Thermodynamic instabilities in compact stars

A. Lavagno[a,b] and D. Pigato[a]

[a]*Department of Applied Science and Technology, Politecnico di Torino, I-10129, Italy*
[b]*INFN, Sezione di Torino, I-10125 Torino, Italy*

Abstract

We investigate the presence of thermodynamic instabilities in the high density nuclear matter reached in the central core of compact stars. In the framework of a relativistic mean-field theory, we study the cold hadronic equation of state in beta-equilibrium and charge neutral matter, including hyperons and Δ-isobar degrees of freedom. By considering fluctuations of the electric charge concentration of strongly interacting matter, we analyze a finite density phase transition characterized by pure hadronic matter with both mechanical instability that by chemical-diffusive instability. It turns out that in this situation hadronic phases with different values of electric charge content may coexist, with several implications in the bulk properties of compact stars.

Keywords: phase transition, fluctuations of conserved charges, neutron stars

1. Introduction

The physics of compact star is strictly connected with statistical mechanics and possible phase transition phenomena due to a large average number of particles involved in the high density core of the stars. In the recent years, many data from X-ray satellites provide important information on the structure and formation of compact stellar objects giving a unique opportunity to explore the bulk thermodynamics and the equation of state (EOS) of strongly interacting matter at different regimes [1, 2, 3, 4, 5, 6].

Relativistic heavy-ion collisions have provided several information about the nuclear EOS in regime of high temperature and low baryon chemical potential where new phase of strongly interacting matter, named quark gluon plasma, can be generated and non-conventional statistical mechanics effects can take place [7, 8, 9, 10, 11, 12].

At low temperatures and subnuclear densities, a liquid-gas type of phase transition was first predicted theoretically and later observed experimentally in a nuclear multifragmentation phenomenon at intermediate-energy nuclear reactions [13, 14, 15, 16]. On the other hand, the behavior of matter at large densities is still poorly known but, on general grounds, new degrees of freedom with the inclusion of baryon heavier than the nucleons are expected to appear and they should generate a softening of the equation of state. In the recent year, liquid-gas phase transition in the nuclear EOS has been extended in different regimes below and above the nuclear saturation density [17, 18, 19, 20].

By requiring the Gibbs conditions on the global conservation of baryon number and zero net electric charge, in this paper we are going to investigate the possible presence of thermodynamic instabilities and subsequent phase transitions in the high density hadronic matter. Differently of previous investigations, we will see that the inclusion of the Δ-isobar degrees of freedom in the EOS plays a crucial role in the generation of mechanical and chemical instability in the core of compact stars.

2. Hadronic β-stable equation of state

We study the hadronic β-stable nuclear matter at zero temperature in the framework of a relativistic mean-field model in which the interaction between baryons is mediated by the exchange of a scalar meson σ, an isoscalar vector meson ω, and a isovector vector ρ. We consider the recently introduced parametrization of the nuclear EOS, called SFHo [21], which accounts for the experimental observation related to the symmetry energy and of constraints from terrestrial and astrophysical data relative to the density derivative of the symmetry energy. In this context, it is relevant to observe that the nuclear EOS is obtained at the mean-field level. Recently, the effect of bosonic quantum fluctuations have been estimated by means of a functional renormalization group technique with massless fermions coupled to scalars through Yukawa coupling [22, 23]. Within this approach, due to quantum fluctuations, an effect of about 5% in the mass-radius relation of a compact star were obtained [24].

Hyperon degrees of freedom are included in the EOS by fixing the values of the hyperon-meson coupling constants to reproduce the potential depth of hyperons at saturations ($U_\Lambda^N = -28$ MeV, $U_\Sigma^N = +30$ MeV, $U_\Xi^N = -18$ MeV) [25]. Besides hyperons, a state of high density resonance $\Delta(1232)$-isobar matter may be formed in the core of the compact star. Transport model calculations and experimental results indicate that an excited state of baryonic matter is dominated by the Δ-resonance at the energy from AGS to RHIC [26, 27, 28, 29]. It has been pointed out that the existence of Δ-isobars can be very relevant also in the core of neutron stars [30, 31, 32, 33]. Moreover, in symmetric nuclear matter and in the framework of a non-linear Walecka model, it has been predicted that a phase transition from nucleonic matter to Δ-excited nuclear matter can take place and the occurrence of this transition sensibly depends on the value of the Δ-meson coupling constants [27, 34].

