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How strange are compact star interiors ?

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Abstract. We discuss a Nambu–Jona-Lasinio (NJL) type quantum field theoretical approach to the quark matter equation of state with color superconductivity and construct hybrid star models on this basis. It has recently been demonstrated that with increasing baryon density, the different quark flavors may occur sequentially, starting with down-quarks only, before the second light quark flavor and at highest densities also the strange quark flavor appears. We find that color superconducting phases are favorable over non-superconducting ones which entails consequences for thermodynamic and transport properties of hybrid star matter. In particular, for NJL-type models no strange quark matter phases can occur in compact star interiors due to mechanical instability against gravitational collapse, unless a sufficiently strong flavor mixing as provided by the Kobayashi-Maskawa-’t Hooft determinant interaction is present in the model. We discuss observational data on mass-radius relationships of compact stars which can put constraints on the properties of dense matter equation of state.

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1. Introduction

The question of strangeness in compact star interiors is a multifaceted one [1] and has been discussed controversially ever since the first discussion of hyperons [2] and kaon condensates [3, 4, 5] for the degenerate matter phases of neutron star cores. Present-day state-of-the-art calculations of hyperonic matter within the Brueckner-Bethe-Goldstone scheme [6] reveal the problem that due to the softening of the high-density equation of state (EoS) the maximum mass of hyperonic stars is below the measured mass of binary radiopulsars $M_{\text{BRP}} = 1.35 \pm 0.04 M_{\odot}$ [7]. As a possible solution to this problem a sufficiently early onset of quark deconfinement in neutron star matter at baryon densities $n = 0.3 - 0.5 \text{ fm}^{-3}$ has been suggested [8]. In the present contribution we will not touch the question of absolutely stable strange quark matter [9] in compact stars but rather focus the discussion on models for hybrid stars with deconfined quark matter cores and recent observational constraints for their masses (M) and radii (R), see [10, 11].

The status of the theoretical approach to the neutron star matter equation of state is very different from that for the high-temperature case at low or vanishing net baryon densities, where *ab initio* lattice QCD simulations provide EoS with almost physical quark masses systematically approaching the continuum limit [12]. This guidance is absent at zero temperature and high baryon number densities, where a variety of models exists on different levels of the microphysical description which make different predictions for the state of matter. A common feature is that the transition from hadronic to quark matter cannot yet be described on a unique footing where hadrons would appear as bound states (clusters) of quarks and their possible dissociation at high densities as a kind of Mott transition [13] like in nonideal plasmas [14] or in nuclear matter [15, 16]. Early nonrelativistic potential model approaches [17, 18] are insufficient since they cannot accommodate the chiral symmetry restoration transition in a proper way. Therefore, at present the discussion is restricted to so-called two-phase approaches where the hadronic and the quark matter EoS are modeled separately followed by a subsequent phase transition construction to obtain a hybrid EoS.

Widely employed for a description of quark matter in compact stars are thermodynamical bag models of three-flavor quark matter with eventually even density-dependent bag pressure $B(n)$, as in Ref. [8]. A qualitatively new feature of the phase structure appears in chiral quark models of the Nambu–Jona-Lasinio type which describe the dynamical chiral symmetry breaking of the QCD vacuum and its partial restoration in hot and dense matter, see Ref. [19] for a review. In contrast to bag models, in these approaches at low temperatures the light and strange quark degrees of freedom may appear sequentially with increasing density [20, 21, 22], so that strangeness may even not appear in the quark matter cores of hybrid stars, before their maximum mass is reached. Once chiral symmetry is restored, a rich spectrum of color superconducting quark matter phases may be realized in dense quark matter, depending on its flavor composition and isospin asymmetry [23] with far-reaching consequences for hybrid star phenomenology, e.g., $M - R$ relationships and cooling behavior.

We will consider here a color superconducting three-flavor NJL model with selfconsistently determined density dependences of quark masses and scalar diquark gaps, developed in Refs. [24] and [25] which differ in the fact that the former includes the flavor-mixing Kobayashi-Maskawa-'t Hooft (KMT) determinant interaction [26, 27] while the latter does not. Only recently it became clear [28] that this flavor mixing is crucial for the possible stability of strange quark matter phases in hybrid stars.

