Neutron star matter in a modified PNJL model

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We discuss a three-flavor Nambu–Jona-Lasinio model for the quark matter equation of state with scalar diquark interaction, isoscalar vector interaction and Kobayashi-Maskawa-'t Hooft interaction. We adopt a phenomenological scheme to include possible effects of a change in the gluon pressure at finite baryon density by including a parametric dependence of the Polakov-loop potential on the chemical potential. We discuss the results for the mass-radius relationships for hybrid neutron stars constructed on the basis of our model EoS in the context of the constraint from the recently measured mass of 1.97 ± 0.04 $M_\odot$ for the pulsar PSR J1614-2230.

1. INTRODUCTION

In this contribution we discuss a model for the equation of state (EoS) of compact stars with deconfined quark matter cores and compare solutions for the masses M and radii R of resulting sequences of stable hybrid star configurations with observational constraints [1, 2], in particular with the recent mass measurement of PSR J1614-2230 [3]. It is the current hope that very accurate measurements of the M-R relationship for compact stars (CS's), e.g., with the *International X-Ray Observatory (IXO)* project [4], will allow to falsify some of the models for the EoS of cold and dense matter. In order to extract relevant information from observational data a systematic numerical analysis of EoS needs to be performed.

Nambu–Jona-Lasinio (NJL) type models describe the dynamical chiral symmetry breaking in the QCD vacuum and its partial restoration at high temperatures and chemical potentials. For review see, e.g., Ref. [5]. Chiral symmetry restoration at low temperatures and

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high densities is accompanied by the possible occurrence of various color superconducting phases [6]. Color superconductivity, i.e. the condensation of diquark Cooper pairs, can have significant impact on transport properties of CS matter as, e.g., the neutrino emissivities and the viscosity [6–8].

In this paper we will consider a 3-flavor color superconducting NJL model [9–11], with Kobayashi-Maskawa-'t Hooft (KMT) determinant interaction [12, 13]. The flavor mixing KMT term has been shown to qualitatively change the M-R relation for hybrid stars [14, 15]. Additionally we will couple the quark sector to a Polyakov-loop potential [16, 17] with additional chemical potential dependence taken from [18].

2. MODIFIED PNJL MODEL WITH COLOR SUPERCONDUCTIVITY

The interaction Lagrangian for model that we study is $\mathcal{L}_{\rm int} = \mathcal{L}_{\bar{q}q} + \mathcal{L}_{qq}$, where

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

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

with τ_a and λ_b being the antisymmetric Gell-Mann matrices in flavor and color space. The couplings (G_S, G_D, G_V, K) are to be determined by hadron phenomenology, see [19]. The Polyakov-loop Φ is an order parameter for confinement, weighted with the phenomenological potential [18]

$$\mathcal{U}(\Phi) = (aT^4 + b\mu^2 T^2 + c\mu^4)\Phi^2 + a_2 T_0^4 \ln(1 - 6\Phi^2 + 8\Phi^3 - 3\Phi^4) \ . \tag{3}$$

We base our description on the grand canonical thermodynamic potential [5, 9–11, 20] which in the mean-field approximation is

$$\begin{aligned}\Omega_{\rm MF}(T,\{\mu\}) &= \frac{\phi_u^2+\phi_d^2+\phi_s^2}{8G_S} + \frac{K\phi_u\phi_d\phi_s}{16G_S^3} - \frac{\omega_u^2+\omega_d^2+\omega_s^2}{8G_V} + \frac{\Delta_{ud}^2+\Delta_{us}^2+\Delta_{ds}^2}{4G_D} \\ &- \int \frac{d^3p}{(2\pi)^3} \sum_{n=1}^{18} \left[E_n + 2T \ln\left(1+e^{-E_n/T}\right)\right] - \Omega_0 + \mathcal{U}(\Phi_0) \ , \end{aligned} \tag{4}$$

where $E_n = E_n(p,\, \mu;\, \mu_Q, \mu_3, \mu_8,\, \phi_u, \phi_d, \phi_s,\, \omega_u, \omega_d, \omega_s,\, \Delta_{ud}, \Delta_{us}, \Delta_{ds}, \Phi_0)$ are the quasiparticle dispersion relations. The values of order parameters are obtained by minimization of

$\Omega(T, \{\mu\})$. To obtain zero pressure in vacuum we subtract Ω_0. For CS matter, the contribution of leptons shall be included and the conditions of color and electric neutrality as well as β-equilibrium should be applied.

The Polyakov-loop potential can be viewed as a T, μ-dependent bag function accounting for the partial melting of the gluon condensate. We will compare the results obtained with a simple bag constant ΔB with those for a modified Polyakov-loop potential.