Qualitatively, it has been possible to establish that the Δ-isobars inside a nucleus feel an attractive potential. There are several purely theoretical studies on the properties of the isobars in the nuclear medium: for instance, in Ref. [35], from QCD sum rules, it has been found that the coupling ratio $\Delta - \omega$ with respect to the nucleons-ω is significantly smaller than one. One the other hand, in Ref. [36], by studying coherent pion production in neutrino-nucleus scattering a good agreement with the experimental data was obtained by assuming a Δ potential equal to the nucleon one.

From phenomenological analysis of electron-nucleus, photoabsorption and pion nucleus scattering data can be extracted different experimental constraints related to the physical values of the Δ-meson coupling constants $x_{\sigma\Delta} = g_{\sigma\Delta}/g_{\sigma N}$ and $x_{\omega\Delta} = g_{\omega\Delta}/g_{\omega N}$, which can be used in the nuclear EOS [31, 37, 38, 39, 40, 41]. For what concerns the coupling with the $\Delta - \rho$ meson is not possible to extract experimental constraints and from here on we will fix the same coupling with the nucleons ($x_{\rho\Delta} = g_{\rho\Delta}/g_{\rho N} = 1$).

In Fig. 1, we report the relation between the coupling ratios obtained by considering the experimental constraints (see Ref.[31] for details) for the SFHo EOS [21]. Furthermore, as we will see, for coupling ratios below the red line, the EOS results to be unstable and there is therefore a window of parameters, compatible with the experimental constraints, for which an hadronic phase transition can take place. In the next Sections, we are going to investigate how this matter of fact can influence the bulk properties of compact stars.

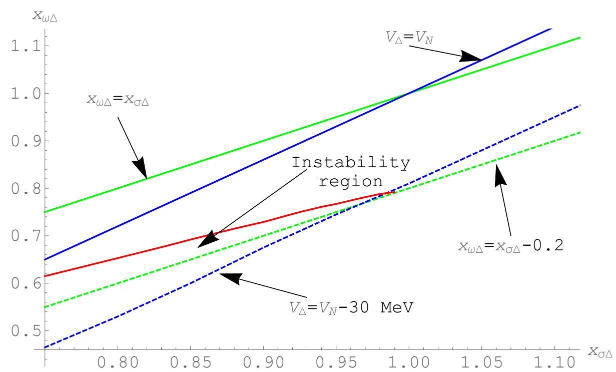

Figure 1: Relation between the coupling ratios $x_{\omega\Delta}$ and $x_{\sigma\Delta}$ in terms of experimental constraints related to pion and electron scattering and from photoabsorption on nuclei. Below the red line, thermodynamic instabilities are present in the equation of state.

3. Thermodynamic instabilities in β-stable nuclear matter

As previously observed, we are dealing with the study of a multi-component system with two conserved charges: baryon number and zero net electric charge (strangeness is not conserved in β-stable matter). The baryon chemical potential μ_i of the ith baryon particle are obtained by the β-equilibrium conditions: $\mu_i = \mu_B + c_i\,\mu_C$, where μ_B and μ_C are the chemical potentials associated with conservation of the baryon number and electric charge, respectively, and c_i is the electric charge of the ith baryon.

Assuming the presence of two phases (denoted as I and II, respectively), the system is stable against the separation in two phases if the free energy of a single phase is lower than the free energy in all two phases configuration. The phase coexistence is given by the Gibbs conditions

$$\mu_B^I = \mu_B^{II}\,, \qquad \mu_C^I = \mu_C^{II}\,, \tag{1}$$

$$P^I(T,\mu_B,\mu_C) = P^{II}(T,\mu_B,\mu_C)\,. \tag{2}$$

Therefore, at a given baryon density ρ_B and at a given net electric charge density $\rho_C = r_c\,\rho_B$ (with $r_c = Z/A$), the chemical potentials μ_B are μ_C are univocally determined.

An important feature of this conditions is that, unlike the case of a single conserved charge where the pressure in the so-called Maxwell construction is constant, for two conserved charges the pressure in the mixed phase is not constant and, although the total ρ_B and ρ_C are fixed, baryon and electric charge densities can be different in the two phases. For such a system in thermal equilibrium, the binodal coexistence surface is two dimensional and the instabilities in the mixed phase arise from fluctuations in the electric charge concentration (chemical instability) and in the baryon density (mechanical instability) [15, 20, 42].

As usual the condition of the mechanical stability implies

$$\rho_B \left(\frac{\partial P}{\partial \rho_B}\right)_{T,\,\rho_C} > 0\,. \tag{3}$$

When the compressibility becomes negative, at fixed temperature and electric charge density, a mechanical instability is present in the EOS.

