Quark matter nucleation with a microscopic hadronic equation of state

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The nucleation process of quark matter in cold ($T = 0$) stellar matter is investigated using the microscopic Brueckner-Hartree-Fock approach to describe the hadronic phase and using the MIT bag model, the Nambu–Jona-Lasinio, and the chromodielectric models to describe the deconfined phase of quark matter. The consequences of the nucleation process for neutron star physics are outlined. Hyperonic stars are metastable only for some of the quark matter equations of state considered. The effect of a hyperonic three-body force on the metastability of compact stars is estimated, and it is shown that, except for the Nambu–Jona-Lasinio model and the MIT bag model with a large bag pressure, the other models predict the formation of hybrid stars with a maximum mass not larger than ∼$1.62M_\odot$.

I. INTRODUCTION

Quark matter (QM) nucleation in neutron stars has been studied by many authors both at zero [1–9] and finite temperature [11–16], due to its potential connection with explosive astrophysical events such as supernovae and γ-ray bursts. In all these works, the hadronic phase was described using phenomenological models, such as, e.g., the well-known relativistic mean field (RMF) model based on effective Lagrangian densities where the baryon-baryon interaction is described in terms of meson exchanges [17]. Among the different RMF models, one of the most popular parametrizations is the one of Glendenning and Moszkowski [18] of the nonlinear Walecka model which has been widely used to study the effect of the hadronic equation of state (EoS) on the QM nucleation process. In particular, the effect of different hyperon couplings on the critical mass [1,2] for pure hadronic stars (HSs, i.e., neutron stars in which no fraction of QM is present) and the stellar conversion energy [19] was studied in Ref. [7]. It was found that increasing the value of the hyperon coupling constants increases the stellar metastability threshold mass and the value of the critical mass, thus making the formation of quark stars (QSs, i.e., hybrid stars or strange stars depending on the details of the EoS for quark matter used to model the phase transition) less likely. In that work, the hadronic phase was also described using the quark-meson-coupling model [20], concluding, in that case, that the formation of a quark star was only possible with using a small value of the bag pressure. In all these works the MIT bag model [21] was used to describe the quark matter phase. In a recent work [10], two models that contain explicitly the chiral symmetry were applied to describe the quark phase, namely, the Nambu–Jona-Lasinio (NJL) model [22] (see also Refs. [23,24]) and the chromodielectric model (CDM) [25,26]. It was shown there that it is very difficult to populate the quark star branch with the NJL model and, therefore, all compact stars would be pure hadronic stars in that case. On the contrary, with the CDM, both hadronic and quark star configurations can be formed.

In the present work we study the nucleation of quark matter using a hadronic EoS based on microscopic calculations. In particular, we employ two hadronic EoS based on microscopic Brueckner-Hartree-Fock (BHF) calculations of hypernuclear matter. The first one (hereafter called Model 1) is the recent parametrization provided by Schulze and Rijken [27] which uses the Argonne V18 nucleon-nucleon (NN) [28] supplemented by the microscopic three-body force (TBF) of Ref. [29] between nucleons (NNN), and the recent Nijmegen extended soft-core ESC08b hyperon-nucleon (YN) potentials [30]. The second one (hereafter called Model 2) is based on our recent work of Ref. [31] where we used the Argonne V18 NN force and the Nijmegen soft-core NSC89 YN one [32] in a microscopic BHF calculation of hyperonic matter supplemented with additional simple phenomenological density-dependent contact terms, which mimic the effect of NNN, NNY, and NYY TBFs, to establish numerical lower and upper limits to the effect of hyperonic TBF on the maximum mass of neutron stars. To describe the quark phase, in the present work, we use the three different models already mentioned, the MIT bag model [21], the NJL model [22], and the CDM [25].

The paper is organized in the following way. In Secs. II and III, we briefly review the BHF approach and the main features of quark matter nucleation in hadronic stars, respectively. Our results are presented in Sec. IV. Finally, a summary and the main conclusions of this work are given in Sec. V.

