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The effective QCD phase diagram and the critical end point

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Abstract

We study the QCD phase diagram on the temperature T and quark chemical potential μ plane, modeling the strong interactions with the linear sigma model coupled to quarks. The phase transition line is found from the effective potential at finite T and μ taking into account the plasma screening effects. We find the location of the critical end point (CEP) to be $(\mu^{\mathrm{CEP}}/T_c, T^{\mathrm{CEP}}/T_c) \sim (1.2, 0.8)$, where T_c is the (pseudo)critical temperature for the crossover phase transition at vanishing μ. This location lies within the region found by lattice inspired calculations. The results show that in the linear sigma model, the CEP's location in the phase diagram is expectedly determined solely through chiral symmetry breaking. The same is likely to be true for all other models which do not exhibit confinement, provided the proper treatment of the plasma infrared properties for the description of chiral symmetry restoration is implemented. Similarly, we also expect these corrections to be substantially relevant in the QCD phase diagram.

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The different phases in which matter, made up of quarks and gluons, arranges itself depends, as for any other substance, on the temperature and density, or equivalently, on the temperature and chemical potentials. Under the assumptions of beta decay equilibrium and charge neutrality, the representation of the QCD phase diagram is two dimensional. This is customary plotted with the light-quark chemical potential μ as the horizontal variable and the temperature T as the vertical one. μ is related to the baryon chemical potential μ_B by $\mu_B = 3\mu$.

Most of our knowledge of the phase diagram is restricted to the $\mu = 0$ axis. The phase diagram is, by and large, unknown. For physical quark masses and $\mu = 0$, lattice calculations have shown [1] that the change from the low temperature phase, where the degrees of freedom are hadrons, to the high temperature phase described by quarks and gluons is an analytic crossover. The phase transition has a dual nature: on the one hand, the color-singlet hadrons break up leading to deconfined quarks and gluons; this is dubbed as the *deconfinement phase transition*. On the other hand, the dynamically generated component of quark masses within hadrons vanishes; this is referred to as *chiral symmetry restoration*.

Lattice calculations have provided values for the crossover (pseudo)critical temperature T_c for $\mu = 0$ and $2 + 1$ quark flavors using different types of improved rooted staggered fermions [2]. The MILC Collaboration [3] obtained $T_c = 169(12)(4)$ MeV. The RBC-Bielefeld Collaboration [4] reported $T_c = 192(7)(4)$ MeV. The Wuppertal-Budapest Collaboration [5] has consistently obtained smaller values, the latest being $T_c = 147(2)(3)$ MeV. The HotQCD Collaboration has computed $T_c = 154(9)$ MeV [6] and more recently $T_c = 155(1)(8)$ MeV [7]. The differences could perhaps be attributed to different lattice spacings.

The picture presented by lattice QCD for $T \geq 0$, $\mu = 0$ cannot be easily extended to the case $\mu \neq 0$, the reason being that standard Monte Carlo simulations can only be applied to the case where either $\mu = 0$ or it is purely imaginary. Simulations with $\mu \neq 0$ are hindered by the *sign problem*, see, for example, [8], though some mathematical extensions of lattice techniques [9] can probe this region. Schwinger–Dyson equation techniques can also be employed to explore all region of the phase space [10].

On the other hand, a number of different model approaches indicate that the transition along the μ axis, at $T = 0$, is strongly first order [11]. Since the first-order line originating at $T = 0$ cannot end at the $\mu = 0$ axis which corresponds to the starting point of the cross-over line, it must terminate somewhere in the middle of the phase diagram. This point is generally referred to as the critical end point (CEP). The location and observation of the CEP continue to be at the center of efforts to understand the properties of strongly interacting matter under extreme conditions. The mathematical extensions of lattice techniques place the CEP in the region $(\mu^{\text{CEP}}/T_c, T^{\text{CEP}}/T_c) \sim (1.0\text{–}1.4, 0.9\text{–}0.95)$ [12].

In the first reference of [10], it is argued that the theoretical location of the CEP depends on the size of the confining length scale used to describe strongly interacting matter at finite density/temperature. This argument is supported by the observation that the models which do not account for this scale [13–16] produce either a CEP closer to the μ axis (μ^{CEP}/T_c and T^{CEP}/T_c larger and smaller, respectively) or a lower T_c [17] than the lattice based approaches or the ones which consider a finite confining length scale. Given the dual nature of the QCD phase transition, it is interesting to explore whether there are other features in models which have access only to the chiral symmetry restoration facet of QCD that, when properly accounted for, produce the CEP's location more in line with lattice inspired results.

An important clue is provided by the behavior of the critical temperature as a function of an applied magnetic field. Lattice calculations have found that this temperature decreases when the field strength increases [18–20]. It has been recently shown that this phenomenon, dubbed *in-*