Hadron-quark crossover phase transition in hybrid compact stars

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Lattice simulation of QCD at small net baryon densities and high temperature have revealed that the transition from the hadronic phase to the deconfined quark-gluon plasma is a crossover. Recently, the structure of neutron stars have been studied with a crossover equation of state by means of a switching function to model a smooth transition from a pure neutron matter to massless quarks. The switch function parameter was constrained in order to reproduce neutron stars up to about two solar masses, with the constraint that the adiabatic sound velocity cannot exceed the speed of light. Following the same line, such a study has been extended by considering the relevance of color superconducting massless quarks in the cold dense matter. In this contribution, we investigate the crossover phase transition into hybrid compact stars by means of an equation of state which incorporates hadronic matter, composed by nucleons, hyperons and Δ-isobars degrees of freedom, massive quark matter with the inclusion of non-perturbative effects and leptons in β-stable equilibrium.

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In the recent years, it has become increasingly evident that high energy heavy-ion collisions experiments and neutron star studies jointly advance our understanding of the QCD phase diagram under extreme conditions, from the ultra-hot early universe to the ultra-dense matter in neutron stars. In addition, by combining data from gravitational waves, electromagnetic wave and neutrinos, multi-messenger astronomy provides a powerful toolkit for understanding possible phase transitions in compact stars.

The discovery of compact stars having a mass of the order of $2M_\odot$ puts rather severe constraints on the equation of state (EOS) of matter at large densities because β-stable and charge neutral matter, has to be stiff to allow such massive configurations. On the other hand, it is well known that by increasing the density it becomes thermodynamically favorable to form hyperons and maybe deconfined quarks with a consequent softening of the EOS, especially if a first-order quark-hadron phase transition take place. As discussed in Ref.s [1, 2], this problem could be overcome in the scenario of two coexisting families of compact stars: hadronic stars, whose EOS is soft, can be very compact with small radii and with maximum masses of about 1.5 $M_\odot$, while massive strange quark stars, whose EOS is stiff, with masses greater than 2 $M_\odot$.

Recently, several investigations study the possibility that a continuous crossover phase transition from hadronic to quark matter can occur in dense stellar matter [3–7]. A common peculiar feature of a quark-hadron crossover EOS is a peak in the squared speed of sound $c_s^2 = dP/d\epsilon$. As discussed in Ref. [8], such a peak is not caused by the violation of the conformal bound, but can be interpreted as signature of the steep approach to the conformal limit. In particular, Kapusta and Welle [5] have proposed the introduction of a switch function which mimic the crossover feature, present at high temperature in lattice simulation, at high baryon chemical potential in the stellar core. Such a study, based on pure neutron matter and massless quark, has been extended in Ref. [6] by considering color superconducting state in quark matter and, in Ref. [7], with the addition of protons and leptons in β-stable equilibrium.

In this investigation, we study the crossover EOS of hybrid compact stars composed by nucleons, hyperons, Δ-isobars and massive quarks matter with non-perturbative effects. The two conserved charges, baryon number and global charge neutrality, imply the two independent baryon and charge (isospin) chemical potentials, in presence of leptons under the β-stability condition.

Following Ref. [5], the crossover feature is regulated by a switching function $S(\mu_B)$ as

$$P_{HQ}(\mu_B, \mu_C) = [1 - S(\mu_B)]\, P_H(\mu_B, \mu_C) + S(\mu_B)\, P_Q(\mu_B, \mu_C)\,, \tag{1}$$

where the switch function is defined as [5, 6] [1]

$$S(\mu_B) = \exp[-(\mu_0/\mu_B)^r]\,. \tag{2}$$

The hadronic pressure P_H is obtained from the SFHo relativistic mean-field (RMF) model [9] by including the full octect of the lightest baryons: p, n, Λ, Σ^+, Σ^0, Σ^-, Ξ^0, Ξ^- and the $\Delta(1232)$-isobar degrees of freedom. P_Q is the quark pressure in an extended Bag model including first-order $\alpha_s = \pi/2(1 - a_4)$ non-perturbative interaction and massive strange quark (m_s =100 MeV) [10].

[1] In this preliminary investigation we neglect possible dependence on the electric charge chemical potential μ_C (or on the isospin chemical potential μ_I) in the switch function.

The thermodynamic description of the system is completed from the relations for the baryon density

$$\rho_B(\mu_B,\mu_C) = \frac{\partial P}{\partial \mu_B}\Big|_{\mu_C} = (1-S)\,\rho_B^H + S\,\rho_B^Q + (P_Q - P_H)\,\frac{\partial S}{\partial \mu_B}\,, \tag{3}$$

the charge density

$$\rho_C(\mu_B,\mu_C) = \frac{\partial P}{\partial \mu_C}\Big|_{\mu_B} = (1-S)\,\rho_C^H + S\,\rho_C^Q\,, \tag{4}$$

and the energy density

$$\epsilon_{HQ} = -P_{HQ} + \mu_B\,\rho_B + \mu_C\,\rho_C\,. \tag{5}$$

Moreover, we have to require the charge neutrality

$$\rho_C(\mu_B,\mu_C) = \rho_e(\mu_e)\,, \tag{6}$$

and the β-stability condition: $\mu_C = -\mu_e$. Finally, we have $P = P_{HQ} + P_e$ and $\epsilon = \epsilon_{HQ} + \epsilon_e$.

