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Color superconductivity and neutron star structure†

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[MATTER AT HIGH DENSITY, Neutron matter]

The equation of state (EOS) at very high baryon densities, like in the center of a neutron star, is a very active field of recent research. Theoretically it is expected that the matter undergoes a phase transition from nuclear matter (NM) to quark matter (QM), where the latter is most likely in a color superconducting state (SQM). The basic parameter which controls this phase transition is the pairing strength between the quarks in the scalar diquark channel ($J = T = 0$, color $\overline{3}$). In this work, we report on the results for the equation of state of charge neutral matter in β-equilibrium and the masses of compact stars obtained by using the flavor SU(2) Nambu-Jona-Lasinio (NJL) model, which is an effective quark theory based on QCD.

The effective potential for NM is[1)] $V^{\rm NM} = V_{\rm vac} + V_{\rm N} + V_\omega + V_\rho + V_{\rm e}$, where the vacuum term $V_{\rm vac}$ accounts for the polarization of the quark Dirac sea, $V_{\rm N}$ represents the Fermi motion of the nucleons which are described as quark-diquark bound states in the NJL model, V_ω and V_ρ arise from the isoscalar and isovector mean vector fields respectively, and $V_{\rm e}$ is the electron contribution. For QM we have[2)] $V^{\rm QM} = V_{\rm vac} + V_{\rm Q} + V_{\rm e} + V_\Delta$, where the vacuum and electron terms are as above and the term for the Fermi motion of the quarks $V_{\rm Q}$ is analogous to $V_{\rm N}$, but referring to up and down quarks. The effect of the quark pairing is expressed by the term V_Δ, which involves the gap and a coupling constant (G_s) for the pairing interaction in the scalar diquark channel, which we express as $G_s = r_s\, G_\pi$. Here r_s is a parameter, and the coupling constant in the pionic channel (G_π) is fixed by reproducing the pion mass. The NM/QM mixed state is constructed by using the Gibbs conditions of phase equilibrium[3)].

In Fig.1 we show the EOS corresponding to the cases $r_s = 0$ and $r_s = 0.25$, and in Fig.2 we show the resulting star sequences. (The results for the pure NM case are also shown for comparison.) In the first case, for central densities between $3.7\rho_0$ and $6.0\rho_0$ ($\rho_0 = 0.15 \text{fm}^{-3}$), stable hybrid stars exist with a NM/QM phase in the center. In the second case, stable hybrid stars exist with central densities between $2.3\rho_0$ and $5.0\rho_0$ with a very small region of NM/SQM mixed phase in the center, and for central densities between $6.0\rho_0$ and $15.0\rho_0$ stable quark stars exist, which are composed of SQM in the central region. Comparison of these two cases indicates that color superconductivity has a major effect on the EOS: With increasing r_s, both the density and the pressure for the phase transition to QM are reduced, the EOS becomes softer, and the star masses decrease for given central density.

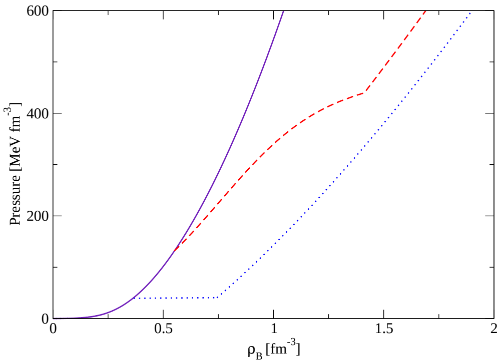

Fig. 1. Pressure vs. baryon density for pure NM (solid line) and the transition to QM for $r_s = 0$ (dashed line) and $r_s = 0.25$ (dotted line).

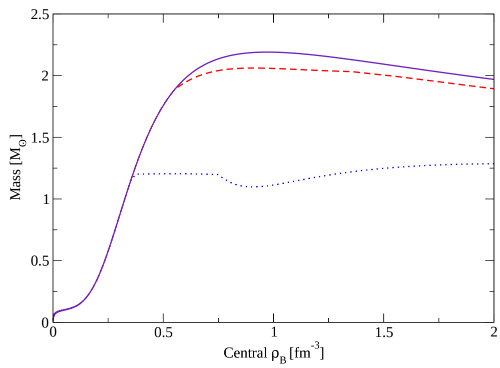

Fig. 2. Star masses vs. central density for the 3 cases of Fig.1.

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