II. THE BHF APPROACH

The BHF approach is the lowest order of the Brueckner-Bethe-Goldstone (BBG) many-body theory [33]. In this theory, the ground-state energy of nuclear matter is evaluated in terms of the so-called hole-line expansion, where the perturbative diagrams are grouped according to the number of independent hole lines. The expansion is derived by means of the in-medium two-body scattering G matrix. The G matrix, which takes

into account the effect of the Pauli principle on the scattered particles and the in-medium potential felt by each nucleon, has a regular behavior even for short-range repulsions, and it describes the effective interaction between two nucleons in the presence of a surrounding medium. In the BHF approach, the energy is given by the sum of only *two-hole-line* diagrams including the effect of two-body correlations through the G matrix. It has been shown by Song *et al.* [34] that the contribution to the energy from *three-hole-line* diagrams (which account for the effect of three-body correlations) is minimized when the so-called continuous prescription [35] is adopted for the in-medium potential, which is a strong indication of the convergence of the hole-line expansion. The BHF approach has been extended to hyperonic matter by several authors [27,31,36]. The interested reader is referred to these works for the specific details of the BHF calculation of hyperonic matter and to Ref. [33] for an extensive review of the BBG many-body theory.

III. QUARK MATTER NUCLEATION IN HADRONIC STARS

The conditions of phase equilibrium, in the case of a first-order phase transition [37], are given by the Gibbs' phase rule, which in the case of cold ($T = 0$) matter can be written as

$$P_H = P_Q \equiv P_0, \quad \mu_H(P_0) = \mu_Q(P_0), \quad (1)$$

where

$$\mu_H = \frac{\epsilon_H + P_H}{n_H} \quad \text{and} \quad \mu_Q = \frac{\epsilon_Q + P_Q}{n_Q} \quad (2)$$

are the Gibbs energies per baryon for the hadron (H) and quark (Q) phases, respectively, and the quantities $\epsilon_H(\epsilon_Q)$, $P_H(P_Q)$, and $n_H(n_Q)$ denote, respectively, the total (i.e., including leptonic contributions) energy density, total pressure, and baryon number density of the two phases. Above the transition pressure P_0 the hadronic phase is metastable, and the stable quark phase will appear as a result of a nucleation process. Quantum fluctuations will form virtual drops of quark matter. The characteristic oscillation time ν_0^{-1} of these drops, in the potential energy barrier separating the metastable hadronic phase and the quark phase, is set by strong interactions, which are responsible of the deconfinement transition, thus $\nu_0^{-1} \sim 10^{-23}$ s. This time is many orders of magnitude smaller than the weak interaction characteristic time ($\tau_{\text{weak}} \sim 10^{-8}$ s), consequently quark flavor must be conserved forming a virtual drop of quark matter. We call the Q^* phase this deconfined quark matter, in which the flavor content is equal to that of the β-stable hadronic phase at the same pressure and temperature. Soon after a critical size drop of quark matter is formed, the weak interactions have enough time to act, changing the quark flavor fraction of the deconfined droplet to lower its energy, and a droplet of β-stable quark matter is formed. (hereafter the Q phase).

This first seed of quark matter will trigger the conversion [19,38,39] of a pure hadronic star to a quark star. Thus, pure hadronic stars, with values of the central pressure P_c higher

than P_0 and corresponding masses $M > M_{\text{thr}} \equiv M(P_0)$, are metastable to the decay (conversion) to quark stars [1–8]. The mean lifetime of the metastable stellar configuration is related to the time needed to nucleate the first drop of quark matter in the stellar center, and it depends dramatically on the value of the stellar central pressure.

