Equations of State of Quark Star in Color-Flavour-Locking Phase

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Introduction

Recently [1], proposed QCD chiral symmetry breaking scheme for quarks at high density nuclear matter has suggested the existence of color superconductors in form of Color-Flavour-Looking (CFL) with gluon excitation, along with the existence of Goldstone bosons and modified gauge effectve interactions. Therefore, many attempts have been made by various theoretical groups to understand the various phases of color superconductivity in high density QCD, and effects of gluon excitation on the equations of state (EOS) of high density quark matter. The Astrophysical precise experimental observations for compact stars [2] and references therein have provided a reliable and important source of information to contrain the interior composition of plausible equations of state of compact objects. A set of stiff EOS of dense nuclear matter is required to construct a compact star of maximum gravitational mass $\approx$ 2.0 $M_\odot$.

The main objective of present work is to investigate the effects of CFL color superconducting gaps in quarks and Goldstone bosons in the EOS of high density quark matter and mass-radius (M-R) relationship of strange quark stars and quark stars with CFL phase.

Theoretical Framework

The total thermodynamical potential of quarks matter in the CFL color superconducting phase may written as,

$$\Omega_{CFL}(\bar{\mu},\mu_e) = \Omega^{quarks}_{CFL}(\bar{\mu}) + \Omega^{GB}_{CFL}(\bar{\mu},\mu_e) + \Omega^{electron}(\mu_e), \quad (1)$$

where $\bar{\mu}$ is the average chemical potential for quarks and, μ_e is the electron chemical potential. The contribution to (1) from CFL color superconducting quarks is given by,

$$\Omega^{quarks}_{CFL} = -\sum_i \frac{g_i}{24\pi^2}\Big[\mu_i\left(\nu_i^2 - \frac{3}{2}m_i^2\right) + \frac{3}{2}m_i^4 \ln\frac{\mu_i+\nu_i}{m_i}\Big] - \frac{3\Delta^2\bar{\mu}^2}{\pi^2} + B(\rho), \quad (2)$$

where ν is fermi momentum and, Δ is CFL color superconducting gap parameter of CFL phase of quark matter. The B(ρ) is as usual phenomenological MIT bag constant introduced to account for free energy quark matter. We employ the Gaussian parametrization for bag pressure as a function of the baryon density. The composition of β-stable quark matter is determined by imposing the following conditions. First, the conservation of the total baryon number is implied as,

$$\rho = \frac{1}{3}(\rho_u + \rho_d + \rho_s), \quad (3)$$

where ρ is the total baryon number density. Further quark matter is considerd to be charge neutral,

$$2\rho_u - \rho_d - \rho_s - 3\rho_{e^-} = 0, \quad (4)$$

Due to the weak processes in the quark core of a compact star, all fermion species are assumed to be in chemical equilibrium with the corresponding conditions

$$\mu_d = \mu_u + \mu_{e^-} \quad (5)$$

$$\mu_d = \mu_s \quad (6)$$

Correspondingly, we have the particle number density

$$\rho_q = \frac{g_i\nu^3}{6\pi^2} + \frac{2\Delta^2\bar{\mu}}{\pi^2} \quad (7)$$

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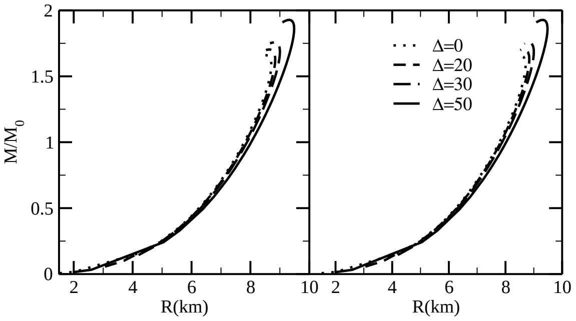

FIG. 1: The Mass-Radius relationship for strange quark stars in the left pannel and quark stars in the right pannel with increasing CFL color superconducting gap parameter $\Delta(MeV)$.

The $\Omega^{GB}_{CFL}(\bar{\mu}, \mu_e)$ is the contribution to (1) from Goldstone bosons arising due to the breaking of chiral symmetry in the CFL phase and $\Omega^{electron}(\mu_e)$ is the contribution from leptons. The total energy density and pressure for CFL color superconducting quarks matter can be calculated as,

$$\mathcal{E}_{QM} = \Omega_{CFL}(\bar{\mu}, \mu_e) + 3\bar{\mu}\rho_q + \mu_e(\rho_e + \rho_\mu) \quad (8)$$

$$P_{QP} = -\Omega_{CFL}(\bar{\mu}, \mu_e). \quad (9)$$

1. Results and Discussions

We study the structure properties of Strange Quark Stars and Quark Stars composed of CFL color superducting quarks matter in high density QCD, for set of EOS obtained with different values of CFL superconducting gaps Δ in quarks and deconfinement phase transition densities. In the present work, we consider fixed value of CFL superconducting gaps Δ from 0-50 MeV. One set of EOS is obtained with massless up and down quarks and mass of strange quark m_s = 120MeV, whereas other set of EOS is obtained with quark masses, $m_u = m_d$ = 5MeV and m_s = 120MeV. In Fig.(1), we present the Mass-Radius relationship for strange quark stars in the left pannel and for quark stars in the right pannel with increasing CFL color superconducting gap parameter Δ, respectively.

TABLE I: The variation in gravitational radius R in km, gravitational maximum mass in unit of solar $M_\odot$ and coresspounding values of moment of inertia of strange quark stars with increasing CFL color superconducting gap parameter Δ in quarks

$\Delta(MeV)$	$R(km)$	$M_{max}(M_\odot)$	MI($10^{45} gcm^2$)
0	8.5013	1.6598	0.764
20	8.6395	1.7031	0.7031
30	8.8075	1.7570	0.861
50	9.3162	1.9275	1.044

TABLE II: Same as Table I but for quark star with increasing CFL color superconducting gap parameter Δ in quarks.

$\Delta(MeV)$	$R(km)$	$M_{max}(M_\odot)$	MI($10^{45} gcm^2$)
0	8.5036	1.6595	0.762
20	8.6161	1.7028	0.797
30	8.8066	1.7567	0.861
50	9.3152	1.9271	1.044

In Tables (I and II), we present the variation in gravitational radius R in km, gravitational maximum mass in unit of solar $M_\odot$ and coresspounding values of moment of inertia of strange quark stars and quarks stars, respectively, with increasing value of CFL color superconducting gap parameter Δ in quarks.

Acknowledgments

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References

[1] M. Alford, K. Rajagopal and F. Wilczek, Nucl. Phys. B**537**, 443 (1999).
[2] J. Antoniadis, et al., Science **340**, 6131 (2013).