CROSSOVER TRANSITION TO QUARK MATTER IN HEAVY HYBRID STARS*

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We study the possibility that the transition from hadron matter to quark matter at vanishing temperatures proceeds via crossover, similar to the crossover behavior found with lattice QCD studies at high temperatures. The purpose is to examine astrophysical consequences of this postulate by constructing hybrid star sequences fulfilling current experimental data.

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1. Introduction

Recent simulations of quantum chromodynamics (QCD) on the lattice [1, 2] show that the hadron-to-quark matter transition in the region of small quark chemical potential ($\mu \simeq 0$) in the QCD phase diagram is a crossover. To

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what extent this result persists in the regime for cold ($T = 0$), dense ($\mu_{\rm B} = 3\mu > m_{\rm N}$) matter is an open question eventually to be answered by heavy-ion collision experiments of the third generation such as NICA and FAIR.

An alternative is to measure masses and radii of compact stars, where the Bayesian analysis is used to invert the Tolman–Oppenheimer–Volkoff (TOV) equations [3] and obtain the most probable equation of state (EoS) corresponding to a chosen set of observational constraints. The challenge within this approach is a reliable measurement of neutron star radii. We quote results from millisecond pulsar timing analyses [4] rather than burst sources used in [3].

Prompted by recent findings of a second $2M_\odot$ neutron star [5, 6], we reexamine the EoS for dense matter by constructing non-rotating sequences and studying the possibility of a hybrid star with $2M_\odot$.

The hybrid EoS is constructed from a non-local Nambu–Jona-Lasinio model (nl-NJL) [7–9] with appreciable vector interaction strength [10], while for the nuclear matter we use the DD2 EoS [11, 12].

In this work, we abandon the standard Maxwell construction for a first order phase transition, anticipating instead a crossover transition described by an interpolation of the pressure $p(\mu_{\rm B})$ as a thermodynamic potential for the above EoS. This procedure is equivalent to the one described in [13] using energy density ε *versus* baryon density $n_{\rm B}$, which corrects an earlier suggested inappropriate construction in the $p(n_{\rm B})$ plane [14]. The construction leads to a characteristic stiffening on the hadron-dominated side followed by a softening and smooth joining to the quark-dominated side of the EoS. While the former maybe due to quark substructure effects (Pauli blocking) initiating the hadron dissociation (Mott effect), the appearance of finite size structures (pasta phases) at the quark–hadron interface [15] and strong hadronic fluctuations [16] might be responsible for the latter.

2. Equation of state

The thermodynamic potential for quark matter is provided by the nl-NJL model

$$\Omega = \Omega_{\rm cond} + \Omega^{\rm reg}_{\rm kin} + \Omega^{\rm free}_{\rm reg}\,, \tag{1}$$

$$\Omega_{\rm cond} = \frac{\sigma_1^2 + \kappa_{\boldsymbol{p}}^2\sigma_2^2 + \kappa_{p_4}^2\sigma_3^2}{2G_{\rm S}} - \frac{\omega^2}{2G_{\rm V}}\,, \tag{2}$$

$$\Omega^{\rm reg}_{\rm kin} = -2N_{\rm f}N_{\rm c}\int\frac{d^4p}{(2\pi)^4}\log\left[\frac{\boldsymbol{p}^2A^2\left(\tilde{p}^2\right) + \tilde{p}_4^2C^2\left(\tilde{p}^2\right) + B^2\left(\tilde{p}^2\right)}{\tilde{p}^2 + m^2}\right], \tag{3}$$

$$\Omega^{\rm free}_{\rm reg} = -\frac{N_{\rm c}}{24\pi^2}\left[2\tilde{\mu}^3\tilde{p}_{\rm F} - 5m^2\tilde{\mu}\tilde{p}_{\rm F} + 3m^4\log\left(\frac{\tilde{p}_{\rm F}+\tilde{\mu}}{m}\right)\right]. \tag{4}$$

Here, $A(p^2) = 1 + \sigma_2 f(p^2)$, $B(p^2) = 1 + \sigma_1 g(p^2)$ and $C(p^2) = 1 + \sigma_3 f(p^2)$, where $f(p^2)$ and $g(p^2)$ are appropriately chosen formfactors [7]. We denote $\tilde{p} = (\boldsymbol{p}, \tilde{p}_4)$, $\tilde{p}_4 = p_4 - i\tilde{\mu}$. The vector channel is introduced as a background field, similar to the way the Polyakov loop is introduced in NJL models; via renormalization of the quark chemical potential $\tilde{\mu} = \mu - \omega$ and completed by a classical term in the thermodynamic potential (2).