Furthermore, the chemical stability condition is satisfied if [15, 20]

$$\left(\frac{\partial \mu_C}{\partial r_c}\right)_{T,P} > 0 \quad \text{or} \quad \left\{ \begin{array}{l} \left(\dfrac{\partial \mu_B}{\partial r_c}\right)_{T,P} < 0\,, \quad \text{if } r_c > 0\,, \\[2ex] \left(\dfrac{\partial \mu_B}{\partial r_c}\right)_{T,P} > 0\,, \quad \text{if } r_c < 0\,. \end{array} \right. \tag{4}$$

Whenever the above stability conditions are not respected, the system becomes unstable. The coexistence line of a system with one conserved charge becomes in this case a binodal surface in (T, P, r_c) space enclosing the area where the system undergoes to the phase transition.

In Fig. 2, we show the pressure as a function of baryon density for different Δ-meson couplings. Let us observe that for the upper curve, corresponding to $x_{\sigma\Delta} = 1.05$ and $x_{\omega\Delta} = 0.95$, the equation of state is stable. Otherwise, for the two lower curves, the chosen coupling constants are below the red line of Fig. 1 (as well as satisfying experimental constraints) and it is possibly to observe that the mechanical stability condition in Eq.(3) is not satisfied.

In Fig. 3, we report the same curves of Fig. 2 where thermodynamical instabilities are present with the solution obtained by means of the Gibbs construction (red lines). Let us note that, depending on the Δ-meson couplings, the baryon density region in which the equation of state is unstable can become very large ($2 \div 3\,\rho_0$) and it is realized for typical values present in the core of the compact stars.

Let us further remark that, although the system has globally zero net electric charge (r_c=0), in the mixed phase there are two phases with different and finite

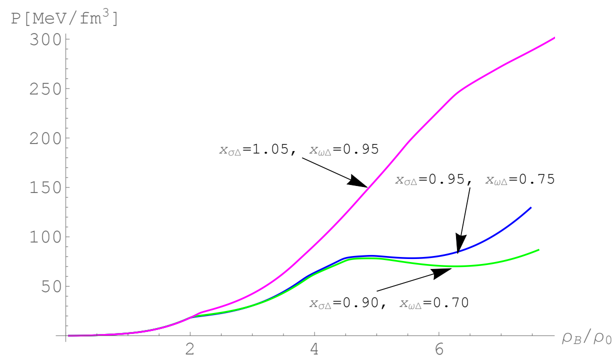

Figure 2: Pressure as a function of baryon density (in units of the nuclear saturation density ρ_0) for different coupling ratios $x_{\sigma\Delta}$ and $x_{\omega\Delta}$. In the two lower curves instability conditions are present.

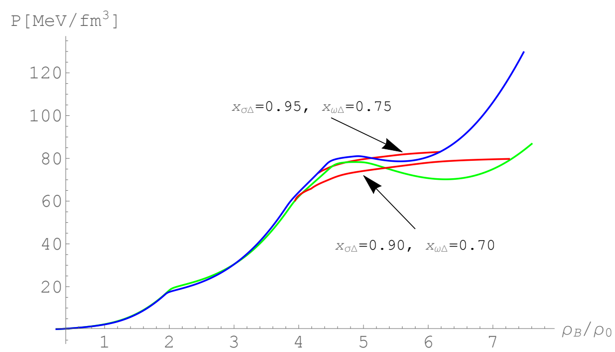

Figure 3: The same of Fig. 2 with the Gibbs construction (red lines) in region of the unstable EOSs.

values of electric charge (baryon and electric charges are globally conserved but are different in the two hadronic phases).

In order to better understand the different content of electric charge density in the phase coexistence of the system and the evolutions of the two phases in the mixed phase, in Fig. 4, we show the binodal section for the value of the Δ-meson coupling ratios $x_{\sigma\Delta} = 0.95$ and $x_{\omega\Delta} = 0.75$ (the same couplings of the blue curve of Fig. 3) where both mechanical and chemical-diffusive instabilities are present.

The right branch (phase I at lower density, red line) corresponds to the initial phase, where the dominant component of the system is given by nucleons. The left branch (phase II at higher density, blue line) is related to the final phase, where the system has a large content of Δ-isobar particles. In the presence of Δ-isobars the phase coexistence region extends up to regions of negative electric charge fraction r_c due to the formation of Δ^- particles. The binodal surface enclose the area where the system undergoes to the phase transition.

