q}(1-\gamma_5)q\right]\right\} + \mathcal{U}\left(\Phi,\bar{\Phi};T\right) .$$

The $q=(u,d,s)^T$ is the three flavor quark field with corresponding (current) mass matrix $\hat{m}_f = \mathrm{diag}_f(m_u, m_d, m_s)$. The (electro)magnetic tensor is given by $F_{\mu\nu} = \partial_\mu A_\nu^\mathrm{EM} - \partial_\nu A_\mu^\mathrm{EM}$, and the covariant derivative $D^\mu = \partial^\mu - iq_f A^\mu_\mathrm{EM} - iA^\mu$ couples the quarks to both the magnetic field B via A^μ_EM, and to the effective gluon field via $A^\mu(x) = g\mathcal{A}^\mu_a(x)\frac{\lambda_a}{2}$, where $\mathcal{A}^\mu_a$ is the $\mathrm{SU_c}(3)$ 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, $A_\mu^\mathrm{EM} = \delta_{\mu 2}x_1 B$. The logarithmic effective potential $\mathcal{U}\left(\Phi,\bar{\Phi};T\right)$ [3] is used, fitted to reproduce lattice calculations ($T_0 = 210$ MeV). The divergent ultraviolet sea quark integrals are regularized by a sharp cutoff Λ in three-momentum space.

The used model parameters are: $\Lambda = 602.3$ MeV, $m_u = m_d = 5.5$ MeV, $m_s = 140.7$ MeV, $G_\mathrm{s}^0\Lambda^2 = 1.835$, and $K\Lambda^5 = 12.36$ [4]. Besides, two model variants with distinct scalar interaction coupling are analyzed: a constant coupling, $G_\mathrm{s} = G_\mathrm{s}^0$, and a magnetic field-dependent coupling $G_\mathrm{s} = G_\mathrm{s}(eB)$ [5, 6]. The magnetic field coupling dependence, $G_\mathrm{s} = G_\mathrm{s}(eB)$, 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

$$\chi_B^n(T,\mu_B) = \frac{\partial^n\left(P(T,\mu_B)/T^4\right)}{\partial(\mu_B/T)^n} . \tag{1}$$

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 $\langle q\bar{q}\rangle(T,\mu_B)/\langle q\bar{q}\rangle(0,0)$ 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 ($T > T^\mathrm{CEP}$), it undergoes a first-order phase transition at lower temperatures ($T < T^\mathrm{CEP}$).

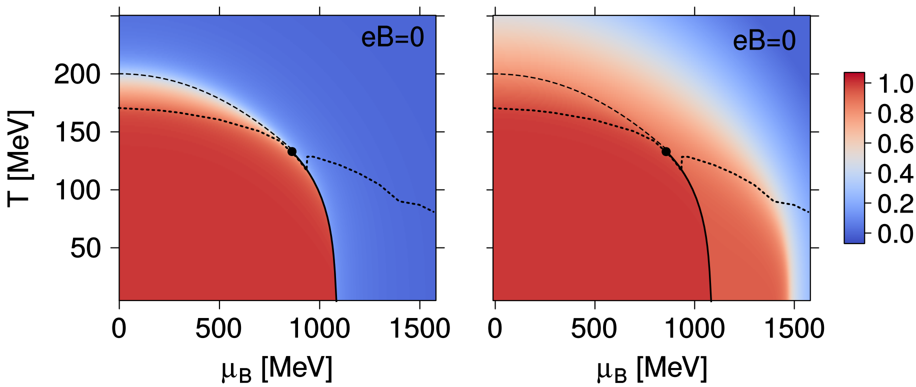

Fig. 1. The (vacuum normalized) light-quark (left panel) and strange-quark (right panel) condensates $\langle q\bar{q}\rangle(T,\mu_B)/\langle q\bar{q}\rangle(0,0)$. The chiral first-order phase transition (solid line), the CEP (black dot), and both the chiral (dashed line) and deconfinement (dotted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

The first-order phase transition boundary ends up in a CEP (dot) at $(T^{\rm CEP} = 133\,\text{MeV},\ \mu_B^{\rm CEP} = 862\,\text{MeV})$. 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 interesting feature is seen when we look at the χ_B^3 and χ_B^4 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 $\mu_B \approx 1500$ MeV [8]. This indicates that a slight change on the model parametrization (*e.g.*, a stronger scalar coupling)

