PROCEEDINGS OF SCIENCE

Thermal Nucleation of Quark Matter in a Lepton-Rich Environment

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PoS(NIC XI)158

Soon after the collapse of a massive star, very high densities and temperatures can be achieved. In particular, such conditions may allow for a phase transition from nuclear matter to quark matter. Assuming this phase transition to be of first order, the simplest mechanism for phase conversion is the nucleation of bubbles of the quark phase inside the uniform nuclear matter phase. In this work, we compare the nucleation time scales with the typical time scale of the early post-bounce phase in a supernova explosion. We find that nucleation is a feasible mechanism for phase conversion in this scenario only if the surface tension between the nuclear and the quark phases has a relatively small value.

11th Symposium on Nuclei in the Cosmos, NIC XI
July 19-23, 2010
Heidelberg, Germany

*Speaker.

1. Introduction

Core-collapse supernovae are among the most energetic astrophysical phenomena. Soon after the bounce stage of the explosion, when the star is still lepton-rich, its temperature can reach few tens of MeV (1 MeV$\sim 10^{10}$K) and its density rapidly becomes considerably higher than that of atomic nuclei (roughly between 1-2 ρ_0).

Such extreme conditions may have dramatic effects on the matter which form these objects. For example, it is expected that at sufficiently high baryon densities and relatively low temperatures strongly interacting matter undergoes a phase transition from hadronic matter to quark matter.

It has been long proposed that first order phase transitions may trigger violent processes in the restless environment of a proto-neutron star [1]. In fact, as shown in [2], a phase transition from nuclear to quark matter soon after the bounce may destabilise the stellar core and provoke a second delayed collapse and bounce. This second bounce, intimately related to the phase transition, would be sufficiently energetic to revive the stalled accretion shock front and allow an explosion of the supernova.

2. Thermal Nucleation

In this work, we assume a necessary (although not sufficient) condition for the phase transition to happen during the lepton-rich phase soon after bounce: the microscopic, out-of-equilibrium phase conversion mechanism must be faster than the duration of the pre-deleptonization phase. (If this is not fulfilled, the transition may still happen at later stages, especially when the star is colder and denser [3].)

It is a general feature of first-order phase transitions that, for systems close to (and beyond) the coexistence line, the dominant fluctuations that initiate the phase conversion are bubbles of the stable phase (i.e., the quark phase for high densities) which are nucleated inside the metastable (nuclear) phase. Such bubbles grow, as long as their radii are larger than a critical value (the critical radius), and complete the phase conversion.

Given the conditions of high temperature in the post-bounce phase, the main mechanism for phase conversion is thermal nucleation of bubbles of the (stable) quark phase which appear inside the (metastable) nuclear phase. The formation of such bubbles, although spontaneous, is not an instantaneous process. Due to the energy barrier that has to be overcome in order to form a bubble containing the stable phase, the rate of formation of such bubbles can be strongly suppressed. Such a suppression is very strongly influenced by one physical parameter, the surface tension σ between the hadron and the quark phases.

The number of critical bubbles formed per unit volume per unit time is given in the thin-wall approximation by [4, 5, 6] (ΔF is the activation barrier, T is the temperature and Δp is the difference of pressure between the hadron and the quark bulk phases)

$$\Gamma = \mathscr{P} \exp\left[-\frac{\Delta F}{T}\right], \tag{2.1}$$

where

$$\Delta F = \frac{16\pi}{3}\frac{\sigma^3}{(\Delta p)^2}. \tag{2.2}$$

Once we wish to estimate the minimum time scale associated with the phase conversion, we consider this to be the time of nucleation of one single critical bubble in the whole stellar ultradense core. Although the formation of one single bubble is probably not sufficient to complete the phase conversion, it is surely a necessary condition. Therefore, if the formation time for this single bubble is higher than the dynamical time scale of the stellar evolution (say ∼100ms), it is very unlikely that the phase conversion may proceed at this point via bubble nucleation.

We estimate the time scale for the nucleation of one critical quark matter bubble in the core of a proto-neutron star. Given the relatively flat density and temperature profiles very close to the center of the proto-neutron star, we assume that the probability per unit time where such a bubble is allowed to appear should be approximately constant in a volume of the order of $1\mathrm{km}^3$. So, the typical time scale for the nucleation of the first bubble is given by

$$\tau \equiv \left(\frac{1}{\mathrm{km}^3}\right)\frac{1}{\Gamma}. \qquad (2.3)$$

In order to calculate the nucleation rate (2.1), we consider the following set of equations of state (in the presence of free electrons and neutrinos):

- Relativistic mean-field (Shen et al.) [7] for the hadronic phase;
- Quark Bag model (2+1 flavors) for the quark phase.

We assume that nuclear matter becomes metastable in a relatively low density ($\rho_c = 1.5\rho_0$), in order to make the transition to quark matter possible soon after the bounce. Local charge neutrality and local lepton fraction are fixed in both phases (the results presented are for $Y_L = 0.4$). We also assume beta-equilibrium in both phases. This choice leaves us with one independent parameter for the chemical composition (e.g., the baryon chemical potential). More details of the model that we adopted can be found in [6].

