Physics Letters B 680 (2009) 448–452

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Quark matter nucleation in hot hadronic matter

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ARTICLE INFO

Article history:
Received 25 May 2009
Received in revised form 24 July 2009
Accepted 4 September 2009
Available online 17 September 2009
Editor: J.-P. Blaizot

PACS:
26.60.+c
25.75.Nq
97.60.Jd

Keywords:
Dense matter
Elementary particles
Stars: neutron

ABSTRACT

We study the quark deconfinement phase transition in hot β-stable hadronic matter. Assuming a first order phase transition, we calculate the enthalpy per baryon of the hadron–quark phase transition. We calculate and compare the nucleation rate and the nucleation time due to thermal and quantum nucleation mechanisms. We compute the crossover temperature above which thermal nucleation dominates the finite temperature quantum nucleation mechanism. We next discuss the consequences for the physics of proto-neutron stars. We introduce the concept of limiting conversion temperature and critical mass M_{cr} for proto-hadronic stars, and we show that proto-hadronic stars with a mass $M < M_{cr}$ could survive the early stages of their evolution without decaying to a quark star.

1. Introduction

In the last few years there has been a growing interest in the study of the nucleation process of quark matter (QM) in the core of massive neutron stars. In particular, it has been shown [1–8] that above a threshold value of the central pressure a pure hadronic compact star (HS) is metastable to the decay (conversion) to a quark star (QS) (*i.e.*, to a hybrid neutron star or to a strange star [9,10], depending on the details of the equation of state (EOS) for quark matter used to model the phase transition [11–14]). This stellar conversion process liberates a huge amount of energy (a few 10^{53} erg) [15] and it could be the energy source of some of the long Gamma Ray Bursts (GRBs).

The research reported in Refs. [1–8] has focused on the quark deconfinement phase transition in cold ($T = 0$) and neutrino-free neutron stars. In this case the formation of the first drop of QM could take place solely via a quantum nucleation process.

A neutron star at birth (proto-neutron star) is very hot ($T =$ 10–30 MeV) with neutrinos being still trapped in the stellar interior [16,17]. Subsequent neutrino diffusion causes deleptonization and heats the stellar matter to an approximately uniform entropy per baryon $\tilde{S} = 1$–2 (in units of the Boltzmann's constant k_B). Depending on the stellar composition, during this stage neutrino escape can lead the more "massive" stellar configurations to the formation of a black hole [17,18]. However, if the mass of the star is sufficiently small, the star will remain stable and it will cool to temperatures well below 1 MeV within a cooling time $t_{cool} \sim$ a few 10^2 s, as the neutrinos continue to carry energy away from the stellar material [16,17]. Thus in a proto-neutron star, the quark deconfinement phase transition will be likely triggered by a thermal nucleation process. In fact, for sufficiently high temperatures, thermal nucleation is a much more efficient process with respect to the quantum nucleation mechanism.

Some of the earlier studies on quark matter nucleation (see *e.g.* [19–23]) have already dealt with thermal nucleation in hot and dense hadronic matter. In these studies, it was found that the prompt formation of a critical size drop of quark matter via thermal activation is possible above a temperature of about 2–3 MeV. As a consequence, it was inferred that pure hadronic stars are converted to quark stars within the first seconds after their birth. However, these works [19–22] reported an estimate of the thermal nucleation based on "typical" values for the thermodynamic properties characterizing the central part of neutron stars.

Our main objective in this and next related works, is to establish if a newborn hadronic star (proto-hadronic star) could survive the early stages of its evolution without "decaying" to a quark

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doi:10.1016/j.physletb.2009.09.039

star. In the present Letter, we calculate the thermal nucleation rate of quark matter in hot ($T \neq 0$) and neutrino-free hadronic matter using a finite temperature EOS for hadronic and quark matter. In addition, we calculate the quantum nucleation rate at finite temperature, and compare the thermal and quantum nucleation time at different temperatures and pressures characterizing the central conditions of metastable proto-hadronic compact stars. We compute the crossover temperature above which thermal nucleation dominates above the finite temperature quantum nucleation mechanism. Finally we briefly discuss some consequences for the physics of proto-neutron stars.