2. Role of the Kobayashi-Maskawa-'t Hooft (KMT) interaction

Our description of quark matter is based on the grand canonical thermodynamic potential [19, 24, 25, 29, 30]

$$\begin{aligned} \Omega(T, \{\mu\}) = & \frac{\phi_u^2 + \phi_d^2 + \phi_s^2}{8G_S} + \frac{K\phi_u\phi_d\phi_s}{16G_S^3} - \frac{\omega_u^2 + \omega_d^2 + \omega_s^2}{8G_V} + \frac{\Delta_{ud}^2 + \Delta_{us}^2 + \Delta_{ds}^2}{4G_D} \\ & - \int \frac{d^3p}{(2\pi)^3} \sum_{n=1}^{18} \left[E_n + 2T \ln \left(1 + e^{-E_n/T} \right) \right] + \Omega_{lep} - \Omega_0, \end{aligned} \quad (1)$$

where $E_n = E_n(p, \mu; \mu_Q, \mu_3, \mu_8, \phi_u, \phi_d, \phi_s, \omega_u, \omega_d, \omega_s, \Delta_{ud}, \Delta_{us}, \Delta_{ds})$ are the quasiparticle dispersion relations, obtained by numerical diagonalization of the quark propagator matrix in color-, flavor-, Dirac- and Nambu-Gorkov spaces. The values of the meanfields (order parameters) are obtained from a minimization of $\Omega(T, \{\mu\})$, which is equivalent to the selfconsistent solution of the set of corresponding gap equations. Ω_{lep} is the contribution from leptons (*e.g.*, electrons, muons and the corresponding neutrino flavors) and the subtraction of Ω_0 guarantees that in the vacuum $\Omega(0, 0) = 0$. Eq. (1) is obtained in the meanfield approximation to the path integral representation of the partition function for the three-flavor NJL model Lagrangian with the interaction channels

$$\begin{aligned} \mathcal{L}_{\bar{q}q} = & G_S \sum_{a=0}^8 \left[(\bar{q}\tau_a q)^2 + (\bar{q}i\gamma_5\tau_a q)^2 \right] + G_V (\bar{q}i\gamma_0 q)^2 \\ & - K [\det_f(\bar{q}(1 + \gamma_5)q) + \det_f(\bar{q}(1 - \gamma_5)q)], \end{aligned} \quad (2)$$

$$\mathcal{L}_{qq} = G_D \sum_{a,b=2,5,7} (\bar{q}i\gamma_5\tau_a\lambda_b C\bar{q}^T)(q^T C i\gamma_5\tau_a\lambda_b q), \quad (3)$$

where τ_a and λ_b are the antisymmetric Gell-Mann matrices acting in flavor and color space, respectively. The scalar (G_S), diquark (G_D), vector (G_V) and KMT (K) couplings are to be determined by hadron phenomenology, see [31].

As pointed out in [19], due to the mixing of the light and strange flavor sectors by the KMT interaction, the difference in the critical chemical potentials for the chiral phase transitions in these sectors (which coincide with the onset of 2SC and CFL phases, respectively) gets diminished. This entails that the phase transition between hadronic matter (described by a realistic nuclear EoS, *e.g.*, the DBHF one, see [30]) and superconducting quark matter may eventually proceed directly into the CFL phase, provided the diquark coupling is sufficiently strong, see the left panel of Fig. 1. For consistency with nuclear matter phenomenology, one may check that the corresponding isospin symmetric EoS would not predict a too low transition density and is not in

