# Thermodynamics of hot quark matter in quasi-particle model

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## Introduction

The equation of state for dense matter in neutron stars is of current interest, as quark matter may exist in their cores. First-principles methods struggle due to the sign problem in lattice Monte Carlo simulations and because of the limitation of perturbative QCD. Various advanced models aim to account for nonperturbative effects. In recent studies, researchers have extensively employed phenomenological quark models like the MIT model and quark mass model or quasi-particle model to investigate the thermodynamic properties of strange quark matter, quark stars. In Ref. [1], the authors examined the MIT bag model and found that incorporating medium effects via density-dependent bag pressure in the grand canonical ensemble violates the Euler relation. Using the Euler relation results in the minimum energy per baryon occurring at non-zero pressure. To resolve this issue, they proposed modeling the medium effects of strange quark matter using chemical potential-dependent bag pressure in the grand canonical ensemble. In this work, we study the quasi-particle model at finite temperature where medium effect ia taken through chemical potential-dependent mass. In the case of the finite temperature equation of state, we have considered the isothermal process, where the temperature remains constant and from the thermodynamics, the minimum of $\frac{f}{\rho}$ should occur at zero pressure. Our main aim in this work is to provide a self-consistent thermodynamic treatment in the quasi-particle model for the description of the quark matter in the context of the quark star.

## Formalism

In the dense system, quarks interact with each other to create an effective mass, causing them to behave as quasiparticles. In the hard dense loop approximation, an effective quark propagator is obtained by resumming one-loop self-energy diagrams, which is used to determine the zero-momentum limit of the dispersion relations, leading to the effective quark masses as given by [2]

$$m_i^* = \frac{m_{i0}}{2} + \sqrt{\frac{m_{i0}^2}{4} + \frac{g_i^2}{6\pi^2}\mu_i^2} \tag{1}$$

where $g_i$ is taken as

$$g_i = g_0 e^{-\alpha_\mu \frac{\mu_i}{\mu_0}} \tag{2}$$

Here $\alpha_\mu$ is the parameter determining the $\mu$ dependent effective running coupling constant and the value of $\alpha_\mu$ should be greater than zero for the restoration of the chiral symmetry. The model parameters are $g_0$,$\alpha_\mu$ and $B_0$. The thermodynamic potential can be then written as,

$$\Omega_{quasi} = -\sum_{f=u,d,s,} \frac{1}{3}\frac{\gamma_i}{2\pi^2}\int_0^\infty \frac{k^4}{\sqrt{k^2+(m_f^*)^2}}[f_i^+ + f_i^-]dk + \frac{1}{3}\frac{\gamma_l}{2\pi^2}\sum_{l=e,\nu_e}\int_0^\infty \frac{k^4}{\sqrt{k^2+m_l^2}}[f_l^+ + f_l^-] + B_0 \tag{3}$$

The Fermi distribution functions for particles and antiparticles are : $f_i^\pm = \frac{1}{1+exp\left(\frac{E_i(k)\mp\mu_i}{T}\right)}$ , where $E_i(k) = \sqrt{k^2+(m_i^*)^2}$.

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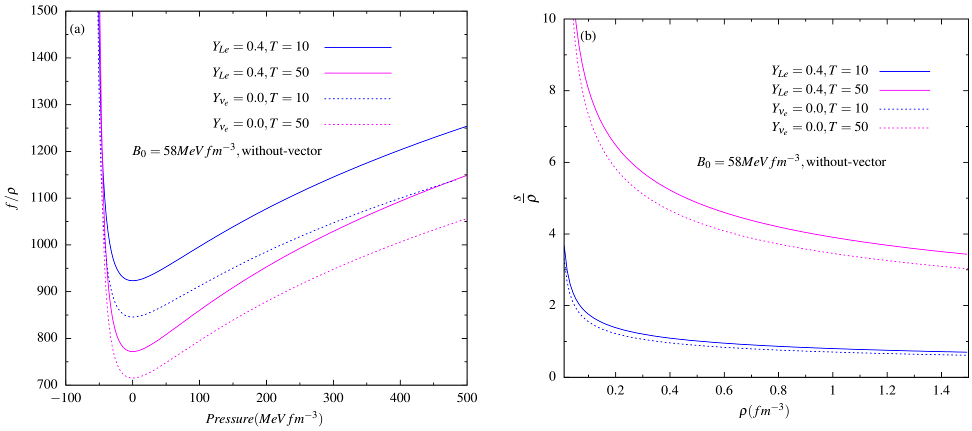


FIG. 1: Plots for (a)free energy density vs. pressure and (b) entropy density for temperatures $T =$ 10 and 50 MeV , and the lepton fraction of $Y_{Le} = 0.4$ and $Y_{L_{\nu_e}} = 0.0$. The model parameters are $g_0 = 1.0$, $\alpha_\mu = 20.0$, and $B_0 = 58$ MeV fm$^{-3}$.

## Results

In our investigation of quark matter within quark stars, at finite temperature, when the neutrinos are trapped in the system, the chemical equilibrium condition is modified as $\mu_d = \mu_u + \mu_e - \mu_{\nu_e} = \mu_s$. Because of the neutrino trapping, the number of leptons per baryon of each flavor neutrino is conserved on a dynamical timescale : $Y_{Le} = Y_e + Y_{\nu_e}$. The description of the proto quark star in the isothermal process is determined for a given density with different temperatures and lepton fractions. In this description, the entropy density per baryon density ($\sigma$) is varied with the baryon density. As we have mentioned earlier in the introduction section, In Fig. 1, we examine the thermodynamic properties of strange quark matter within the framework of the proto-quark star. The model parameters are determined based on the stability criterion [1]. The model parameters are determined by the stability criterion. At finite temperature, the free energy per baryon for three-flavor quark matter must also stay below 930 MeV, while ensuring stability at zero temperature. In Fig. 1(a), we show the thermodynamic stability for the two temperatures (T=10MeV and 50MeV) and neutrino transparent and neutrino trapped quark matter. The free energy density per baryon density occurs exactly at zero pressure. As the temperature ($T$) increases, the minimum values of the free energy density per baryon density get lower, and also in the neutrino transparent case, the minimum free energy density per baryon density gets lower. Next, we plot entropy density per baryon density ( $\sigma$) in Fig. 1(b). As the density increases the value of $\sigma$ decreases and then nearly saturates to fixed values. The value of $\sigma$ in the neutrino transparent case is lower as compared to the trapped neutrino case for a fixed temperature.

## Summary and Conclusion

In this work, we have studied the quasi-particle model where the medium effect has been incorporated via chemical potential-dependent quark mass. We perform a self-consistent thermodynamic analysis of the finite-temperature equation of state.

## References


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