2. Phase equilibrium

For a first-order phase transition[1] the conditions for phase equilibrium are given by the Gibbs' phase rule

$$T_H = T_Q \equiv T, \qquad P_H = P_Q \equiv P_0, \tag{1}$$

$$\mu_H(T, P_0) = \mu_Q(T, P_0) \tag{2}$$

where

$$\mu_H = \frac{\varepsilon_H + P_H - s_H T}{n_H}, \qquad \mu_Q = \frac{\varepsilon_Q + P_Q - s_Q T}{n_Q} \tag{3}$$

are the Gibbs' energies per baryon (average chemical potentials) for the hadron and quark phase, respectively, ε_H (ε_Q), P_H (P_Q), s_H (s_Q) and n_H (n_Q) denote respectively the total (*i.e.*, including leptonic contributions) energy density, total pressure, total entropy density, and baryon number density for the hadron (quark) phase. Above the "transition point" (P_0) the hadronic phase is metastable, and the stable quark phase will appear as a results of a nucleation process.

Small localized fluctuations in the state variables of the metastable hadronic phase will give rise to virtual drops of the stable quark phase. These fluctuation are characterized by a time scale $\nu_0^{-1} \sim 10^{-23}$ s. This time scale is set by the strong interactions (which are responsible for the deconfinement phase transition), and it is many orders of magnitude shorter than the typical time scale for the weak interactions. Therefore quark flavor must be conserved during the deconfinement transition. We will refer to this form of deconfined matter, in which the flavor content is equal to that of the β-stable hadronic system at the same pressure and temperature, as the Q^*-phase. Soon afterward a critical size drop of quark matter is formed, the weak interactions will 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 [15,24,25] of the pure hadronic star to a hybrid star or to a strange star. Thus, pure hadronic stars with values of the central pressure larger than P_0 are metastable to the decay (conversion) to hybrid stars or to strange stars [1–5]. 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 depends dramatically on the value of the stellar central pressure [1–5].

3. Quantum and thermal nucleation rates

The main effect of finite temperature on the quantum nucleation mechanism of quark matter is to modify the energy barrier separating the quark 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

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

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 $\mathcal{R}_c = 2\sigma/[n_{Q^*}(\mu_H - \mu_{Q^*})]$. Notice that we have neglected the term associated with the curvature energy, and also the terms connected with the electrostatic energy, since they are known to introduce small corrections [2,29]. The value of the surface tension σ for the interface separating the quark and hadron phase is poorly known, and typically values used in the literature range within 10–50 MeV fm^{-2} [26,28,29]. We assume σ to be temperature independent and we take $\sigma = 30$ MeV fm^{-2}.

The quantum nucleation time τ_q can be straightforwardly evaluated within a semi-classical approach [27–29]. First one computes, in the WKB approximation, the ground state energy E_0 and the oscillation frequency ν_0 of the drop in the potential well $U(\mathcal{R}, T)$. Then, the probability of tunneling is given by

$$p_0 = \exp\left[-\frac{A(E_0)}{\hbar}\right] \tag{5}$$

where $A(E)$ is the action under the potential barrier, which in a relativistic framework reads

$$A(E) = \frac{2}{c}\int_{\mathcal{R}_-}^{\mathcal{R}_+} \sqrt{\left[2m(\mathcal{R})c^2 + E - U(\mathcal{R})\right]\left[U(\mathcal{R}) - E\right]} \tag{6}$$

being $\mathcal{R}_\pm$ the classical turning points and $m(\mathcal{R})$ the droplet effective mass. The quantum nucleation time is then equal to

$$\tau_q = (\nu_0 p_0 N_c)^{-1}, \tag{7}$$

with $N_c \sim 10^{48}$ being the number of nucleation centers expected in the innermost part ($r \leqslant R_{nuc} \sim 100$ m) of the hadronic star, where the pressure and temperature can be considered constant and equal to their central values.

