PROCEEDINGS OF SCIENCE

# Deconfinement phase transition in a thermodynamically consistent quark matter model

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Since an absolute stable strange quark matter (SQM) was conjectured, based on a simple model known as the MIT bag model, different versions of density dependent quark models were proposed, but they lack thermodynamic consistency. By using a thermodynamically consistent quark matter model called equiparticle model, based on a density dependent mass, the quark confinement/deconfinement transition is studied. In order to do that, the model is modified by the introduction of a dependence on the traced Polyakov loop at zero temperature. The thermodynamic potential is obtained and suggests that the model is now capable of describing confined and deconfined thermodynamic phases.

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## 1. Introduction

In order to understand the possible states of matter, the theory of strong interactions takes place, known as Quantum Chromodynamics (QCD). Different approaches such as Lattice QCD and effective models are commonly used to study these thermodynamic phases of matter. However, due to the difficult of solving QCD exactly for non-perturbative regimes, effective models become necessary. In this work, a modification is done in an effective model to describe the confinement/ deconfinement phase transition of quarks at zero temperature.

## 2. The Equiparticle Model

In the seventies, an absolute stable strange quark matter was conjectured by Bodmer [1] and Witten [2] where the absolute stable state of matter would be strange quark matter. Over time many effective models where proposed based on this hypotheses. Among them, there is the equiparticle model [3]. This model is based on the assumption that the quarks mass is density dependent. The model corrects the lack of thermodynamic consistency present in the QMDD models [4, 5].

To briefly describe the model, we consider a system of interacting quarks up, down and strange, where the interaction effect is included as a density dependent quantity in the quark masses, given by:

$$m_i = m_{i0} + \frac{D}{\rho_b^{1/3}} + C\rho_b^{1/3}, \tag{1}$$

where $m_{i0}$ ($i = u, d, s$) is the current mass of the $i$ quark, $C$ and $D$ are adjustable parameters and $\rho_b$ is the baryonic density. The parameters C and D must be chosen from a stability window [6]. Besides, to ensure the thermodynamic consistency we introduce the effective chemical potential as follows:

$$\mu_i = \mu_i^* + \frac{1}{3}\frac{\partial m_i}{\partial \rho_b}\frac{\partial \Omega_0}{\partial m_i}, \tag{2}$$

where $\mu_i$ is the true chemical potential for the i quark, $\mu_i*$ is the effective one and $\Omega_0$ is the free particle contribution. At zero temperature, we find the equations of state for the energy density and pressure:

$$\varepsilon = \Omega_0 - \sum_i \mu_i^* \frac{\partial \Omega_0}{\partial \mu_i^*}, \qquad \text{and} \qquad P = -\Omega_0 + \sum_{i,j} \frac{\partial \Omega_0}{\partial m_j}\rho_i \frac{\partial m_j}{\partial \rho_i}, \tag{3}$$

where $\rho_i$ is the quark i density. The free particle contribution needs to be evaluate for each case of interest. In our case we consider the unpaired SQM case that reads as:

$$\Omega_0 = -\sum_i \frac{g_i}{24\pi^2}\left[\mu_i^*\nu_i\left(\nu_i^2 - \frac{3}{2}m_i^2\right) + \frac{3}{2}m_i^4 \ln\frac{\mu_i^* + \nu_i}{m_i}\right]. \tag{4}$$

where $g_i$ is the degeneracy factor (for quarks = 6) and $\nu_i$ is the quark i Fermi momentum. Moreover, the thermodynamic potential is determined simply by $\Omega = -P$.

Concerning the thermodynamic consistency itself, the model needs to obey the Cauchy conditions and the condition where pressure must be zero at the minimum point of the energy density per baryon. They are, respectively, as follows

$$\Delta_i \equiv \left.\frac{dS}{d\rho_i}\right|_{T,\ \{\rho_{k\neq i}\}} - \left.\frac{d\mu_i}{dT}\right|_{T,\ \{\rho_k\}} = 0, \qquad \Delta_{ij} \equiv \left.\frac{d\mu_i}{d\rho_j}\right|_{T,\ \{\rho_{k\neq j}\}} - \left.\frac{d\mu_j}{d\rho_i}\right|_{T,\ \{\rho_{k\neq i}\}} = 0 \tag{5}$$

$$\text{and} \qquad \Delta = P - \rho_b^2 \frac{d}{d\rho_b}\left(\frac{\varepsilon}{\rho_b}\right)_T = 0. \tag{6}$$

## 3. The Polyakov Equiparticle Model

To be able to describe confinement/ deconfinement phase transition, a Polyakov loop [7–10] is introduced in the equiparticle model. The Polyakov loop is an effective field of gluonic origin ($\Phi$ and $\Phi^*$), that more practically, we insert as a Polyakov Potential ($U_0$) into pressure:

$$P = -U_0 - \Omega_0 + \sum_{i,j} \frac{\partial \Omega_0}{\partial m_j} \rho_i \frac{\partial m_j}{\partial \rho_i}. \tag{7}$$

The Polyakov potential has different known forms. The one used in this work is given by ($\Phi = \Phi^*$):

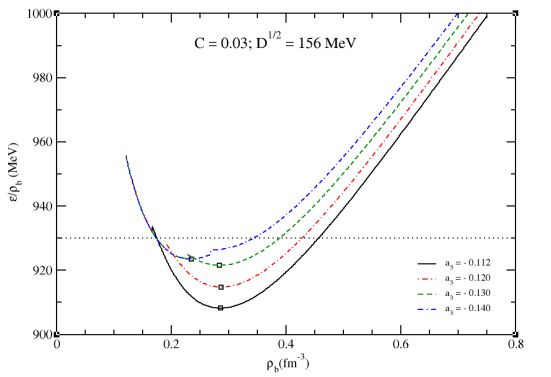
$$U_0(\Phi) = a_3 T_0^4 ln(1 - 6\Phi^2 + 8\Phi^3 - 3\Phi^4), \tag{8}$$

where $a_3$ is a dimensionless free parameter and $T_0 = 190$ MeV (a value very often used in literature).

