

## DENSE HADRONIC MATTER IN NEUTRON STARS\*

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The existence of stars with masses up to  $2M_{\odot}$  and the hints of the existence of stars with radii smaller than  $\sim 11$  km seem to require, at the same time, a stiff and a soft hadronic equation of state at large densities. We argue that these two, apparently contradicting, constraints are actually an indication of the existence of two families of compact stars: hadronic stars which could be very compact and quark stars which could be very massive. In this respect, a crucial role is played, in the hadronic equation of state, by the delta isobars whose early appearance shifts to large densities the formation of hyperons. We also discuss how recent experimental information on the symmetry energy of nuclear matter at saturation indicates, indirectly, an early appearance of delta isobars in neutron star matter.

DOI:10.5506/APhysPolBSupp.7.451

PACS numbers: 21.65.Qr, 26.60.Dd

**1. Introduction**

The discoveries of massive neutron stars, with  $M = 2M_{\odot}$ , [1, 2] represent a challenge for nuclear and hadron physics: the central densities of these stellar objects are in the range from three to seven times nuclear saturation density, depending on the model adopted for calculating the nucleonic equation of state, see [3]. At such large densities, new hadrons are likely to form, such as hyperons and delta isobars which, however, strongly soften the equation of state leading to a maximum mass smaller than the measured masses. The softening of the equation of state allows, however, to obtain stellar configurations which can be very compact and thus compatible with the results of recent analyses of the thermal emission of quiescent

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\* Presented at "Excited QCD 2014", Bjelašnica Mountain, Sarajevo, Bosnia and Herzegovina, February 2–8, 2014.

low-mass X-ray binaries suggesting the existence of stars with radii smaller than  $\sim 11$  km [4–6]. Although these analyses are still under debate, we investigate here what would they imply for the composition of matter at high densities.

Presently, none of the proposed equations of state for dense matter allows to fulfill, at the same time, the astrophysical constraints, *i.e.* maximum mass of at least  $2M_\odot$  and radii  $\lesssim 11$  km, and the hadronic physics constraints of the appearance, at large baryon chemical potentials, of new degrees of freedom of the baryon octet and decuplet. In Ref. [7], we argue that a possible way out to this problem is that actually two families of compact stars exist: hadronic stars which can be very compact (radii could be smaller than  $\sim 10$ – $11$  km) and have maximum masses up to  $\sim 1.5$ – $1.6M_\odot$  and quark stars which have larger radii and can reach masses up to  $2.75M_\odot$ , as resulting from pQCD calculations [8]. For this scenario to be feasible, the formation in the stellar matter of delta isobars is crucial and, as we will show in the following, the recent constraints on the symmetry energy of nuclear matter at saturation favor an early appearance of delta isobars.

## 2. Equation of state and mass-radius relations

We adopt a Walecka-type relativistic mean field model for the hadronic equation of state introduced in Ref. [9]. In this model, additional non-linear terms are added (in the vector mesons sector) to the original Glendenning model [10] which allow to better constrain the equation of state at saturation by use of new experimental information on symmetry energy  $S_v$ , giant monopole resonances and finite nuclei properties. In particular, we use the recent parametrization proposed in [11], SFHo, but including also delta isobars and hyperons. Let us first discuss the results obtained for  $S_v$  as a function of the baryon density  $n_B$ . In Fig. 1 we show  $S_v$  for the GM3 [12] and the SFHo models. Notice the splitting of the two results as the density exceeds the saturation density, with the SFHo result lying below the GM3 result. We remark that in the GM3 model no constraint is imposed in particular on the derivative with respect to density of the symmetry energy at saturation, the parameter  $L$  [13] and which turns out to be of about 81 MeV. On the other hand, in the SFHo model, the additional parameters introduced in the Lagrangian, allow to fix  $L$  to  $\sim 45$  MeV, a value compatible with the analyses of Ref. [13], where a window of values of  $L$  between 40 and 60 MeV has been obtained by use of laboratory and astrophysical constraints. The term of the symmetry energy related to the interaction, as obtained in the SFHo model, reads [9]:  $\frac{g_\rho^2/m_\rho^2 n_B}{8(1+2g_\rho^2/m_\rho^2 f)}$ , where  $g_\rho$  and  $m_\rho$  are the baryon- $\rho$  meson coupling and the mass of the  $\rho$  meson, respectively, and  $f$  is a polynomial function of the  $\sigma$  and  $\omega$  fields. In the GM3 model,  $f = 0$  and  $S_v$  increases