As in Refs. [1–3], we define as the *critical mass* M_{cr} of the hadronic star sequence the value of the stellar gravitational mass for which the nucleation time of a Q^*-matter droplet is equal to 1 year: $M_{\text{cr}} \equiv M_{\text{HS}}(\tau = 1 \text{ yr})$. Pure hadronic stars with $M > M_{\text{cr}}$ are thus very unlikely to be observed. M_{cr} plays the role of an effective maximum mass [3] for the hadronic branch of compact stars.

In a cold and neutrino-free hadronic star the formation of the first drop of quark matter could take place solely via a quantum nucleation process. The basic quantity needed to calculate the nucleation time is the energy barrier separating the Q^* phase from the metastable hadronic phase. This energy barrier, which represents the difference in the free energy of the system with and without a Q^*-matter droplet, can be written as [3,40]

$$U(\mathcal{R}) = \tfrac{4}{3}\pi n_{Q^*}(\mu_{Q^*} - \mu_H)\mathcal{R}^3 + 4\pi\sigma\mathcal{R}^2, \quad (3)$$

where $\mathcal{R}$ is the radius of the droplet (supposed to be spherical) and σ is the surface tension for the surface separating the hadron from the Q^* phase. The energy barrier has a maximum at the critical radius $\mathcal{R}_c = 2\sigma/[n_{Q^*}(\mu_H - \mu_{Q^*})]$.

The quantum nucleation time τ_q can be straightforwardly evaluated within a semiclassical approach [2–4,40] and it can be expressed as

$$\tau_q = (\nu_0 p_0 N_c)^{-1}, \quad (4)$$

where p_0 is the probability of tunneling the energy barrier $U(\mathcal{R})$ in its ground state, ν_0 is the oscillation frequency of a virtual drop of the Q^* phase in the potential well, and $N_c \sim 10^{48}$ is the number of nucleation centers expected in the innermost part ($r \leqslant R_{\text{nuc}} \sim 100$ m) of the hadronic star, where the pressure and temperature (in finite T case) can be considered constant and equal to their central values.

IV. RESULTS AND DISCUSSION

We now discuss the results obtained with the two miscroscopic hadronic EoS considered and, in particular, we comment on whether the possible discussed scenarios are compatible with the recent measurement [41] of the mass of the pulsar PSR J1614-2230 with mass $M = (1.97 \pm 0.04)M_\odot$.

In Fig. 1 we plot the Gibbs energy per baryon as a function of pressure using the microscopic approach of Ref. [27] (Model 1) for the hadronic phase and one of the following models for the Q^* phase: MIT bag model [panels (a) and (b)], CDM [panel (c)], and NJL [panel (d)] model. It is interesting to note that the formation of the Q^* phase is possible only in the case of the MIT bag model EoS with a low value of the bag constant ($B = 85$ MeV fm^{-3}). In all the other cases considered in Fig. 1, the curve for Gibbs energy per baryon for the Q^* phase never crosses the one for the hadronic phase; consequently, the hadronic phase will always remain stable
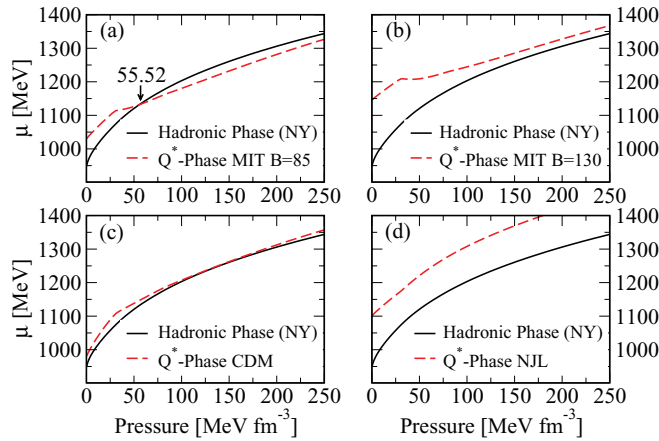
FIG. 1. (Color online) Gibbs energy per baryon at zero temperature as a function of the pressure for the hadronic phase (solid lines) and the Q^* phase (dashed lines). Model 1 has been used to describe the hadronic phase. Results for the MIT bag model with $m_u = m_d = 0$, $m_s = 150$ MeV, and two different values of the bag constant B are presented in panels (a) and (b), whereas those for the CDM and the NJL model are shown in panels (c) and (d). The arrow and the corresponding number indicate the value (in MeV fm^{-3}) of the transition pressure P_0.