As was pointed out in [5] the KMT interaction diminishes the difference in critical chemical potentials of light and strange sectors. This suggest that a direct transition from hadronic matter (e.g., the Dirac-Bruckner Hatree-Fock(DBHF) EoS, see [20]) to the color-flavor locked (CFL) phase may occur for sufficiently strong diquark coupling, see Ref. [15]. The dependence of the thermodynamics on the coupling strengths has been investigated in [15]. Here, we will focus on Fierz values of the couplings i.e., $G_V = 0.5\ G_S$ and $G_D = 0.75\ G_S$. The remaining model parameters are fixed by vacuum properties of mesons and baryons, while the KMT coupling is fixed by $\eta - \eta'$ mass splitting.

The M-R and M-n_c relationships obtained as solutions of the Tolman-Oppenheimer-Volkoff equation are presented in Fig. 1 for different values of the c-parameter of the modified PNJL (mPNJL) model (3) and the bag constant ΔB. Stable hybrid stars with 2SC quark core are obtained for $\Delta B = -50$ and -40 MeV/fm^3. Other parameters choices lead to a direct transition from hadronic to CFL matter; only small sequences of stable CFL quark core hybrid stars are obtained.

The recent mass constraint from pulse timing observations of PSR J1614-2230 [3] is accommodated by the present EoS. The well known constraint from from RXJ 1856.5-3754 [21] is also fulfilled. It should be noted that the NJL model with KMT interaction without modifications of either the Polakov-loop potential or adding a bag pressure is unable to meet the PSR J1614-2230 constraint [3]. This raises the question of including interaction channels obtained from KMT by Fierz transformation [22]. It has been shown [23] that such a modification may lead to an additional critical point in QCD phase diagram and we will investigate its role for hybrid star structure in subsequent work.

3. CONCLUSIONS

We have investigated effects of density-dependent modifications of the Polyakov loop potential on color superconducting phases in the framework of a thus modified PNJL model with KMT interaction for CS matter. We have employed the strategy of fixing coupling constants to hadron phenomenology and Fierz relations, while one free parameter was left for governing the chemical potential dependence of the Polyakov loop. It was found that the new constraint from the massive pulsar PSR J1614-2230 can be met by this model. With a density dependent Polyakov loop potential and for sufficiently large parameter values (of c or ΔB) stable massive hybrid stars with color superconducting quark matter in their cores can be described.

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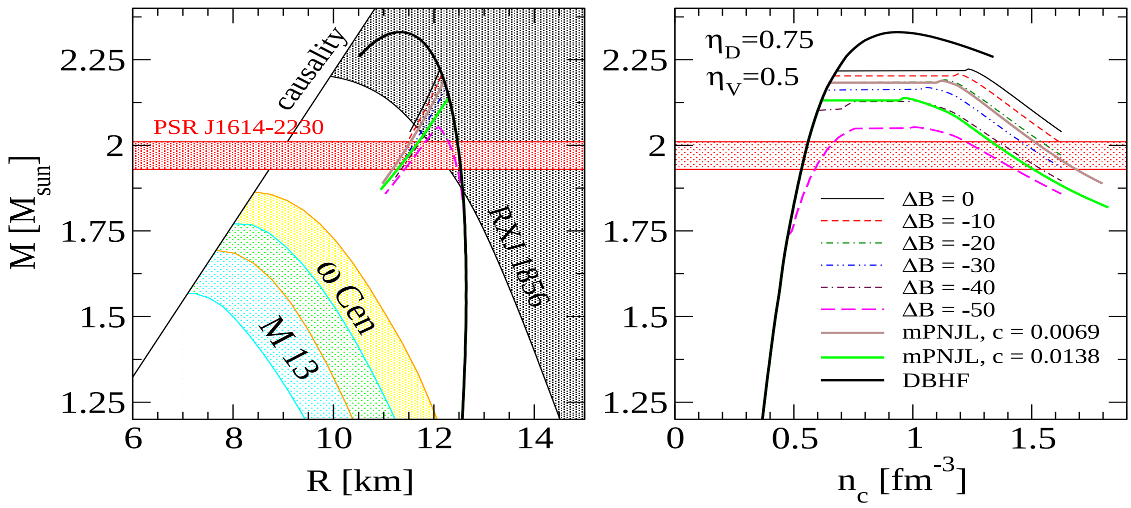

Figure 1. Compact star sequences for different values of the c parameter (bag constant ΔB in MeV/fm^3) in the modified PNJL (abridged mPNJL) model (3). Compared with the recent constraint of PSR J1614-2230 (the stripe). See text for the discussion.

FIGURE CAPTIONS

Fig. 1: Compact star sequences for different values of the c parameter (bag constant ΔB in MeV/fm^3) in the modified PNJL (abridged mPNJL) model (3). Compared with the recent constraint of PSR J1614-2230 (the stripe). See text for the discussion.