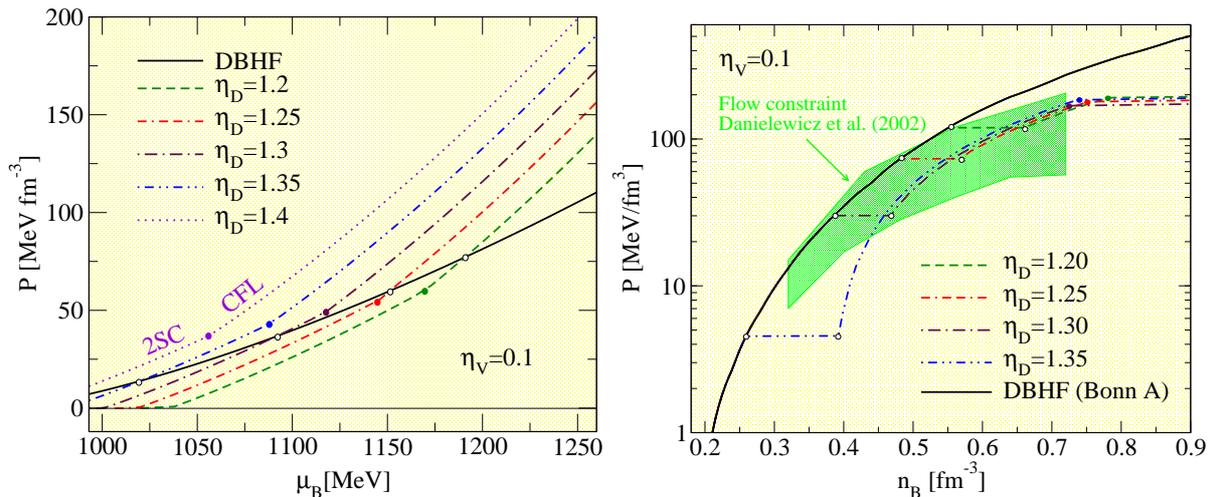


Figure 1. Left: Equations of state for neutron star matter in beta-equilibrium. The hadronic phase is described by the DBHF EoS (solid line) and the quark matter EoS correspond to the NJL model (1) for different choices of the diquark coupling strength $\eta_D = G_D/G_S$ for given vector coupling $\eta_V = G_V/G_S = 0.1$ and KMT coupling K . Phase transitions from two-flavor (2SC) to three-flavor (CFL) quark matter are marked by full dots whereas phase transitions from hadronic to quark matter are indicated by open dots. Right: Hybrid equations of state for symmetric matter compared to the flow constraint [32] from heavy-ion collisions. Except $\eta_D = 1.35$, for which the onset of the 2SC phase has a too low critical density, the parametrizations fulfil the flow constraint, see also [10, 11, 30]. The 2SC-CFL transition lies outside the tested density region.

contradiction with the flow constraint from heavy-ion collisions [32], see the right panel of Fig. 1.

In Fig. 2 we show the $M - R$ and $M - n_c$ relationships for nonrotating compact star sequences obtained as solutions of the Tolman-Oppenheimer-Volkoff equations for the hybrid EoS shown in the left panel of Fig. 1 where the diquark coupling $\eta_D = G_D/G_S$ is a free parameter and the vector coupling is set to $\eta_V = G_V/G_S = 0.1$. For sufficiently large $\eta_D > 1.2$ there is a stable branch of hybrid stars with color superconducting quark matter core. These solutions are more compact and have a higher central density n_c than the purely hadronic stars with the same mass. In the parameter range $1.25 < \eta_D < 1.3$, mass twin solutions are possible, for which the more compact configuration has a CFL quark matter core. Such solutions have not been possible without the KMT interaction term, when the occurrence of CFL quark matter marks the onset of gravitational instability and thus sets the limit for the maximum mass of the hybrid star [30, 33]. The question arises whether other flavor-mixing interactions have to be invoked. It seems necessary in a next step to include channels which appear after Fierz transformation of the KMT interaction and couple chiral condensates with diquark condensates [34]. This may lead to a new critical point in the QCD phase diagram [35] and, depending on the sign of the coupling, to a further reduction of the strange chiral condensate which enforces the flavor mixing effect studied here.

The observational constraints for masses and radii are not yet settled. There is a