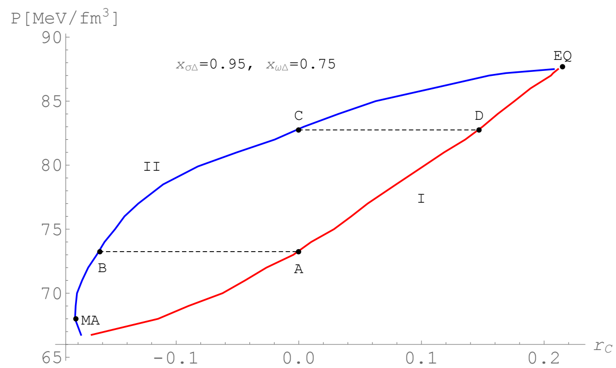

Figure 4: Binodal section with in evidence the point of maximum asymmetry (MA) and the point of equal equilibrium (EQ). In the mixed phase (from the points A to C) the system has different electric charge concentration r_c in the two phases.

During the isothermal compression, the system evolves through configurations at constant $r_c = 0$ and meets the lower branch in a point A. At this point the system becomes unstable and an infinitesimal Δ-dominant phase in B appears at the same temperature and pressure of A, but at higher baryon density and different electric charge content. In the phase transition, each phase evolves towards a configuration with increasing r_c until the value of pressure in the point C in the phase II where the system becomes stable.

In Fig. 5, we display, for the same couplings of Fig. 4, the evolution of the two phases during the phase transition as a function of baryon density. Let us note that, in the branch related to the phase I, the baryon density decrease during the isothermal compression, while in the phase II the baryon density increase. At the point C the system becomes stable in the phase II.

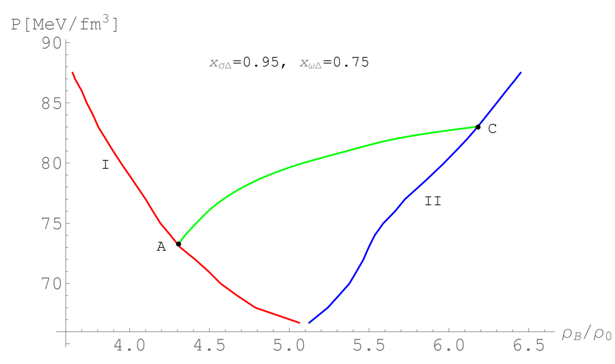

Figure 5: Pressure as a function of the baryon density (in units of the nuclear saturation density ρ_0) during the phase transition from the point A to C related the binodal section of Fig. 4.

4. Bulk properties of compact stars

We are going now to investigate the relevance of the thermodynamic instabilities in the core of the compact stars. In Fig. 6, we report the gravitational mass as a function of radius R of the star in absence (np) and in presence (npH) of hyperons, without Δ-isobar particles. Otherwise, in the three lower curves the Δ-isobar degrees of freedom are open. For the coupling ratios: $x_{\sigma\Delta} = 1.05$, $x_{\omega\Delta} = 0.95$, the equation of state is always stable and the core of the star is composed by nucleons, hyperons and Δ-particles. Instead for the values: $x_{\sigma\Delta} = 0.95$, $x_{\omega\Delta} = 0.75$ and $x_{\sigma\Delta} = 0.90$, $x_{\omega\Delta} = 0.72$, mechanical and chemical-diffusion instability are present and the Gibbs construction must be applied to equation of state.

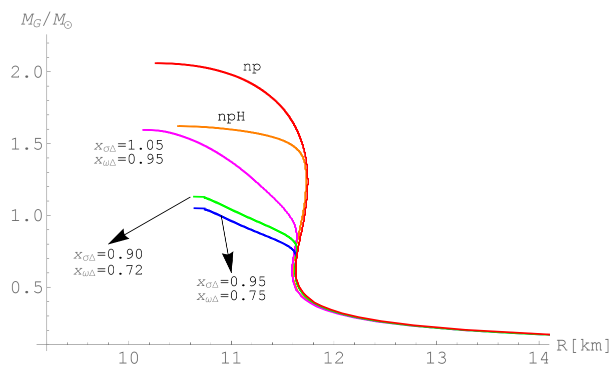

Figure 6: Gravitational mass of the stars (in units of the solar mass) as a function of the radius for different parameter sets. The symbol np stands for stars without hyperons and Δ degrees of freedom, npH with hyperons but without Δ particles. The two lower curves correspond to values of the meson-Δ coupling constants where thermodynamic instabilities are present.

In Fig. 7, we show the gravitational mass as a function of central baryon density ρ_B^c of the star. The notation and the parameter sets are the same of Fig. 6.

