Crossover phase transition in hybrid compact stars

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Recently, neutron-star structure has been explored using crossover equations of state implemented through switching functions that provide a gradual transition from pure neutron matter to massless quark matter. The parameters of these switching functions were constrained to support neutron stars with masses of roughly two solar masses while ensuring that the adiabatic speed of sound remains below the speed of light. Subsequent work extended this approach by including the effects of color-superconducting quark matter in cold, dense environments. In this study, we examine the crossover transition in hybrid compact stars using an equation of state that takes into account hadronic matter with nucleons, hyperons, and Δ-isobar degrees of freedom as well as a quark phase with the inclusion of non-perturbative effects and leptons in β-stable equilibrium.

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Heavy-ion collisions experiments and neutron-star observations explore complementary extremes of the QCD phase diagram. Together, they provide a powerful and unified framework for understanding the fundamental phases of strongly interacting matter. At the same time, multi-messenger astronomy, which combines gravitational-wave observations with electromagnetic and neutrino signals, has emerged as a powerful tool for probing the inner composition of neutron stars and identifying signatures of possible phase transitions at supranuclear densities.

The discovery of compact stars with masses around $2M_\odot$ imposes stringent constraints on the high-density equation of state (EOS). In order for cold, β-stable, charge-neutral matter to support such massive configurations, the EOS must remain sufficiently stiff at large baryon density. However, it is well known that as density increases, it becomes energetically favorable for new degrees of freedom to appear, such as hyperons or deconfined quarks. Their onset generally leads to a softening of the EOS, and this effect is particularly pronounced if the transition from hadronic matter to quark matter is of first order, involving the possible formation of a mixed phase. In this case, the strong softening may reduce the maximum mass below observational limits, thereby generating the so-called hyperon puzzle or more generally the softening problem associated with exotic matter. As discussed in Refs. [1, 2], the tension between exotic degrees of freedom and the existence of $2M_\odot$ stars could be solved by means of the hypothesis of two coexisting families of compact stars. In this picture, hadronic stars, with a relatively soft EOS, are very compact, characterized by smaller radii and maximum masses around 1.5 $M_\odot$. A second family of compact stars, composed of strange quark matter with a much stiffer EOS, can reach masses well above 2 $M_\odot$.

Alternatively, lattice QCD studies at small baryon chemical potential suggest that at high temperature the hadron-quark transition is a smooth crossover, rather than a first-order phase transition. Extending this idea to the cold, dense regime relevant for neutron stars, one can model a gradual transformation of hadronic matter into quark matter without introducing a sharp discontinuity [3–10]. Such crossover constructions, typically implemented through switching or interpolation functions between hadronic and quark EOSs, can avoid the excessive softening produced by a first-order transition, allowing the EOS to remain stiff enough to support massive stars while still accommodating deconfinement at high density. 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 are going to 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.

The hadronic pressure P_H is obtained from the SFHo relativistic mean-field (RMF) model [11–14] 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) [15].

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]

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

In this preliminary investigation we neglect possible dependence on the electric charge chemical potential μ_C 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 $\rho_C(\mu_B,\mu_C) = \rho_e(\mu_e)$ 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, are fixed so that the pressure must be convex for all μ_B [3]

$$\partial^2 P/\partial \mu_B^2 = \partial \rho_B/\partial \mu_B > 0\,. \tag{6}$$

In addition, the sound velocity

$$c_s = \sqrt{\partial P/\partial \epsilon} = \sqrt{\partial \ln \mu_B/\partial \ln \rho_B}\,, \tag{7}$$

cannot exceed the speed of light. A common peculiar feature of a quark-hadron crossover EOS is a peak in the squared speed of sound $c_s^2 = dP/d\epsilon$, such a peak can be interpreted as signature of the steep approach to the conformal limit [8].

In left panel of Fig. 1, the squared sound speed c_s^2 as a function of the central energy density ϵ is reported for the two hadron-quark crossover EOSs: 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, $r = 4$). 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]. In right panel of Fig. 1, for the same above parameters, we report the gravitation stellar mass $M_\odot$ (in units of solar mass) as a function of the radius for the hadronic (H) and the two HQ1 and HQ2 hadron-quark crossover EOSs. 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.

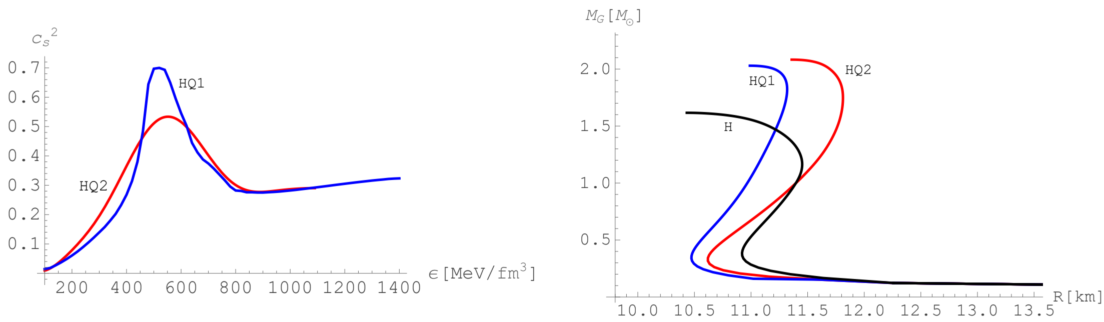

Figure 1: *(Left panel)* Squared sound velocity for the two different crossover parameter sets.
(Right panel) Gravitational stellar mass vr. radius for the hadronic phase H and the two different hadron-quark, HQ1 and HQ2, EOSs (see text for details).

In summary, we have investigated a hadron-quark crossover equation of state for compact stars composed of nucleons, hyperons, Δ-isobars, massive quark matter, and leptons in β-stable equilibrium. Our results show that massive compact-star configurations can be obtained for specific parameter sets when strong non-perturbative effects are included. This outcome highlights the viability of a smooth crossover transition in supporting heavy neutron stars while accommodating the emergence of exotic degrees of freedom.

It is worth noting that the global structure of the QCD phase diagram remains incompletely understood. In particular, the location of the critical end point has not yet been established [16, 17]. This ambiguity further motivates the exploration of crossover scenarios as realistic alternatives for dense matter in neutron stars. As a next step, we plan to extend this preliminary study by incorporating the effects of color-superconducting quark phases and by analyzing the impact of isospin asymmetry on the nature of the crossover transition. Such refinements could help clarify the role of deconfined matter in the interior of compact stars and its possible astrophysical signatures [18].

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