The crossover and, as a consequence, the parameters of the switch function S, μ_0 and r, are fixed so that the pressure must be convex for all μ_B [3]

$$\partial^2 P/\partial\mu_B^2 = \partial\rho_B/\partial\mu_B > 0\,. \tag{7}$$

In addition, the sound velocity

$$c_s = \sqrt{\partial P/\partial\epsilon} = \sqrt{\partial \ln\mu_B/\partial \ln\rho_B}\,, \tag{8}$$

cannot exceed the speed of light.

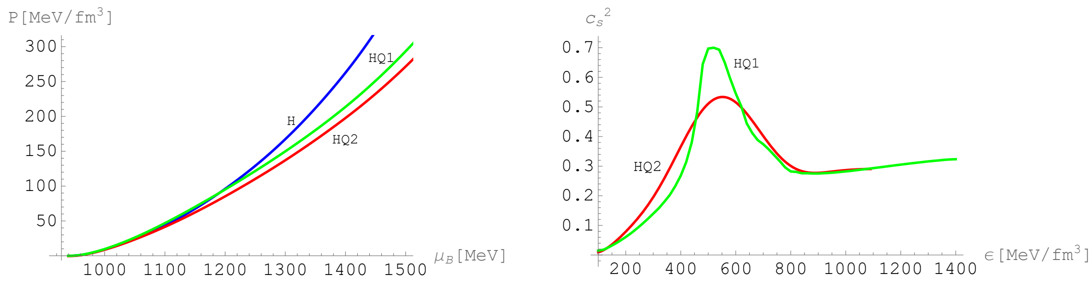

Figure 1: *(Left panel)* Pressure as a function of the baryon chemical potential for the hadronic phase H, and two different mixed hadron-quark (HQ1 and HQ2) crossover EOSs. *(Right panel)* Squared sound velocity for the two different EOS parameter sets (see text for details).

In left panel of Fig. 1, we show the pressure as a function of the baryon chemical potential μ_B for the hadronic EOS (H) [9] and for two different parameters set related to the crossover phase transition: HQ1 ($B_{\rm eff}^{1/4}$=135 MeV, $a_4 = 0.55$, μ_0=1200 MeV, $r = 7$) and HQ2 ($B_{\rm eff}^{1/4}$=135 MeV, $a_4 = 0.4$, μ_0=1300 MeV, $r = 4$). In the right panel of Fig. 1, the squared sound speed c_s^2 is reported for the two hadron-quark crossover EOSs as a function of the central energy density ϵ. The parameter μ_0 in the switch function has been fixed by requiring the peak of c_s^2 at energy density approximately at $\epsilon \simeq$550-580 MeV/fm^3, as suggested by neutron star observations [8].

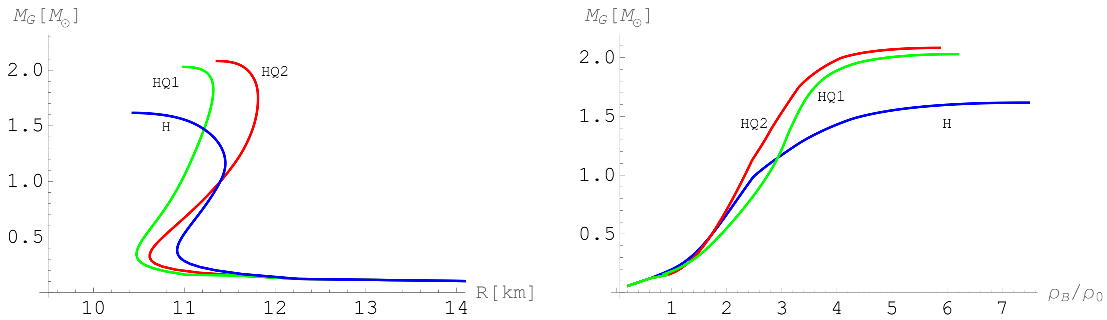

Figure 2: *(Left panel)* Gravitational stellar mass vr. radius for the hadronic phase H and two different mixed hadron-quark (HQ1 and HQ2) crossover EOSs (see text for details). *(Right panel)* Stellar mass as a function of the central baryon density, in units of nuclear saturation density.

In Fig. 2, for the same above parameters, in the left panel, we report the gravitation stellar mass $M_\odot$ (in units of solar mass) as a function of the surface radius and, in the right panel, $M_\odot$ as a function of the central baryon density ρ_B, in units of the nuclear saturation density.

In summary, we have studied the crossover EOS of hybrid compact stars, composed by nucleons, hyperons, Δ-isobars, massive quark matter and leptons in β-stable equilibrium. We have seen that massive compact stars configurations can be realized for particular parameters set in presence of strong non-perturbative effects. In this context, let us remember that we are considering a system with two globally conserved charges, baryon and charge neutrality. In this case the dynamics of the phase transition is more complex with respect to the one conserved charge, related to the crossing of the hadron and quark curves in the $P-\mu_B$ plane. We are planning to extend this preliminary investigation by taking into account color superconducting quarks effects and the role of isospin asymmetry in the crossover phase transition.

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