with respect to the formation of Q^*-phase droplets. For these three QM models, this result implies that the pure hadronic stars (hyperonic stars) described by Model 1 are stable up to their maximum mass configuration $M_{\max}^{\mathrm{HS}} = 1.37 M_\odot$.

By numerical integration of the Tolman-Oppenheimer-Volkov equations [42], we have calculated the structural properties for pure hadronic and quark star sequences. The main results, in the case of the Model 1 EoS for the hadronic phase, are summarized in Table I, where we report the maximum gravitational mass $M_{\max}^{\mathrm{HS}}$ (third column), the gravitational threshold mass $M_{\mathrm{thr}} \equiv M(P_0)$ for metastable configurations (fourth column), and the gravitational (baryonic) critical mass M_{cr} (M_{cr}^b) [fifth (sixth) column] for the pure hadronic star sequence. M_{fin} (seventh column) is the gravitational mass of the hybrid star formed by the stellar conversion process of the HS with $M = M_{\mathrm{cr}}$ and assuming baryon number conservation in the process [19] (i.e., assuming $M_{\mathrm{fin}}^b = M_{\mathrm{cr}}^b$). Finally E_{conv} is the total energy liberated in the stellar conversion. It is

interesting to note that hybrid star configurations can be obtained with the MIT bag model with $B = 85$ MeV fm^{-3} and with the CDM. In the latter case, however, the transitory non-β-stable Q^* phase is not energetically achievable [see Fig. 1(c)]. Thus in this case the hadronic star sequence is stable up to the maximum mass configuration (thus we have no entries in Table I for the quantities M_{thr}, M_{cr}, M_{cr}^b, M_{fin}, and E_{conv}). In the case of the MIT bag model with $B = 85$ MeV fm^{-3} the Q^*-matter nucleation is possible and one has $M_{\mathrm{cr}} = 1.272 M_\odot$. The conversion of this star will produce a hybrid star with $M_{\mathrm{fin}} = 1.233 M_\odot$. If this object is a member of a binary stellar system, eventual accretion of matter from the companion will allow it to reach a maximum mass of $1.544 M_\odot$. In this case the pulsar PSR J1614-2230 will be neither a hyperonic star nor a hybrid star.

We have also artificially turned off the hyperonic degrees of freedom in the Model 1 EoS and considered pure nucleonic stars. In this case we have $M_{\max}^{\mathrm{HS}} = 2.27 M_\odot$ and a critical mass $M_{\mathrm{cr}} \sim 2.2 M_\odot$ for all the quark matter EoS considered in Table I. In all cases, however, the critical mass configuration will collapse to a black hole (BH entry in seventh column in Table I) and thus the hybrid star sequence cannot be populated. In this case the pulsar PSR J1614-2230 would be a hadronic star containing only nucleons and leptons. We next discuss the results obtained with the hadronic EoS based on our recent work of Ref. [31] (Model 2) where, as we said, a microscopic Brueckner-Hartree-Fock approach of hyperonic matter based on the Argonne V18 NN and the NSC89 NY forces is supplemented with additional simple phenomenological density-dependent contact terms that mimic the effect of nucleonic and hyperonic three-body forces. In particular, we consider three different parametrizations of this model corresponding to different values of the incompressibility coefficient, K_∞, of symmetric nuclear matter at saturation, and the parameter x, which characterizes the strengh of the hyperonic three-body forces: P_1 ($K_\infty = 236$ MeV and $x = 1$), P_2 ($K_\infty = 236$ MeV and $x = 1/3$), and P_3 ($K_\infty = 285$ MeV and $x = 1$). The interested reader is referred to Ref. [31], and particularly to Tables I and II of this reference, for details. The results for this model are shown in Table II and Fig. 2. As in the previous case, we summarize in Table II the main stellar properties obtained with this model in combination with the MIT bag model and the CDM.