The thermal nucleation rate can be written [32] as

$$I = \frac{\kappa}{2\pi}\Omega_0 \exp\bigl(-U(\mathcal{R}_c, T)/T\bigr) \tag{8}$$

where κ is the so-called dynamical prefactor, which is related to the growth rate of the drop radius $\mathcal{R}$ near the critical radius ($\mathcal{R}_c$), Ω_0 is the so-called statistical prefactor, which measures the phase-space volume of the saddle-point region around $\mathcal{R}_c$, and $U(\mathcal{R}_c, T)$ is the activation energy, *i.e.*, the change in the free energy of the system required to activate the formation of a critical size droplet. The Langer theory [30–33] of homogeneous nucleation has been extended in Refs. [34,35] to the case of first order phase transitions occurring in relativistic systems, as in the case of the quark deconfinement transition. The statistical prefactor, can be written [34] as

$$\Omega_0 = \frac{2}{3\sqrt{3}}\left(\frac{\sigma}{T}\right)^{3/2}\left(\frac{\mathcal{R}}{\xi_Q}\right)^4 \tag{9}$$

where ξ_Q is the quark correlation length, which gives a measure of the thickness of the interface layer between the two phases (the droplet "surface thickness"). In the present calculation we take $\xi_Q = 0.7$ fm according to the estimate given in Refs. [22,34].

[1] We assume the quark deconfinement phase transition to be of the first order. This assumption is common in most of the studies of quark deconfinement in compact stars.

For the dynamical prefactor we have used a general expression which has been derived by Venugopalan and Vischer [35] (see also Refs. [34,36])

$$\kappa = \frac{2\sigma}{\mathcal{R}_c^3(\Delta w)^2}\left[\lambda T + 2\left(\frac{4}{3}\eta + \zeta\right)\right], \tag{10}$$

where $\Delta w = w_{Q^*} - w_H$ is the difference between the enthalpy density of the two phases, λ the thermal conductivity, η and ζ are the shear and bulk viscosities respectively of hadronic matter. Notice that the nucleation prefactor used in the present work differs significantly from the one used in previous works [19–21] where, based on dimensional grounds, the prefactor was taken to be equal to T^4.

There are not many calculations of the transport properties of dense hadronic matter. With a few exceptions (see *e.g.* [37,38]), most of them are relative to nuclear or pure neutron matter [39–43]. These quantities have been calculated by Danielewicz [40] in the case of nuclear matter. According to the results of Ref. [40], the dominant contribution to the prefactor κ comes from the shear viscosity η. Therefore, we take λ and ζ equal to zero, and we use for the shear viscosity the following relation [40]:

$$\eta = \frac{7.6\times 10^{26}}{(T/\mathrm{MeV})^2}\left(\frac{n_H}{n_0}\right)^2 \frac{\mathrm{MeV}}{\mathrm{fm\,s}}, \tag{11}$$

with $n_0 = 0.16\ \mathrm{fm}^{-3}$ being the saturation density of normal nuclear matter.

The thermal nucleation time τ_{th}, relative to the innermost stellar region ($V_{nuc} = (4\pi/3)R_{nuc}^3$) where almost constant pressure and temperature occur, can thus be written as $\tau_{th} = (V_{nuc} I)^{-1}$.

4. Equation of state

Over the last decade, it has been realized that strong interacting matter at high density and low temperature may possess a large assortment of phases. Different possible patterns for color superconductivity have been conjectured (see *e.g.* [44,45] and references therein quoted). Very recently, a new phase of QCD, named quarkyonic phase, has been predicted [46,47]. This hypothetical matter phase is characterized by chiral symmetry and confinement [46–48].

In the present work, we have adopted a more traditional view, assuming a single first order phase transition between the confined (hadronic) and deconfined phase of dense matter, and we have used rather common models for describing them. For the hadronic phase we have used models which are based on a relativistic Lagrangian of hadrons interacting via the exchange of σ, ρ and ω mesons. We have used one of the parameters sets given in Ref. [49]: hereafter we refer to this model as the GM1 equation of state. For the quark phase we have adopted a phenomenological EOS [11] which is based on the MIT bag model for hadrons. In this work, we have used the following set of parameters: $m_u = m_d = 0$, $m_s = 150$ MeV for the masses of the *up*, *down* and *strange* quark, respectively, $B = 85\ \mathrm{MeV/fm^3}$ for the bag constant, and $\alpha_s = 0$ for the QCD structure constant. The two models for the EOS have been generalized to the case of finite temperature.