3. Nucleation time scales and importance of surface tension

In Fig. 1 we show typical examples of the dependence of the nucleation time scale with baryon density. As can be seen from (2.1) and (2.2), the nucleation time depends very strongly on the baryon density (via pressure difference) and even more strongly on the surface tension of separation between hadron and quark phases. (Notice the logarithmic scale in the time axis.)

The dependence of the nucleation time τ with density is so strong that one can think of a threshold density for quark matter nucleation, at which the nucleation time is of the order of, say, 100ms. In Fig. 2, we show how the threshold density changes with the surface tension: points to the left of the lines have very slow nucleation and points to its right have very fast nucleation.

4. Discussion

When the dynamics of the phase transition is taken into account, it is possible that the formation of the new phase might be considerably delayed, or even suppressed, unless the surface tension is very small.

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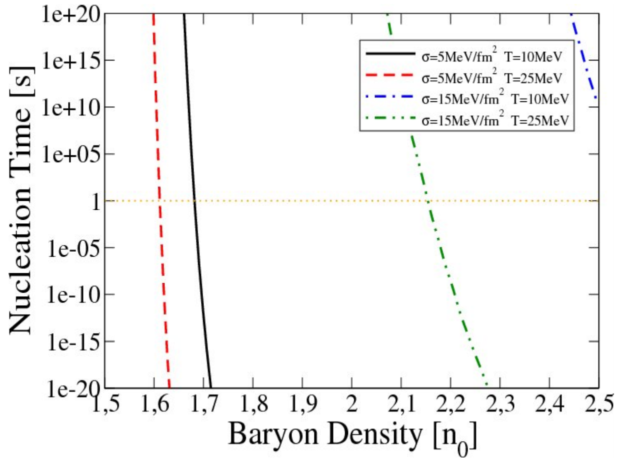

Figure 1: Nucleation time as a function of baryon density for u-d quark matter ($n_c = 1.5n_0$). The horizontal line corresponds to $\tau = 1$s. Higher temperatures and lower surface tensions make nucleation faster.

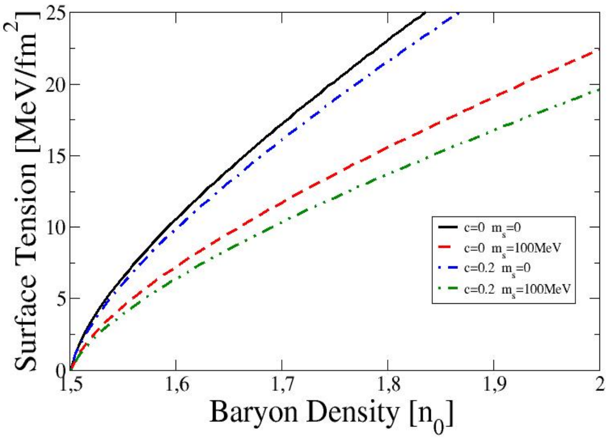

Figure 2: Contour plots of nucleation time (τ=100ms) for T=25MeV ($n_c = 1.5n_0$). For a given surface tension, points to the right of the curves give very short nucleation times, whereas points to the left correspond to very slow nucleation (see Fig. 1). As in [6], $c = 0$ ($c \neq 0$) corresponds to free (interacting) quarks and m_s is the current mass of the strange quark.

Recently, an estimate of the surface tension was made in the context of the linear sigma model [8]. The results show a low value of the surface tension (between 5 and 15 MeV/fm^2). Of course, being an estimate in an effective model, the numbers are not expected to correspond to actual values for cold and dense matter, although they point to the possibility of the surface tension not being extremely high. Further estimates of the surface tension in other effective models would be highly welcome.

This work considers only the appearance of the first critical bubble inside a metastable overcompressed volume of nuclear matter. A more detailed approach would consider the time evolution of the (volume) fraction of quark matter and how it could influence its (initially hadronic) environment. Preliminary results [9] indicate that, once nucleation is started, it brings the system from a metastable state to the mixed phase quite early (i.e., with a low quark fraction) and in a relatively short time scale. From this point on, the evolution is governed by the dynamics of phase conversion in equilibrium through the mixed phase. However, the transition from the metastable nuclear state to the mixed phase implies a reduction of the pressure of the fluid. If such a rarefaction is strong enough, the protoneutron star can suffer a destabilization (beyond that related to the appearance of the mixed phase [2]). Work is currently in progress to study this possibility [9].

Acknowledgements

B. W. M. thanks I. Sagert and M. Hempel for fruitful discussions. B. W. M. and E. S. F. acknowledge CAPES, CNPq, FAPERJ, and FUJB/UFRJ for financial support. The work of G. P. is supported by the Alliance Program of the Helmholtz Association (HA216/EMMI) and by the Deutsche Forschungsgemeinschaft (DFG) under Grant No. PA1780/2-1. J. S. B. is supported by the DFG through the Heidelberg Graduate School of Fundamental Physics. The authors also thank the CompStar program of the European Science Foundation.

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