The pressure corresponds to the thermodynamic potential in equilibrium by $p_Q(\mu) = -\Omega$, where the latter is found from Eq. (1) for a given chemical potential as a minimum with respect to variations of the mean fields

$$\frac{\partial \Omega}{\partial(\sigma_1, \sigma_2, \sigma_3)} = 0\,. \tag{5}$$

The value of the vector meanfield ω is found from the constraint of a given baryon density $n_\mathrm{B} = \partial p_Q / \partial \mu_\mathrm{B}$, namely $\omega = G_\mathrm{V}\; n_\mathrm{B}(\tilde{\mu}_\mathrm{B})$.

For describing dense nuclear matter, we choose the DD2 EoS [11, 12]. The transition region is constructed by a Gaussian interpolation

$$p(\mu_\mathrm{B}) = \begin{cases} p_\mathrm{H}(\mu_\mathrm{B})\,, & \mu_\mathrm{B} < \bar{\mu}\,, \\ [p_\mathrm{H}(\mu_\mathrm{B}) - p_Q(\mu_\mathrm{B})]\, e^{-(\mu_\mathrm{B} - \bar{\mu})^2/\Gamma^2} + p_Q(\mu_\mathrm{B})\,, & \mu_\mathrm{B} > \bar{\mu}\,, \end{cases} \tag{6}$$

where $\bar{\mu}$ and Γ are parameters controlling the onset and the width of the transition, respectively. This approach is equivalent to the crossover construction in the ϵ–n_B plane [13] where a tanh function was used, but corrects the inappropriate construction suggested in [14]. Note that in Refs. [17, 18] the crossover construction was utilized for interpolating between quark matter EoS for two different values of the vector coupling thus mimicking its medium dependence. There the transition from the hadronic to the quark phase is seen as a sharp first order, while here we assume a smooth crossover.

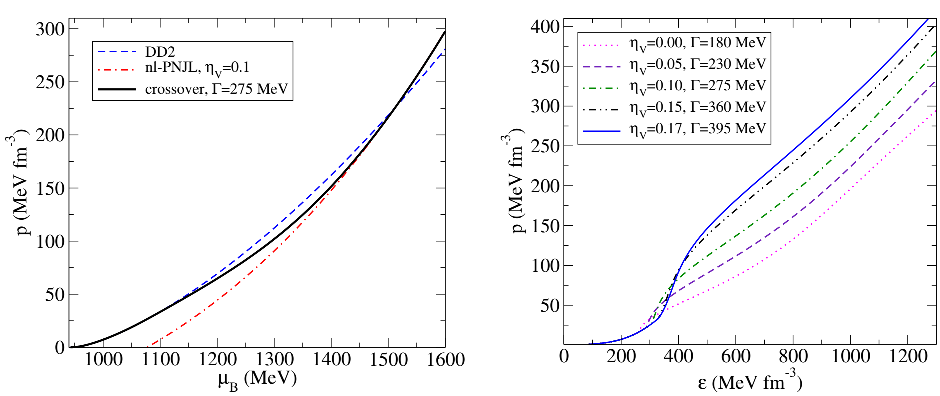

Fig. 1. Left panel shows the crossover construction Eq. (6) in the p–μ_B plane. In the right panel, we give the EoS used in this work.

There is an obvious benefit from our approach. With the Maxwell construction p as a function of energy density ϵ in the transition region is flat, making the EoS soft, while the crossover construction leads to a stiffening in the transition region.

We set $\bar{\mu} = \mu_c$, where μ_c is the onset of quark matter in the nl-NJL model and use the minimal possible Γ consistent with causality. This leaves $\eta_V = G_V/G_S$ as a free parameter. The resulting EoS are shown in the right panel of Fig. 1.

3. Astrophysical implications

It is known that within the Maxwell construction scheme hybrid stars with small or almost zero vector coupling do not reach $2M_\odot$ before turning unstable [19]. The softness of quark matter is then regulated by a strong vector coupling channel. However, the delay the quark matter onset caused by large vector couplings can be compensated by a strong diquark coupling. In total, if quark matter appears through a first order transition, model calculations indicate that stable stars may require large couplings in both vector and diquark channels.