5. Results and discussion

In Fig. 1 we plot the Gibbs' energies per baryon for the hadron-phase and the Q^*-phase at different temperatures, $T = 0$, 10, 20, 3 MeV; lines with the larger slope refer to the hadron-phase. As we see, the transition pressure P_0 (indicated by a full dot) decreases when the hadronic matter temperature is increased. The

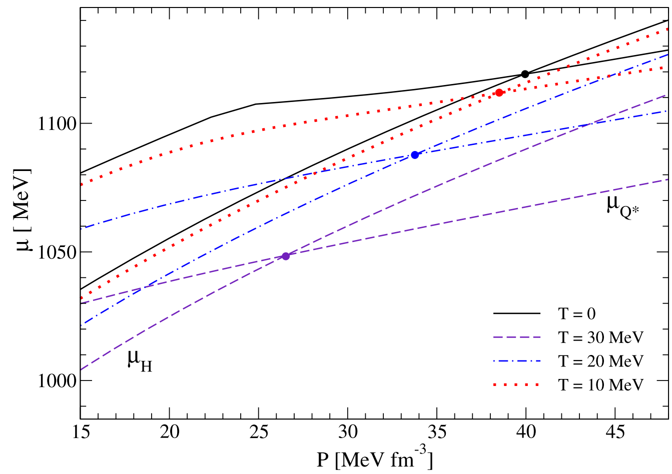

Fig. 1. (Color online.) Gibbs energy per baryon as a function of pressure for the hadronic and quark phases at different temperatures. Lines with the larger slope refer to the hadronic phase. Full dots indicate the transition pressure P_0 for each temperature.

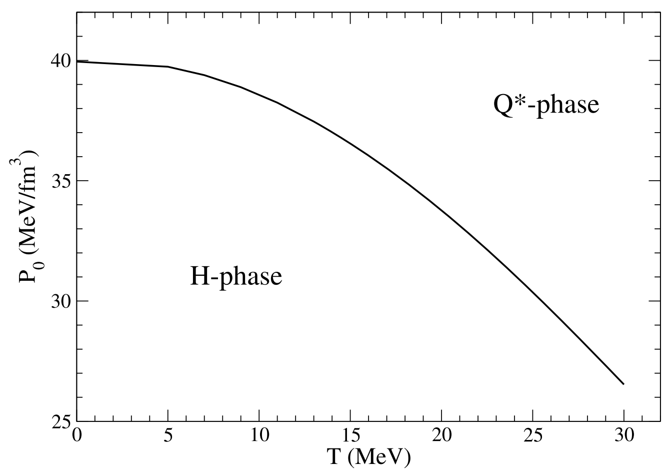

Fig. 2. Phase equilibrium curve for the hadron to quark matter phase transition.

phase equilibrium curve $P_0(T)$ for the hadron–quark phase transition (within the present schematic model for the EOS) is shown in Fig. 2. As it is well known, for a first-order phase transition the derivative dP_0/dT is related to the specific (*i.e.*, per baryon) latent heat $\mathcal{Q}$ of the phase transition by the Clapeyron–Clausius equation

$$\frac{dP_0}{dT} = -\frac{n_H n_{Q^*}}{n_{Q^*} - n_H}\frac{\mathcal{Q}}{T}, \tag{12}$$

$$\mathcal{Q} = \tilde{W}_{Q^*} - \tilde{W}_H = T(\tilde{S}_{Q^*} - \tilde{S}_H) \tag{13}$$

where $\tilde{W}_H$ ($\tilde{W}_{Q^*}$) and $\tilde{S}_H$ ($\tilde{S}_{Q^*}$) denote respectively the enthalpy per baryon and entropy per baryon for the hadron (quark) phase. The specific latent heat $\mathcal{Q}$ and the phase numbers densities n_H and n_{Q^*} at phase equilibrium are reported in Table 1. As expected for a first order phase transition one has a discontinuity jump in the phase number densities: in our particular case $n_{Q^*}(T, P_0) > n_H(T, P_0)$. This result, together with the positive value of $\mathcal{Q}$ (*i.e.*, the deconfinement phase transition absorbs heat) tell us (see Eq. (12)), that the transition temperature decreases with pressure (as in the melting of ice).