TABLE I. Stellar properties for the hadronic EoS of Ref. [27] (Model 1) in the case nuclear matter (only nucleons) or hyperonic matter (nucleons + hyperons) and different models for the quark phase. $M_{\max}^{\mathrm{HS}}$ is the gravitational maximum mass of the pure hadronic star sequence, $M_{\mathrm{thr}} \equiv M(P_0)$ is the gravitational threshold mass for metastable stellar configurations, M_{cr} (M_{cr}^b) is the gravitational (baryonic) critical mass, M_{fin} is the mass of the hybrid star which is formed by the stellar conversion of the hadronic star with $M = M_{\mathrm{cr}}$ and assuming baryon number conservation in the process (i.e., $M_{\mathrm{fin}}^b = M_{\mathrm{cr}}^b$), and finally E_{conv} is the total energy, in units of 10^{51} erg, liberated in the stellar conversion. All stellar masses are expressed in units of the solar mass $M_\odot = 1.9889 \times 10^{33}$ g. The bag pressure B is given in MeV fm^{-3}.

		$M_{\max}^{\mathrm{HS}}$	M_{thr}	M_{cr}	M_{cr}^b	M_{fin}	E_{conv}	$M_{\max}^{\mathrm{HybS}}$
Nucleons + hyperons	MIT ($B = 85$)	1.37	1.227	1.272	1.397	1.233	71.26	1.544
	CDM	1.37	–	–	–	–	–	1.591
Only nucleons	MIT ($B = 85$)	2.27	2.193	2.226	2.677	BH	–	1.544
	MIT ($B = 130$)	2.27	2.242	2.254	2.720	BH	–	1.471
	NJL	2.27	2.229	2.246	2.708	BH	–	1.879
	CDM	2.27	2.242	2.255	2.722	BH	–	1.592

TABLE II. Same as in Table I, but now for the hadronic EoS of Ref. [31] (Model 2) and three different parametrizations of this model: P_1 ($K_\infty = 236$ MeV and $x = 1$), P_2 ($K_\infty = 236$ MeV and $x = 1/3$), and P_3 ($K_\infty = 285$ MeV and $x = 1$).

		M_{max}^{HS}	M_{thr}	M_{cr}	M_{cr}^b	M_{fin}	E_{conv}	M_{max}^{HybS}
P_1	MIT $B = 85$	1.48	1.245	1.368	1.526	1.335	60.32	1.574
P_2	MIT $B = 85$	1.38	1.210	1.230	1.356	1.203	47.62	1.574
P_3	MIT $B = 85$	1.60	1.293	1.504	1.688	1.456	85.57	1.574
P_3	CDM	1.60	1.397	1.472	1.648	1.440	56.96	1.624

Note that in this case with the NJL model no transition occurs for any of the three parametrizations: P_1, P_2, and P_3. In Fig. 2 we plot the Gibbs energy per baryon as a function of pressure using the following: the MIT bag model for the Q^* phase and a hadronic parametrization with the incompressibility $K_\infty = 236$ MeV (P_1) and $K_\infty = 285$ MeV (P_3) with $x = 1$ in both cases. Results for parametrization P_2 and for the CDM and NJL models are not shown for conciseness. It is interesting to note that the parameter x does not influence much the mass and radius of the hybrid star maximum mass configurations.