In this work, we limit ourselves to the region of small vector coupling ($\eta_V < 0.17$) and offer an alternative mechanism that compensates such relative softness of the quark EoS. We solve the TOV equations by using the EoS with the crossover construction (6). The results shown in Fig. 2 are able to predict stable stars reaching and exceeding $2M_\odot$ already with a small η_V.

Our calculations show that quark matter appears for sequences with mass heavier than $M \sim M_\odot$, and central densities higher than $n_c \sim 2n_0$, where $n_0 = 0.16$ fm^{-3}. For vector couplings $\eta_V > 0.05$, sequences with masses above $2M_\odot$ do not have pure quark matter in their cores. If we vaguely consider the crossover region as a mixed phase of hadrons and quarks, we might describe these stars to have a hadronic mantle and a mixed phase core. For mild vector coupling $\eta_V = 0.05$, the sequence with pure quark matter lies on the verge of stability, as shown by the triangle on the dashed line in the right panel of Fig. 2. In addition, it is interesting to note that this sequence lies within the 1σ band of both the $2M_\odot$ constraint for PSR J0348-0432 [6] and PSR J1614-2230 [5].

The possibility of having only a mixed phase in the $M > 2M_\odot$ stars is due to the tension between the vector coupling and the width of the crossover. With lower values of the vector coupling hadronic matter and quark matter EoS lie closer to each other in the p–μ_B plane so that a smaller crossover region is needed to achieve a causal EoS. By increasing the vector coupling the onset density of quark matter increases and the two EoS separate, requiring a larger crossover region.

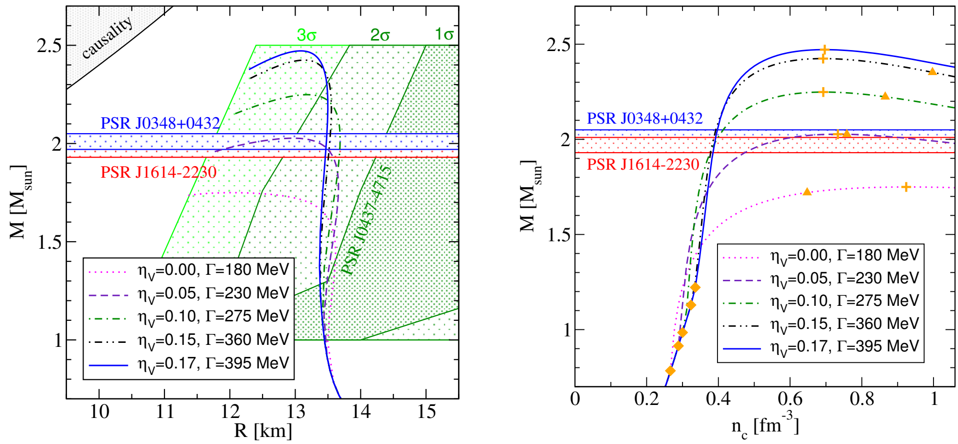

Fig. 2. The left panel shows sequences in the M–R plane, while the right panel gives mass as a function of central density for these sequences. The black/orange diamonds represent the onset of the crossover region, while black/orange triangles denote its end corresponding to the onset of pure quark matter in the core of the neutron star. The black/orange plusses are the maximum mass configurations for the given EoS.

4. Conclusions

Requiring the transition from hadron to quark matter being unique, any viable hybrid EoS model should be able to fulfill the constraint of the recent observational lower limit of $2M_\odot$ for the maximum mass of the corresponding hybrid star sequence. For a wide class of NJL models, this is not possible with the standard Maxwell construction unless quark matter is in a color superconducting state and has a strongly repulsive vector meanfield.

We have offered an alternative based on the requirement that the transition between quark and hadron matter is a crossover. We have found that hybrid star configurations reaching or even exceeding the $2M_\odot$ mass constraint have cores comprised of a mixed phase of quarks and hadrons. This conclusion is similar to the one drawn when promoting the local charge neutrality condition to a global one via Gibbs construction [20].

Our work might be considered as a first step towards a microscopically based construction of the transition from hadron to quark matter either via pasta phases or beyond mean-field studies taking into account the quark substructure of hadrons and their dissociation in the dense medium [21, 22].

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