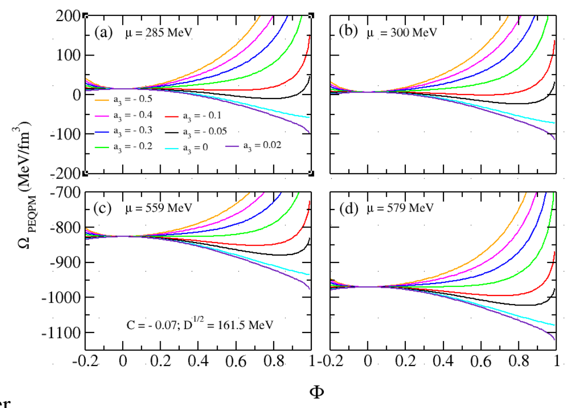
The deconfinement will occur when the Polyakov loop ($\Phi$) increases and approaches to 1. On the opposite direction, when it goes towards zero, the confinement is expected to happen. To make sure that is the case, the free parameters $C$ and $D$ are rewritten as dependent on $\Phi$ as follows, $C \longrightarrow C(1 - \Phi^2)$, and $D \longrightarrow D(1 - \Phi^2)$.

## 4. Results and Discussion

Regarding the thermodynamic consistency, we can see in Figure 1a that the minimum energy density per barion is less than 930 MeV (iron energy binding). At this point pressure is zero, as requested by the consistency criteria. These results make it clear that the model maintain its thermodynamic consistency after the modifications.




**(a)** Thermodynamical consistency for symmetric matter ($m_{u0} = 5$, $m_{d0} = 10$ and $m_{s0} = 100$ MeV).



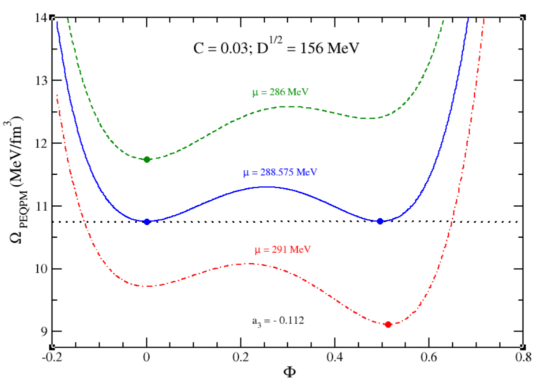

**(b)** Ω as function of Φ.

**Figure 1:** Panels 1a and 1b present the first results concerning the effects of the Polyakov loop in the model.

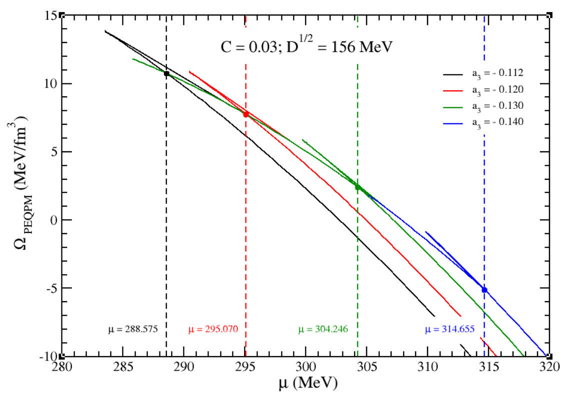
Following, the first result concerning the phase transition was obtained by plotting the thermodynamic potential as function of $\Phi$ as figure 1b shows. From a set of different pairs of $C$ and $D$ parameters, this one was chosen because it allows us to see that there is a local minimum for $\Phi = 0$ and a global minimum for $\Phi > 0$. This happens only for a few choices of $a_3$ and $\mu$ as the red and black curves show. It is important to address that in this symmetric case the quarks chemical potential is set to be equal ($\mu_u = \mu_d = \mu_s = \mu$).

Setting the parameters properly, it is possible to pick one curve to further examine the effects of $\Phi$ as figure 2a shows. The green curve indicates that the quarks are still confined as the original model predicts, since the global minimum is given at $\Phi = 0$. As the chemical potential slightly increases, there will be two different values of $\Phi$ for only one thermodynamic potential, meaning that a first order phase transition is happening. If we keep increasing the chemical potential, the global minimum in the red curve shows that quarks are now deconfined.

To find the two minimums, a different algorithm is written where the baryonic density is the input. As result, figure 2b presents $\Omega$ as function of $\mu$, where the highlighted point in each curve indicates the exactly chemical potential where the phase transition happens.




**(a)** Ω as function of Φ.




**(b)** Ω as function of $\mu$.

**Figure 2:** Analysis done concerning the thermodynamic potential.

## 5. Conclusions

In the present work, a modification was done, by introducing the Polyakov loop, to a thermodynamically consistent density dependent quark mass model in order to achieve the confinement/deconfinement phase transition. The results showed that this was successfully done for symmetric matter when the parameters involved were properly adjusted. The inclusion of electrons is in progress, so the model will be able to study the effects of the Polyakov loop in stellar matter.

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