Note also (see Table II) that, similarly to Model 1, for parametrizations P_1 and P_2, the formation of the Q^* phase is possible only in the case of the MIT bag model EoS with a low value of the bag constant ($B = 85$ MeV fm^{-3}). Nevertheless, for parametrization P_3, the stable hybrid sequence may be populated from the stellar conversion of the critical mass hadronic star if the quark phase is described either with the MIT bag model (with $B = 85$ MeV/fm^3) or with the CDM. As already said, no transition is found for the NJL model. We also note that in the case of the parametrization P_3 plus the MIT bag model with $B = 130$ MeV fm^{-3} the Q^*-phase nucleation time at the center of the maximum mass (M_{max}^{HS})
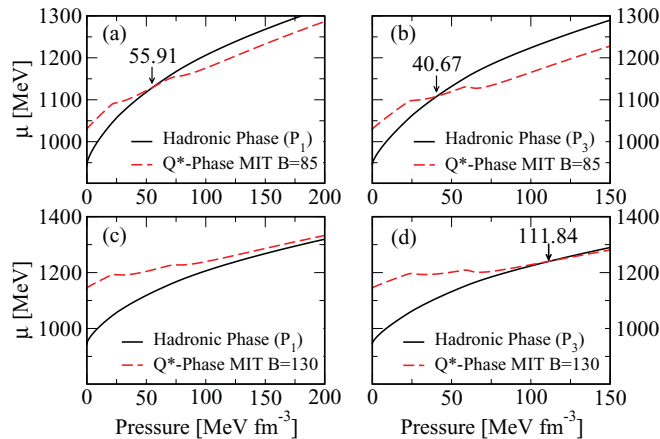

FIG. 2. (Color online) Gibbs energy per baryon at zero temperature as a function of the pressure for the hadronic phase (solid lines) and the Q^* phase (dashed lines). The parametrizations P_1 [panels (a) and (c)] and P_3 [panels (b) and (d)] of Model 2 introduced in Ref. [31] have been used to describe the hadronic phase. Results for the MIT bag model with $B = 85$ [panels (a) and (b)] and 130 MeV fm^{-3} [panels (c) and (d)] are presented. The arrow and the corresponding number indicate the value (in MeV fm^{-3}) of the transition pressure P_0.

hadronic star is much larger than the age of the universe, and thus, it is extremely unlikely to populate the hybrid star branch in this case. In the most favorable scenario the possible largest star mass would be $1.624 M_\odot$ (for CDM). This mass could occur if, after the conversion, the star accreted mass from an eventual companion star if the object was in a binary system.

V. SUMMARY AND CONCLUSIONS

Using the microscopic Brueckner-Hartree-Fock approach to describe the EoS of dense hadronic matter we have studied the possibility of the occurrence of a deconfinement phase transition into quark matter in neutron star cores. Quark matter has been described with three different models, namely, the MIT bag model, the CDM, and the NJL model. We have concluded that hyperonic hadronic stars will not suffer a deconfinement phase transition except if the quark EOS is obtained using the MIT bag model with a value of the bag pressure of $B = 85$ MeV fm^{-3}. In this case, however, it is not possible to get a star with a mass above $1.54 M_\odot$. On the other hand, we have found that if the hadronic matter has no hyperons then deconfinement will occur only in very massive stars, with $M > 2.2 M_\odot$, and the stars will decay into a black hole. Within this microscopic approach to the hadronic phase the pulsar PSR J1614-2230 would be a hadronic star containing only nucleons and leptons.

We have also studied the possible effect of a hyperonic TBF using the model proposed in Ref. [31]. It has been shown that for the hardest EOS with $K_\infty = 285$ MeV and $x = 1$ a hybrid star could be formed. Only the NJL model and the MIT bag model with $B = 130$ MeV fm^{-3} did not predict a metastable star in this case. Within this scenario a maximum mass of $1.624 M_\odot$ was predicted, very far from the mass of the PSR J1614-2230. However, it was also shown that it was not so much the hyperonic TBF strength but more the incompressibility of the nucleonic part of the EoS that defines the possible deconfinement transition.

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