In Fig. 3, we represent the energy barrier for a virtual drop of the Q^*-phase as a function of the droplet radius and for different temperatures at a fixed pressure $P = 57\ \mathrm{MeV/fm^3}$. As expected, from the results plotted in Fig. 1, the energy barrier $U(\mathcal{R}, T)$ and

Table 1
The specific latent heat $\mathcal{Q}$ and the phase numbers densities n_H and n_{Q^*} at phase equilibrium.

T MeV	$\mathcal{Q}$ MeV	n_{Q^*} fm^{-3}	n_H fm^{-3}	P_0 $\mathrm{MeV/fm}^{-3}$
0	0.00	0.453	0.366	39.95
5	0.56	0.451	0.364	39.74
10	2.40	0.447	0.358	38.58
15	5.71	0.439	0.348	36.55
20	10.60	0.428	0.334	33.77
25	17.17	0.414	0.316	30.36
30	25.44	0.398	0.294	26.53

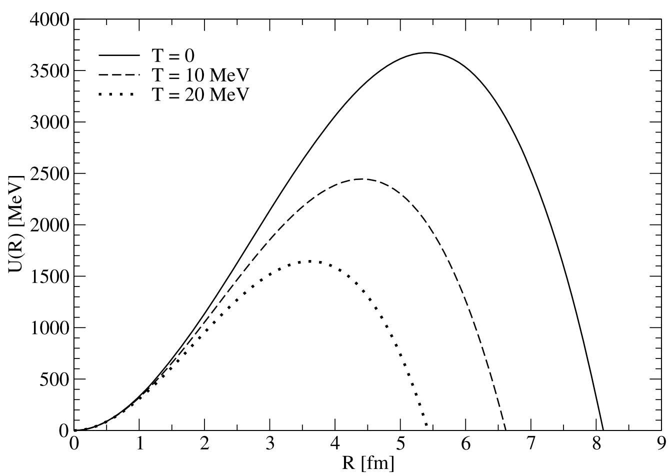

Fig. 3. Energy barrier for a virtual drop of the Q^*-phase as a function of the droplet radius and for different temperatures for a pressure $P = 57\ \mathrm{MeV/fm}^3$.

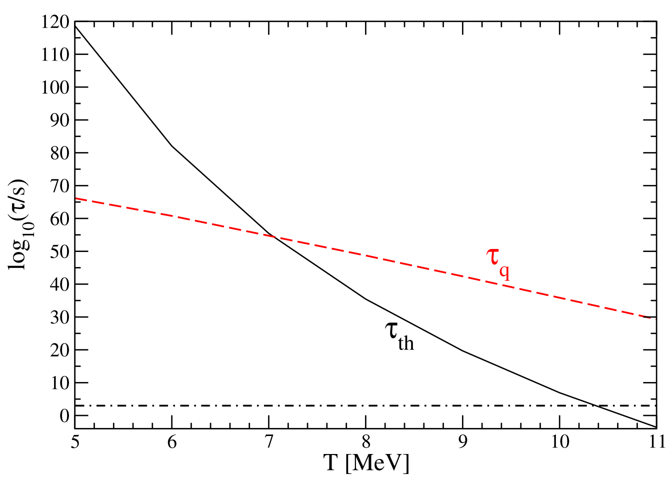

Fig. 4. (Color online.) Thermal (τ_{th}) and quantum (τ_q) nucleation time of quark matter (Q^*-phase) in β-stable hadronic matter as a function of temperature at fixed pressure $P = 57\ \mathrm{MeV/fm}^3$. The crossover temperature is $T_{co} = 7.05$ MeV. The limiting conversion temperature for the proto-hadronic star is, in this case, $\Theta = 10.3$ MeV, obtained from the intersection of the thermal nucleation time curve (continuous line) and the dot-dashed line representing $\log_{10}(\tau/s) = 3$.

the droplet critical radius $\mathcal{R}_c$ decrease as the matter temperature is increased. This effect favors the Q^*-phase formation, and in particular increases (decreases) the quantum nucleation rate (nucleation time τ_q) with respect to the corresponding quantities calculated at $T = 0$.