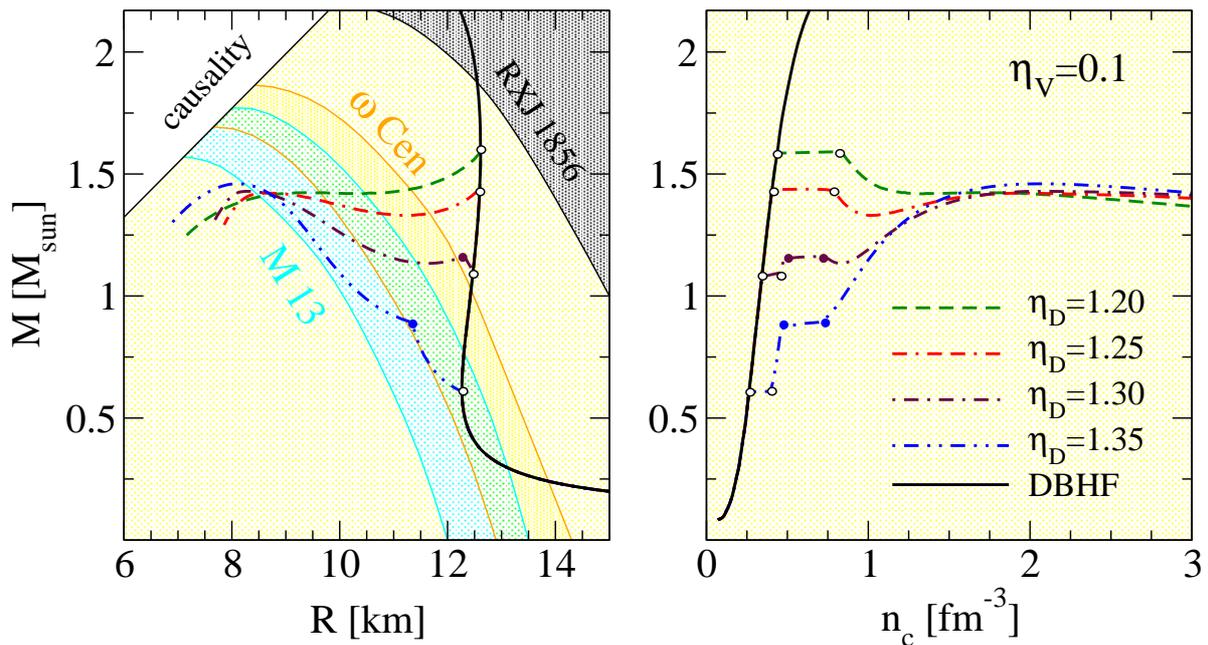


Figure 2. Compact star sequences for different values of the diquark coupling strength η_D . For $\eta_D = 1.2$ no stable configurations with quark matter exist while for the strong coupling $\eta_D = 1.35$ there is an early onset of 2SC quark core configurations at $M = 0.6 M_\odot$ followed by a stable branch of hybrid stars CFL quark matter cores in the mass range $0.9 < M/M_\odot < 1.46$. For comparison recent mass radius constraints are shown coming from RX J1856 [36, 11], M13 [37] and ω Cen [38], see also [10].

lower limit for the $M - R$ relation from RXJ 1856.5-3754 [36] which requires either a large radius $R > 14$ km for a star with $M = M_{\text{BRP}}$ or a mass larger than $\sim 2 M_\odot$ for a star with 12 km radius. Both is difficult to accommodate with the present EoS. $M - R$ relations for the quiescent binary neutron stars in globular clusters M13 [37] and ω Cen [38] point to rather compact stars as described by those sequences obtained here. The presented microscopic EoS features an intermediate softening of the EoS due to diquark condensation in the density range $\sim 0.4 - 0.8 \text{ fm}^{-3}$ and predicts two stable branches in an overlapping range of masses (twins) as a robust feature of compact star $M - R$ relationships. The hypothesis of the existence of a “third family” of supercompact stars is testable in future observational campaigns devoted to determine the masses [39] and $M - R$ relationship for compact stars [40] with high precision and thus to constrain the dense matter EoS.

3. Conclusions

The effect of the flavor-mixing KMT determinant interaction on the sequential occurrence of superconducting two- and three-flavor quark matter phase transitions in the EoS for cold dense matter has been studied in an NJL-type model. It is found that at sufficiently strong diquark coupling the deconfinement phase transition in neutron star matter leads directly from the hadronic phase to the CFL phase and occurs at

low enough density to entail the formation of stable branch of CFL core hybrid stars in the $M - R$ diagram of compact stars. This branch may either continuously join that of normal neutron stars or eventually form a “third family” branch, separated from that of the neutron stars by a sequence of unstable configurations. The possibility of such a characteristic feature of mass twins in the $M - R$ diagram suggested by advanced microscopic QCD motivated hybrid EoS with superconducting dense quark matter phases should be kept in the focus of observational programs to deduce the cold dense EoS exploiting measured $M - R$ relationships for compact stars.

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