In according to previous calculations [30, 32], the presence of Δ-isobar degrees of freedom smooths the equation of state. This effect is much more evident when thermodynamic instabilities are present with a sensible reduction of the maximum gravitational mass. This feature is principally due to the fact that in the presence of a phase transition a mixed phase of low (phase I) and high (phase II) baryon density takes place, as displayed in Fig. 5. In the high density phase is enhanced by the early appearance of hyperons in the stars providing a further softening of the EOS, with a consequent further lowering of the maximum mass.

On the other hand, the recent discovery of compact stars having mass of the order of $2\,M_\odot$ indicates the need of a stiff EOS at large densities to allow such massive configurations [1, 2]. This matter of fact seems to be contradictory with a very soft EOS of state realized in the presence of thermodynamic instabilities. On the other hand, the constraint of $2\,M_\odot$ configuration could be satisfied by the existence of quark stars, absolutely stable stellar objects composed entirely

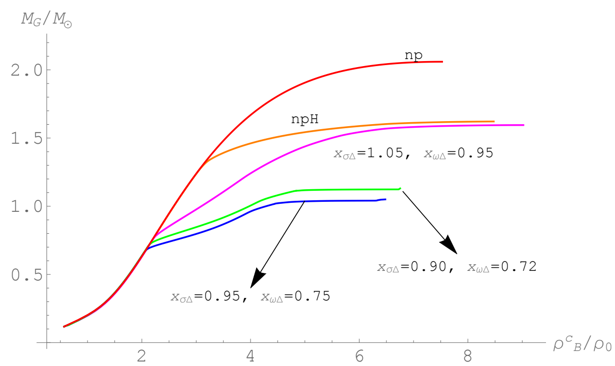

Figure 7: Gravitational mass of the stars (in units of the solar mass) as a function of the central baryon density (in units of the nuclear saturation density ρ_0) for the same parameter sets of Fig. 6.

of quark matter under the validity of the so-called Bodmer-Witten hypothesis [43, 44, 45], since quark matter is known to be rather stiff and to support massive configurations [32, 46, 47] [1].

In order to reconcile the presence of different hadronic degrees of freedom, such as hyperons and Δ-isobars that softer the EOS close to their production threshold, with the observation of large masses compact stars configuration, in literature different papers discuss the hypothesis of a solution based on two family of compact stars, one made of hadrons with small masses and radii and the other made of deconfined quarks which satisfy large mass constraints [32, 48, 49, 50, 51]. A crucial recipe to realize the transition from hadronic to quark stars is the formation of hyperons, which carry strangeness, in the center of the star. Such a feature can be satisfied in the phase transition due to the formation of hyperons in the high density phase (phase II). Under this condition it is relatively easy to have a transition to quark star because droplets of strange quark matter can be formed by means nucleation [52] and the star can decay into a more stable quark star with the same baryon mass, since this process is energetically favored due to the lower value of gravitational mass in the quark star configuration.

More explicitly, in the case of $x_{\sigma\Delta} = 0.95$, $x_{\omega\Delta} = 0.75$, we have a maximun gravitational mass $M_G = 1.05\,M_\odot$ (corresponding to a baryon mass of $M_B = 1.13\,M_\odot$) with a radius $R = 10.6$ km. If we consider the pQCD calculations of Ref. [47] with the scale parameter $X = 3.5$ (for which the maximun mass of quark stars is 2.53 $M_\odot$), at the same baryon mass ($M_B = 1.13\,M_\odot$), the quark star has a lower value of gravitational mass $M_G = 0.96\,M_\odot$ at a radius of

[1] Let us note that in Ref. [33] with a different parametrization of hyperons and Δ-isobars couplings, in the framework of a covariant density functional model, the condition of large stellar masses results to be satisfied also for a pure hadronic star in the presence of hyperons and Δ-isobar degrees of freedom.

$R = 12.5$ km. Similarly, in the case of $x_{\sigma\Delta} = 0.90$, $x_{\omega\Delta} = 0.72$, the maximun gravitational mass is $M_G = 1.13\,M_\odot$ (corresponding to a baryon mass of $M_B = 1.23\,M_\odot$) with a radius $R = 10.6$ km. On the other hand, at the same baryon mass, the above quark star configuration has a smaller gravitational mass ($M_G = 1.03\,M_\odot$) even if its radius is larger ($R = 12.8$ km).

These features can be very relevant in the phenomenological interpretation of compact star objects. Massive quark stars should show anomalous cooling histories and spinning frequency distributions with respect hadronic stars [53]. Moreover a large formation of Δ-isobars in the core of the compact star may significantly influence the thermal evolution of the compact star through modification of the direct Urca neutrino emissivity process [33].

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