In Fig. 4 we plot the quantum and thermal nucleation times of the Q^*-phase in β-stable hadronic matter as a function of temperature and at a fixed pressure $P = 57\ \mathrm{MeV/fm}^3$. As expected, we find a crossover temperature T_{co} above which thermal nucleation is dominant with respect to the quantum nucleation mechanism. For the case reported in Fig. 4, we have $T_{co} = 7.05$ MeV and the corresponding nucleation time is $\log_{10}(\tau/s) = 54.4$. The crossover temperature, for different values of the pressure of β-stable hadronic matter, is reported in Table 2 (second column) together with the nucleation time calculated at $T = T_{co}$ (third column).

Table 2
Crossover temperature T_{co} (in MeV), for different fixed values of the pressure P (in $\mathrm{MeV/fm}^3$) of hadronic matter. The third column reports the logarithm of the nucleation time (in seconds) calculated at the crossover temperature. The value 8.3 MeV defines the value of the limiting conversion temperature Θ for a star with a central pressure $P = 58.85\ \mathrm{MeV\,fm}^{-3}$.

P	T_{co}	$\log_{10}(\tau/s)$
53.98	5.0	233.6
55.48	6.0	121.3
56.94	7.0	56.6
58.42	8.0	16.0
58.85	8.3	3.0

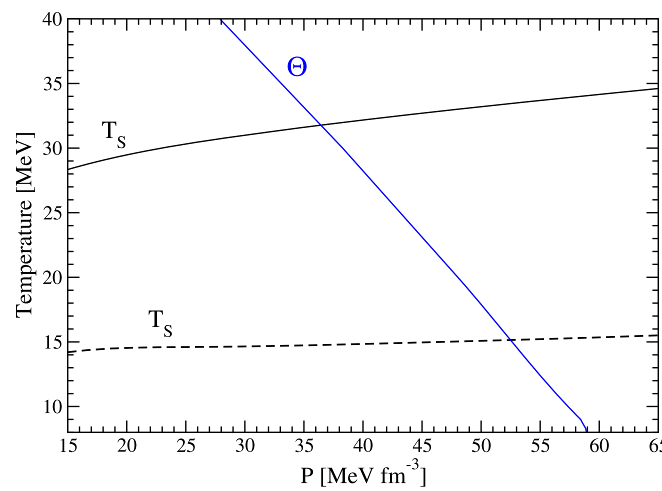

Fig. 5. (Color online.) The limiting conversion temperature Θ for a newborn hadronic star as a function of the central stellar pressure. Newborn hadronic stars with a central temperature and pressure located on the right side of the curve $\Theta(P)$ will nucleate a Q^*-matter drop during the early stages of their evolution, and will finally evolve to cold and deleptonized quark stars, or will collapse to black holes. The lines labeled T_S represent the stellar matter temperature as a function of pressure at fixed entropies per baryon $\tilde{S}/k_B = 1$ (dashed line) and 2 (solid line).

Having in mind the physical conditions in the interior of a proto-hadronic star [16,17] (see Section 1 of the present Letter), to establish if this star will survive the early stages of its evolution without "decaying" to a quark star, one has to compare the quark matter nucleation time $\tau = \min(\tau_q, \tau_{th})$ with the cooling time $t_{cool} \sim$ a few 10^2 s. If $\tau \gg t_{cool}$ then quark matter nucleation will not likely occur in the newly formed star, and this star will evolve to a cold deleptonized configuration. We thus introduce the concept of *limiting conversion temperature* Θ for the proto-hadronic star and define it as the value of the stellar central temperature T_c for which the Q^*-matter nucleation time is equal to 10^3 s. The limiting conversion temperature Θ will clearly depend on the value of the stellar central pressure (and thus on the value of the stellar mass).

