Phase transition in $\beta-$equilibrated Strange quark matter

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Introduction

A complete understanding of QCD phase diagram has been severe subject of theoretical and experimental research in the last decades. One of the main reason is the precise location of the critical end point (CEP) at which chiral transition change its behavior [1]. In the QCD phase diagram, there are abundant phases present at finite chemical potential, μ and temperature, T, that is, the transition from chiral symmetry breaking to symmetry restoration phase, the deconfinement of hadron to quark gluon plasma/quark matter, and the color superconductivity at low T and high μ. Such phases may have existed in early universe or may have created in heavy ion collision experiment. Strange quark matter (SQM) consists of roughly equal numbers of u, d and s quarks, which may be the ground state of strongly interacting matter. The conversion of a neutron star into a quark star occurs through two processes: the first process deals with deconfinement of nuclear matter to quark matter; in second process the $d-$quark is converted into $s-$quark, and thus a $\beta-$equilibrated charge neutral SQM is formed. In present study, we use Polyakov chiral SU(3) quark mean field (PCQMF) model to explore the phase diagram of SQM with $\beta-$equilibrium [2]. The phase diagram of SQM and location of CEP are also studied in the NJL model and Polyakov NJL model [3]. The present study will provide us with a better insight to understand the strongly interacting matter.

Methodology

By applying mean field approximation, the thermodynamical potential density of SQM in the PCQMF model temperature can be elucidated as

$$\Omega = \mathcal{U}(\Phi, \bar{\Phi}, T) + \Omega_{q\bar{q}} - \mathcal{L}_M - \mathcal{V}_{vac}, \quad (1)$$

where $\Omega_{q\bar{q}}$ exemplifies the contribution of quarks and antiquarks to the total thermodynamical potential and is given by

$$\Omega_{q\bar{q}} = -\gamma_i k_B T \sum_{q,l} \int_0^\infty \frac{d^3k}{(2\pi)^3} \times \Big[\ln(1 + e^{-3(E_i^*(k)-\nu_i{}^*)/k_BT} + 3\Phi e^{-(E_i^*(k)-\nu_i{}^*)/k_BT} + 3\bar{\Phi} e^{-2(E_i^*(k)-\nu_i{}^*)/k_BT}) + \ln(1 + e^{-3(E_i^*(k)+\nu_i{}^*)/k_BT} + 3\bar{\Phi} e^{-(E_i^*(k)+\nu_i{}^*)/k_BT} + 3\Phi e^{-2(E_i^*(k)+\nu_i{}^*)/k_BT})\Big]. \quad (2)$$

In above equation, summation runs over constituent quarks and leptons. Moreover, the value of spin degeneracy factor, γ_i, is 2 for quarks while 1 for leptons and $E_i^*(k)$ is the effective single particle energy of quarks. In Eq. (1), the term $\mathcal{L}_M$ defines the meson interaction. Also, the vacuum energy term, $\mathcal{V}_{vac}$, is subtracted to attain zero vacuum energy.

The number (vector) density, ρ_i, and scalar density, ρ_i^s, of quarks is defined as

$$\rho_i = \gamma_i N_c \int \frac{d^3k}{(2\pi)^3} \Big(f_i(k) - \bar{f}_i(k)\Big), \quad (3)$$

$$\rho_i^s = \gamma_i N_c \int \frac{d^3k}{(2\pi)^3} \frac{m_i^*}{E_i^*(k)} \Big(f_i(k) + \bar{f}_i(k)\Big), \quad (4)$$

respectively, where $f_i(k)$ and $\bar{f}_i(k)$ represent the Fermi distribution functions at finite temperature for quarks and anti-quarks. Minimizing the thermodynamical potential density (Ω) of PCQMF model, coupled equations of motion of σ, ζ, δ, χ, ω, ρ, ϕ, Φ and $\bar{\Phi}$ are derived [2]. The $\beta-$equilibrium and charge neutrality condition of quarks and leptons define by these relations

$$\mu_d = \mu_s = \mu_u + \mu_e - \mu_{\nu_e} \quad \text{and} \quad \mu_\mu = \mu_e, \quad (5)$$

$$2\rho_u = \rho_d + \rho_s + 3(\rho_e + \rho_\mu). \quad (6)$$

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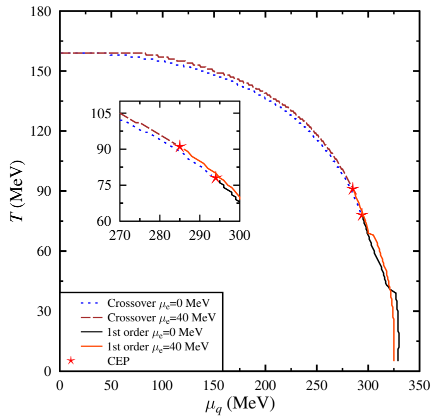

FIG. 1: (Color online) The phase diagram in the $T-\mu$ plane of strange quark matter with $\beta-$equilibrium using PCQMF model at different value of electron chemical potential (μ_e = 0, 40 MeV).

In order to calculate the value of critical temperature, we have defined the temperature derivatives of the chiral condensates: $\sigma'_x = \partial\sigma_x/\partial T$, and $\sigma'_y = \partial\sigma_y/\partial T$. Here, σ_x and σ_y denote the light quark condensate and strange condensate, respectively.

Results and Discussion

In this section, we have explored the phase diagram of strange quark matter with $\beta-$equilibrium condition from PCQMF model within a $T-\mu$ plane at different value of electron chemical potential. Various parameters used in the present work are listed in Ref.[2].

The phase diagram of strange quark matter with $\beta-$equilibrium using PCQMF model in $T-\mu$ plane is plotted in Fig.1 at $g_v = 0$ for $\mu_e = 0$ and 40 MeV. The phase boundary consists of crossover and first order transition which is separated by CEP. The crossover transition is plotted with maximum of $\partial\sigma_x/\partial T$ at given value of μ and first order phase transition is achieved by a maximum of $\partial\rho_i/\partial\mu$ at given T [4]. The presence of electron chemical potential increases the first order transition region and CEP is obtained at higher T and lower μ. For $\mu_e = 0$ and 40 MeV, the position of the CEP is approximately (T_E, μ_E)=(78 MeV, 294 MeV) and (91 MeV, 285 MeV). It is also observed that the phase diagram of $\beta-$equilibrated strange quark matter for μ_e = 0 MeV is identical to the phase diagram of strange quark matter without $\beta-$equilibrium [5]. This is due to the independency of thermodynamical potential at $\mu_e = 0$.

Summary

We have studied the phase diagram of strange quark matter with $\beta-$equilibrium condition for $\mu_e = 0$ and 40 MeV, and calculated the position of critical end point (CEP). With the increase in electron chemical potential the position of CEP move towards higher temperature and lower quark chemical potential. In the future, the observed data in HIC experiments will give valuable information on CEP, which can be compared with these results.

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