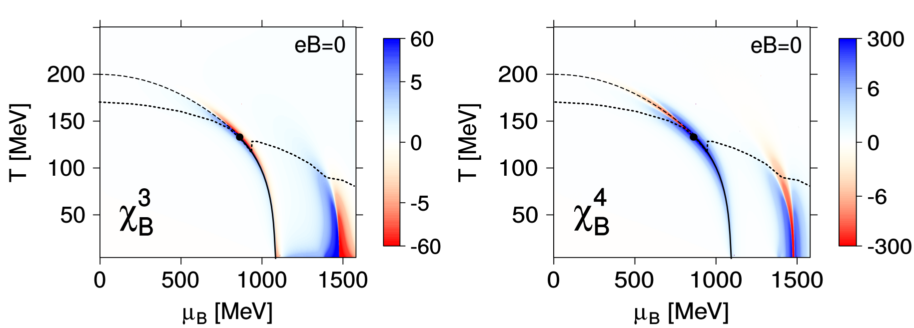

Fig. 2. The χ_B^3 (left panel) and χ_B^4 (right panel) net-baryon number susceptibilities. The chiral first-order phase transition (solid line), the CEP (black dot), and both the chiral (dashed line) and deconfinement (dotted line) crossover boundaries are shown.

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_s^0 (left panel) models at $eB = 0.3$ GeV^2 are shown 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 χ_B^3 and χ_B^4 shows the emergence of several CEPs through the characteristic non-monotonic dependence, which signals the presence of critical behavior.

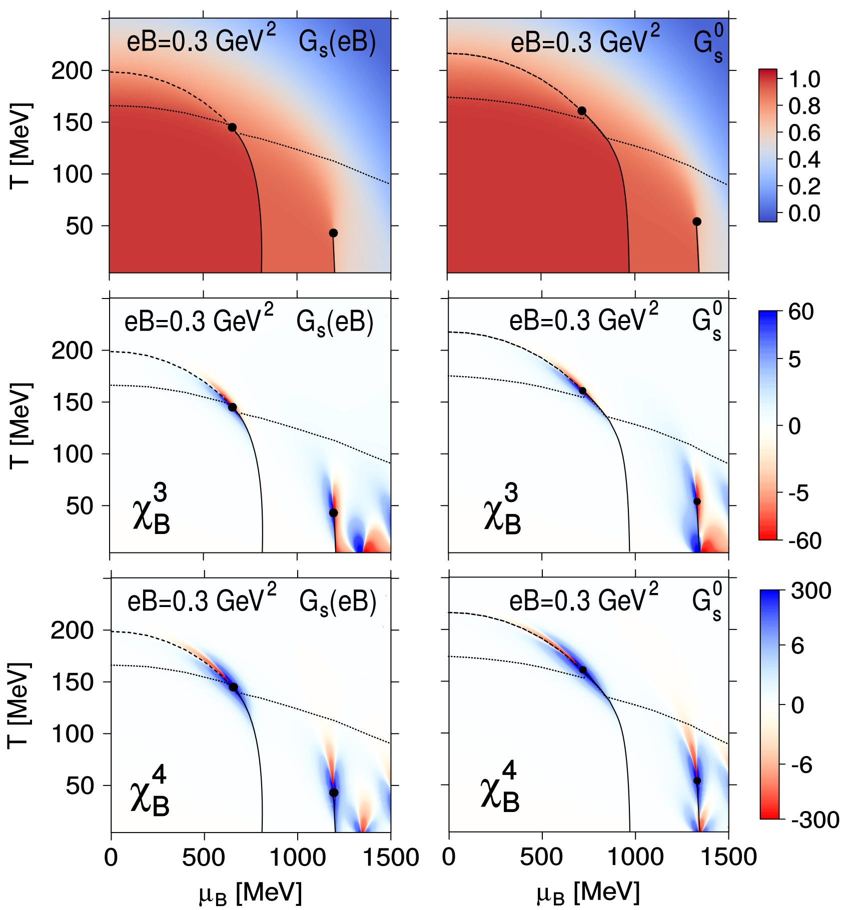

Fig. 3. The (vacuum normalized) strange-quark condensate (top panel), the χ_B^3 (middle panel) and χ_B^4 (bottom panel) net-baryon number susceptibilities for $G_s(eB)$ (left) and G_s^0 (right) models at $eB = 0.3$ GeV^2. The chiral first-order phase transition (solid line), the CEP (black dot), and both the chiral (dashed line) and deconfinement (dotted line) crossover boundaries are shown.

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