The limiting conversion temperature Θ is plotted in Fig. 5 as a function of the stellar central pressure. A proto-hadronic star with a central temperature $T_c > \Theta$ will likely nucleate a Q^*-matter drop during the early stages of its evolution, and will finally evolve to a cold and deleptonized quark star, or will collapse to a black

Table 3
Gravitational (M_{cr}) and baryonic ($M_{B,cr}$) critical mass (see text for more details) for proto-hadronic stars at different entropy per baryon $\tilde{S}/k_B$. $\mathcal{M}$ denotes the gravitational mass of the cold hadronic configuration with the same stellar baryonic mass ($M_{B,cr}$). Stellar masses are in units of the solar mass, $M_\odot = 1.989 \times 10^{33}$ g.

$\tilde{S}/k_B$	M_{cr}	$M_{B,cr}$	$\mathcal{M}$
0.0	1.573	1.752	1.573
1.0	1.494	1.643	1.485
2.0	1.390	1.492	1.361

hole (depending on the particular model adopted for the matter EOS).

For an isoentropic stellar core [16,17], the central temperature of the proto-hadronic star is given, for the present EOS model, by the lines labeled by T_S in Fig. 5, relative to the case $\tilde{S} = 1k_B$ (dashed curve) and $\tilde{S} = 2k_B$ (continuous curve). The intersection point (P_S, Θ_S) between the two curves $\Theta(P)$ and $T_S(P)$ thus gives the central pressure and temperature of the configuration that we denote as the *critical mass* configuration of the proto-hadronic stellar sequence. The value of the gravitational critical mass $M_{cr} = M(P_S, \Theta_S)$ and baryonic critical mass $M_{B,cr}$ are reported in Table 3, for three different choices of the entropy per baryon, $\tilde{S}/k_B = 0$ (corresponding to a cold hadronic star),[2] 1 and 2. In the same table, we also report the value of the gravitational mass $\mathcal{M}$ of the cold hadronic star with baryonic mass equal to $M_{B,cr}$. This configuration is stable ($\tau = \infty$) with respect to Q^*-matter nucleation in the case $\tilde{S}/k_B = 2$, and it is essentially stable (having a nucleation time enormously larger than the age of the universe) in the case $\tilde{S}/k_B = 1$. Note that these numbers are model dependent and, therefore, one must take them just as indicative values. A careful analysis is beyond the scope of the present work and it will be addressed in a future work.

In summary, in this work we have studied the quark deconfinement phase transition in hot β-stable hadronic matter, and we have explored some of its consequences for the physics of neutron stars at birth. Our main finding is that proto-hadronic stars with a mass lower that the critical value M_{cr} could survive the early stages of their evolution without decaying to a quark star. However, the prompt formation of a critical size drop of quark matter could take place when $M > M_{cr}$. These proto-hadronic stars evolve to cold and deleptonized quark stars, or collapse to a black holes. Finally, if quark matter nucleation occurs during post-bounce stage of core-collapse supernova, then the quark deconfinement phase transition could trigger a delayed supernova explosion characterized by a peculiar neutrino signal [50].

Acknowledgements

This work was partially supported by FCT (Portugal) under the project CERN/FP/83505/2008 and by COMPSTAR, an ESF Research Networking Programme.

[2] Notice that in Refs. [1–6] the critical mass for cold ($T = 0$) metastable hadronic stars has been defined as the value of the gravitational mass for which the quantum nucleation time is equal to one year: $M_{cr}(T = 0) = M(\tau_q = 1\ \text{yr})$. It is worth recalling that the nucleation time τ_q is an extremely steep function of the hadronic star mass [1,2], therefore the exact value of τ_q chosen in the definition of $M_{cr}(T = 0)$ is not crucial (one must take a "reasonable small" value of τ_q, much shorter that the age of young pulsars as the Crab pulsar). We have verified that changing τ_q from 1 yr to 10^3 s modifies $M_{cr}(T = 0)$ by $\sim 0.02\%$. On the other hand, the nucleation time $\tau = \min(\tau_q, \tau_{th})$ entering in the definition of the critical mass of proto-hadronic stars $M_{cr}(\tilde{S})$ must be comparable to the proto-hadronic star cooling time t_{cool}.

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