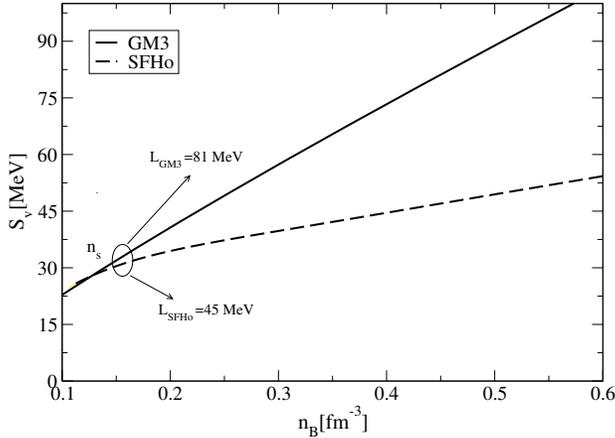


Fig. 1. Symmetry energy as a function of the baryon density: comparison between the GM3 equation of state [12] and the recent SFHo equation of state [11].

linearly with the density. A more complicated dependence on the density arises in the SFHo model which, however, can be mapped into a GM3-like model by use of a density dependent coupling  $g_\rho(n_B)$  which decreases as a function of the density. This parameter is crucial for computing the thresholds of appearance of the different baryons: depending on its value, delta isobars could appear after or before the hyperons as the density increases. As discussed in [10], among the four isobars, the  $\Delta^-$  is likely to appear first because it is “electric charge favored” (the  $\Delta^0$  chemical potential does not get a contribution from the electric charge chemical potential and  $\Delta^+$ ,  $\Delta^{++}$  are electric charge unfavored). However, it is “isospin unfavored” due to its isospin charge  $t_3 = -3/2$ . The coupling with the  $\rho$  meson thus affects more the threshold of the  $\Delta^-$  rather than the thresholds of the hyperons. In the calculations of Ref. [10], delta isobars appear after the hyperons and at densities which are too high to be reached in compact stars. Of course, the crucial inputs for calculating the thresholds are the baryon–meson couplings expressed as the ratios with the nucleon–meson couplings:  $x_{i\sigma} = g_{i\sigma}/g_{N\sigma}$ ,  $x_{i\omega} = g_{i\omega}/g_{N\omega}$ ,  $x_{i\rho} = g_{i\rho}/g_{N\rho}$  where  $i$  runs over the hyperons and the delta isobars. For calculating the beta stable equation of state needed for compact stars, the couplings of the hyperons are fixed as in [7], while for the delta isobars we set:  $x_{\Delta\omega} = x_{\Delta\rho} = 1$  and  $x_{\Delta\sigma}$  is varied in the interval 1–1.15. In Fig. 2 we display the ratio between pressure and energy density (which provides a measurement of the stiffness of the equation of state) for the GM3 and SFHo models in the two cases  $x_{\Delta\rho} = 0, 1$  (here the hyperons degrees of freedom are artificially switched off). Notice that for  $x_{\Delta\rho} = 1$ , which is the standard choice [10], the delta isobars appear at a density slightly above

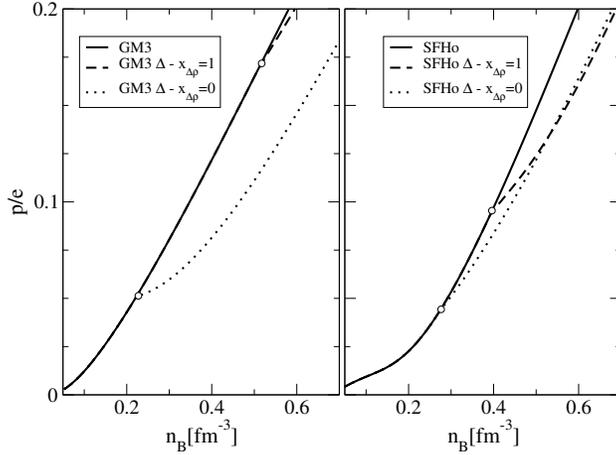


Fig. 2. Ratio between pressure and energy density as a function of the baryon density for the GM3 and SFHo models (left and right panel, respectively). Two cases for the coupling between  $\Delta$  and  $\rho$  are considered:  $x_{\Delta\rho} = 0, 1$ .

