Quantum thermodynamic instabilities in compact stars

Quantum thermodynamic instabilities in compact stars

A Lavagno[1,4], D Pigato[2] and G Gervino[3,4]

[1]Department of Applied Science and Technology, Politecnico di Torino, I-10129 Torino, Italy
[2]U.B.A., I-13897 Occhieppo Inferiore, Italy
[3]Dipartimento di Fisica, Università di Torino, I-10126 Torino, Italy
[4]INFN, Sezione di Torino, I-10125 Torino, Italy

Abstract. We study the existence of thermodynamic instabilities in the nuclear equation of state relative to the high density regime reached in the central core of compact stars. In the framework of a relativistic mean-field theory, we analyze the asymmetric nuclear properties in beta-equilibrium, including hyperons and Delta-isobar degrees of freedom. We investigate a finite density phase transition characterized by pure hadronic matter with the presence of mechanical instability (relative to the fluctuation of baryon number) and of chemical-diffusive instability (relative to the fluctuation of electric charge concentration). We find that, in the presence of thermodynamic instabilities, two hadronic phases with different values of electric charge content may coexist, with several phenomenological consequences in the physics of compact stars.

The new accumulating data from X-ray satellites provide important information on the structure and formation of compact stellar objects giving a unique opportunity to explore the behavior of high density nuclear matter [1]. Comparing the experimental data with different theoretical models, it is possible to study fundamental aspects of nuclear and hadron physics at different regimes [2, 3, 4, 5, 6, 7, 8]. This demands a detailed knowledge of the bulk thermodynamics and the equation of state of strongly interacting matter.

The behavior of matter at large densities is still poorly known but, on general grounds, new degrees of freedom are expected to appear and they should generate a softening of the equation of state. In this direction, many efforts have been focused on searching for possible phase transitions in heavy-ion collisions. 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 [9, 10].

A relevant aspect of a system with two conserved charges (baryon and electric charge numbers) is that the phase transition is of second order from the viewpoint of Ehrenfests definition. At variance with the so-called Maxwell construction for one conserved charge, the pressure is not constant in the mixed phase and, therefore, the incompressibility does not vanish [11]. Moreover, for a binary system with two phases, the binodal coexistence surface is two dimensional and the instabilities in the mixed phase arise from quantum fluctuations in the electric charge concentration (chemical instability) and in the baryon density (mechanical instability) [12, 13, 14].

In the present paper we study β-stable nuclear matter at zero temperature by requiring the Gibbs conditions on the global conservation of baryon number and zero net electric charge in the

framework of a quantum 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 equation of state called SFHo which takes into account of 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 [15].

A crucial contribution to the formation of thermodynamic instabilities is that 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 [12, 16, 17, 18, 19]. It has been pointed out that the existence of Δ-isobars can be very relevant also in the core of neutron stars [20, 21, 22]. 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 Δ-meson coupling constants [23, 24].

Qualitatively, it has been possible to establish that the Δs 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. [25], from QCD sum rules, it has been found that the coupling ratio $\omega - \Delta$ with respect to ω-nucleons is significantly smaller than one. From phenomenological analysis of data from electron-nucleus, photoabsorption and pion nucleus scattering can be extracted different constraints related to the values of the Δ-meson coupling constants $x_{\omega\Delta} = g_{\omega\Delta}/g_{\omega N}$ and $x_{\sigma\Delta} = g_{\sigma\Delta}/g_{\sigma N}$, used in the nuclear equation of state [21].

In Fig. 1, we report the relation between the coupling ratios obtained by considering the experimental constraints (see Ref.[21] for details). Furthermore, for coupling ratios in the lower region of the red line the equation of state contains thermodynamic instabilities. Such a region of values is compatible with the experimental constraints and can be very interesting to investigate how this matter of fact can influence the bulk properties of compact stars.
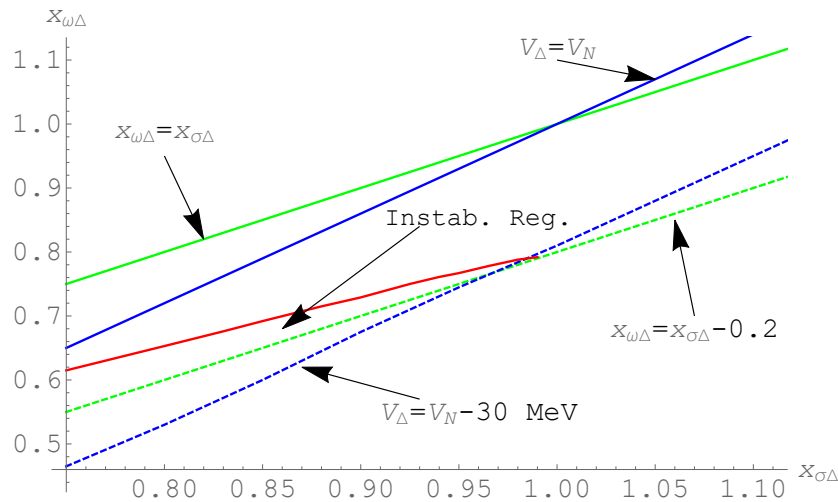
Figure 1. Relation between the coupling ratios $x_{\omega\Delta}$ and $x_{\sigma\Delta}$ in terms of experimental constraints related to pion and electron scattering and from photoabsorption on nuclei. Below the red line, thermodynamic instabilities are present in the equation of state.

Let us remember that we are dealing with the study of a multi-component system with two conserved charges: baryon number and electric charge. 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, the pressure in the mixed phase is not constant and, although the total ρ_B and ρ_C are fixed, baryon and charge densities can be different in the two phases. For such a system in thermal equilibrium, the possible phase transition can be characterized by mechanical and chemical instabilities [11, 12, 26]. As usual the condition of the mechanical stability implies

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

Furthermore, the chemical stability condition is satisfied if [12]

$$\left(\frac{\partial \mu_C}{\partial r_c}\right)_{T,P} > 0 \;\; \text{or} \;\;
\begin{cases}
\left(\dfrac{\partial \mu_B}{\partial r_c}\right)_{T,P} < 0\,, & \text{if } r_c > 0\,, \\[2ex]
\left(\dfrac{\partial \mu_B}{\partial r_c}\right)_{T,P} > 0\,, & \text{if } r_c < 0\,.
\end{cases} \tag{4}$$
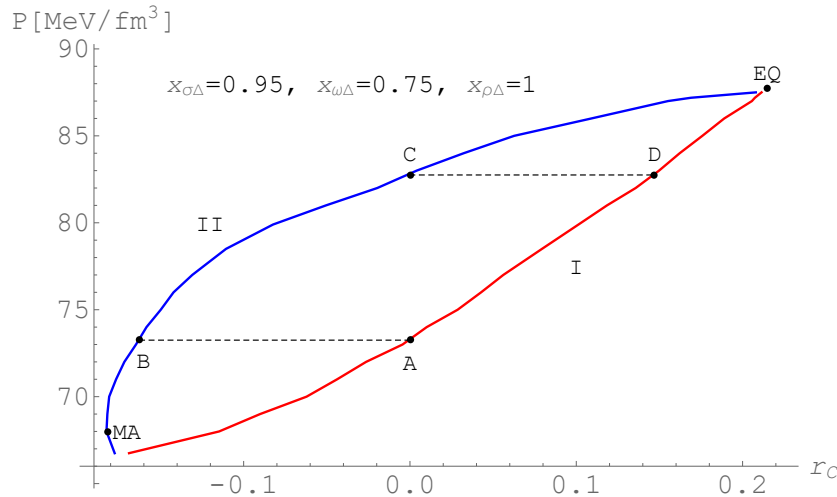
Figure 2. Binodal section with in evidence the point of maximum asymmetry (MA) and the point of equal equilibrium (EQ). In the mixed phase (from the points A to C) the system has different electric charge concentration r_c in the two phases.

In Fig. 2, we show the binodal section for a value of the Δ-meson coupling ratios where both mechanical and chemical-diffusive instabilities are present in the nuclear equation of state.

The right branch (phase I at lower density) corresponds to the initial phase, where the dominant component of the system is given by nucleons. The left branch (phase II at higher density) is related to the final phase, where the system is composed primarily by Δ-isobar degrees of freedom. In 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.