$0.5 \text{ fm}^{-3}$  in GM3 and slightly below  $0.4 \text{ fm}^{-3}$  in SFHo. In turn, this implies that in the GM3 model hyperons appear before the delta isobars, as found in [10], shifting their threshold to very large densities. On the other hand, in SFHo it is the opposite, delta isobars appear first and they shift to large densities the hyperons. As explained before, this different behavior is related to the coupling with the  $\rho$  meson: while in the GM3 model this coupling is constant, in the SFHo model, effectively, it decreases as a function of the density thus favoring states, as the  $\Delta^-$ , with negative isospin charge. This is also clear when looking at the curves obtained for  $x_{\Delta\rho} = 0$ : in GM3 a strong reduction of the threshold density is obtained (of about  $0.3 \text{ fm}^{-3}$ ) while in SFHo it is reduced of only  $0.1 \text{ fm}^{-3}$ .

In Fig. 3, we show the mass-radius relations of compact stars, including pure nucleonic stars (black line), hadronic stars with only delta isobars (dashed/green line), hadronic stars with hyperons and delta isobars (light gray/red lines), and finally pure quark stars (gray/blue line, same as in [7]). The stellar configuration at which the dashed line/green and the black line separate has a central density corresponding to the threshold for the formation of delta isobars. Similarly, for the formation of hyperons (solid light gray/red line and dashed line/green) which in the SFHo model appear after the delta isobars. We also display the two solar mass limit and the recent interval of radii indicated by the analyses of Refs. [4, 5]. The two solar mass limit can be reached only by quark stars (nucleonic stars also reach the limit but only if hyperons and delta degrees of freedom are artificially switched off when computing the equation of state). On the other hand, configura-

tions with small radii and masses close to the canonical  $1.4M_{\odot}$  are obtained with the hadronic equation of state that includes both hyperons and delta isobars (see also [14]) but only if the coupling of the delta with the  $\sigma$  meson is slightly larger than the coupling of the nucleon with the same meson, *i.e.*  $x_{\Delta\sigma} = 1.15$ . Arguments in favor of values of  $x_{\Delta\sigma}$  larger than one can be found in [15, 16]. As we have proposed in [7], if small radii stars do really exist together with massive stars, the scenario of coexistence of two families of compact stars is strongly favored. In this scenario, most of the stars are actually hadronic stars and only very massive stars are composed by pure quark matter. The mechanism which allows to populate the quark star branch and the observational consequences of such a conversion process have been discussed in several papers [7, 17–21]. Notice that the early appearance of delta isobars is crucial for this scenario to be viable: they indeed delay the appearance of hyperons which, once formed, are responsible for the seeding of stable strange quark matter and for the subsequent conversion process.

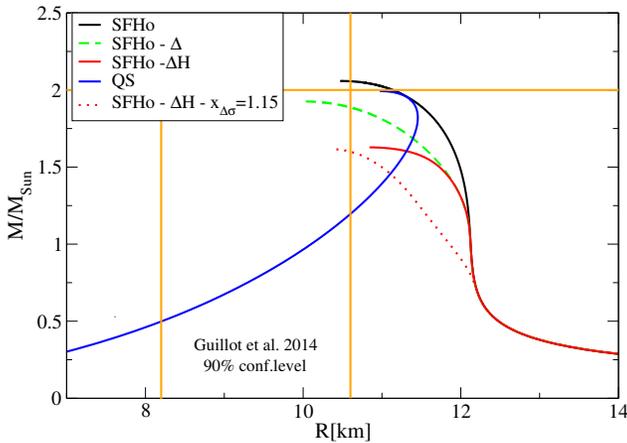


Fig. 3. Mass radius-relations for different equations of state together with the maximum mass constraint and the radii window indicated by the analyses in [4, 5].

### 3. Conclusions

The new constraints on the symmetry energy at saturation, in particular the  $L$  parameter, seem to favor an early appearance of delta isobars in dense matter. These degrees of freedom, together with hyperons, must be included in every calculation aiming at understating the structure of compact stars. The necessary softening of the equation of state allows for the existence of very compact stars although not very massive. However, the tension between the existence of massive neutron stars (with candidates with masses even larger than  $2M_{\odot}$ ) and the recent indications of existence of very compact

stars could be relieved within a scenario of coexistence of two families of compact stars. In particular heavier stars are, in our proposal, quark stars. These stellar objects, apart from their masses and radii larger than the one of hadronic stars, should show anomalous cooling histories and spinning frequency distributions. Moreover, in basically all the processes of merger of neutron stars we expect that the remnant, before collapsing to a black hole, is a quark star.

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