During the isothermal compression from the initial point A, the system becomes unstable and starts to be energetically favorable the separation into two phases, therefore an infinitesimal Δ-dominant phase appears in B, at the same temperature and pressure 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.
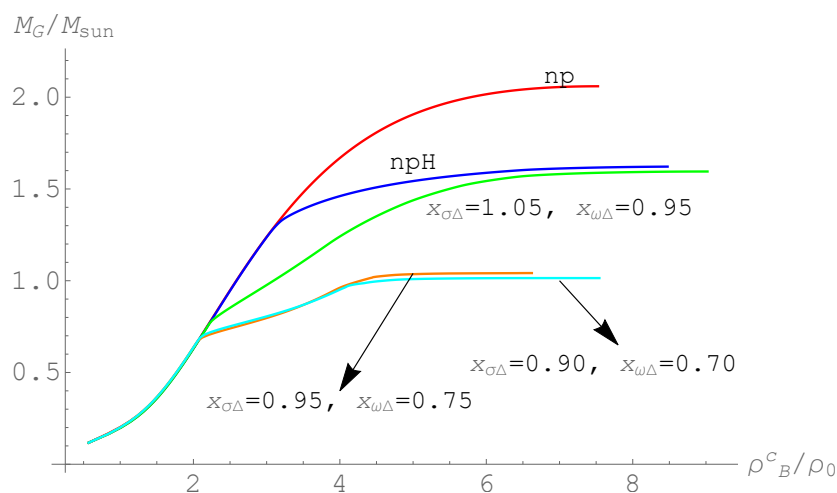
Figure 3. Gravitational mass of the stars (in units of the solar mass) as a function of the central baryon density (in units of the nuclear saturation density ρ_0) for different parameter sets. The symbol np stands for stars without hyperons and Δ degrees of freedom, npH with hyperons but without Δ particles. The two lower curves correspond to values of the meson-Δ coupling constants where thermodynamic instabilities are present.

We are going now to investigate the relevance of the above considered thermodynamic instabilities in the core of the compact stars. In Fig. 3, we report the gravitational mass as a function of central baryon density ρ_B^c of the star in absence (np) and in presence (npH) of hyperons, without Δ-isobar degrees of freedom. Otherwise, the three lower curves contain Δ particles. 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-isobars. Instead for the values: $x_{\sigma\Delta} = 0.95$, $x_{\omega\Delta} = 0.75$ and $x_{\sigma\Delta} = 0.90$, $x_{\omega\Delta} = 0.70$, mechanical and chemical-diffusion instability are present and the Gibbs construction must be applied to equation of state.

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 strong reduction of the maximum gravitational mass. On the other hand, very compact object with smaller radii can be formed. These features can be very relevant in the phenomenological interpretation of compact star objects.

References

[1] Antoniadis J *et al.* 2013 *Science* **340** 1233232
[2] Drago A, Lavagno A, Metzger B D and Pagliara G 2016 *Phys. Rev.* D **93** 103001

[3] Drago A, Lavagno A, Pagliara G and Pigato D 2016 *Eur. Phys. J* A **52** 40
[4] Torres J R, Gulminelli F, Menezes D P 2017 *Phys. Rev.* C **95** 025201
[5] Lavagno A, Pigato D and Quarati P 2010 *J. Phys. G: Nucl. Part. Phys.* **37** 115102
[6] Christian J -E, Zacchi A and Schaffner-Bielich J 2019 *Phys. Rev. D* **99** 023009
[7] Lavagno A and Quarati P 2001 *Phys. Lett.* B **498** 47
[8] Drago A and Lavagno A 2001 *Phys. Lett.* B **511** 229
[9] Goodman A L, Kapusta J I and Mekjian A Z 1984 *Phys. Rev.* C **30** 851
[10] Pochodzalla J *et al.* 1995 *Phys. Rev. Lett.* **75** 1040
[11] Müller H and Serot B D 1995 *Phys. Rev.* C **52** 2072
[12] Lavagno A and Pigato D 2012 *Phys. Rev.* C **86** 024917
[13] Lavagno A and Narayana Swamy P 2010 *Found. Phys.* **40** 814
[14] Lavagno A, Scarfone A M and Narayana Swamy P 2006 *Eur. Phys. J.* C **47** 253
[15] Lattimer J M and Lim Y 2013 *Astrophys. J.* **771** 51
[16] Hofmann M, Mattiello R, Sorge H, Stocker H and Greiner W 1995 *Phys. Rev.* C **51** 2095
[17] Li Z, Mao G, Zhuo Y and Greiner W 1997 *Phys. Rev.* C **56** 1570
[18] Lavagno A 2010 *Phys. Rev.* C **81** 044909
[19] Lavagno A 2013 *Eur. Phys. J.* A **49** 102
[20] Schurhoff T, Schramm S and Dexheimer V 2010 *Astrophys. J.* **724** L74
[21] Drago A, Lavagno A, Pagliara G and Pigato D 2014 *Phys. Rev.* C **90** 065809
[22] Drago A, Lavagno A and Pagliara G 2014 *Phys. Rev. D* **89** 043014
[23] Waldhauser B W *et al.* 1987 *Phys. Rev.* C **36** 1019
[24] Li Z *et al.* 1997 *Phys. Rev.* C **56** 1570
[25] Jin X 1995 *Phys. Rev.* C **51** 2260
[26] Lavagno A, Narayana Swamy P 2010 *Physica* A **389** 993