Early appearance of Δ isobars in neutron stars

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We discuss the formation of Δ isobars in neutron star matter. We show that their threshold density strictly correlates with the density derivative of the symmetry energy of nuclear matter: the L parameter. By restricting L to the range of values indicated by recent experimental and theoretical analysis, i.e., 40 MeV $\lesssim L \lesssim$ 62 MeV, we find that Δ isobars appear at a density of the order of 2 to 3 times the nuclear matter saturation density, i.e., the same range as for the appearance of hyperons. The range of values of the couplings of the Δs with the mesons is restricted by the analysis of the data obtained from photoabsorption, electron and pion scattering on nuclei. If the potential of the Δ in nuclear matter is close to the one indicated by the experimental data then the equation of state becomes soft enough that a "Δ puzzle" exists, similar to the "hyperon puzzle" widely discussed in the literature. Possible solutions to this puzzle are also discussed.

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I. INTRODUCTION

Since the seminal paper of Ref. [1], the possible formation in the core of neutron stars of baryons heavier than the nucleon is one of the most interesting open issue in nuclear astrophysics. While a huge literature is available concerning the appearance of hyperons in neutron stars (see, for instance, Ref. [2] and references therein) only a little work has been done to asses whether Δ(1232) isobars can also take place in those stellar objects [3–9]. The reason why Δ resonances have been neglected is maybe connected with the outcome of Ref. [1] indicating that these particles would appear at densities much higher than the typical densities of the core of neutron stars and they are therefore irrelevant for astrophysics. On the other hand, hyperons could appear already at 2 to 3 times the density of nuclear matter, $n_0 = 0.16\,\mathrm{fm}^{-3}$, and one has to include these degrees of freedom when modeling the equation of state of dense nuclear matter. The consequent softening of the equation of state reduces the maximum mass of neutron stars which, in many calculations, drops below the $2M_\odot$ limit imposed by the precise measurements of the masses of PSR J1614-2230 and PSR J0348+0432 [10,11]. This inconsistency between astrophysics (mass measurements) and hadron physics (the necessary appearance of new degrees of freedom at large densities) is known as the hyperon puzzle. However, the uncertainties on the hyperons' interactions in dense matter are such that it is still possible to tune the parameters, within phenomenological models, in order to fulfill the $2M_\odot$ limit also when hyperons are included in the equation of state [2,12–15]. On the other hand, in microscopic models based on the Brueckner–Hartree–Fock approach, even three-body forces are not enough to allow for the existence of massive stars [16] although more sophisticated calculations based, e.g., on Monte Carlo techniques are needed before a firm conclusion can be drawn [17,18].

In principle, also the appearance of Δ isobars at some critical density $n^{\Delta}_{\mathrm{crit}}$, softens the equation of state, thus reducing the maximum mass. The crucial question, which we investigate in this paper, concerns the value of $n^{\Delta}_{\mathrm{crit}}$ in cold β-stable matter. We will show, in particular, that a significant correlation exists between $n^{\Delta}_{\mathrm{crit}}$ and the density derivative of the symmetry energy S, the parameter L:

$$L = 3n_0 \frac{dS}{dn_B}. \tag{1}$$

It will be clear in the following that the appearance of the Δ isobars is affected by the value of S at a density close to $n^{\Delta}_{\mathrm{crit}}$. Since the value of S at n_0 is determined with a good precision, the crucial quantity becomes L. Only recently it has been possible to strongly constrain the value of L both from terrestrial and astrophysical data [19] with the result that 40.5 MeV $\lesssim L \lesssim$ 61.9 MeV.

II. HADRONIC EQUATION OF STATE

We adopt here the scheme of 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. The threshold for the formation of the ith baryon is given by the following relation:

$$\mu_i \geqslant m_i - g_{\sigma i}\sigma + g_{\omega i}\omega + t_{3i} g_{\rho i}\rho, \tag{2}$$

where σ, ω, and ρ are the expectation values of the corresponding fields, $g_{\sigma i}$, $g_{\omega i}$, and $g_{\rho i}$ are the couplings between the mesons and the baryons, and μ_i, m_i, and t_{3i} are the chemical potential, the mass, and the isospin charge of the baryons, respectively. The baryon chemical potential μ_i 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.

As already extensively discussed in Ref. [1], among the four Δ isobars, the Δ^- is likely to appear first, in β-stable matter, because it can replace a neutron and an electron at the top of their Fermi seas. However, this particle is "isospin unfavored" because its isospin charge $t_3 = -3/2$ has the same sign of the isospin charge of the neutron. For large values of the symmetry energy S and, therefore, of $g_{\rho\Delta}$, the Δ^-

appears at very large densities or it does not appear at all in dense matter, thus playing no role in compact stars. Indeed, in Ref. [1] the Δ isobars could appear in neutron stars only for nonphysical small values of the symmetry energy, obtained by setting $g_{\rho i} = 0$ for all the baryons.

The Lagrangian adopted in Ref. [1] is a Walecka-type model with minimal coupling terms between baryons and the ω and ρ mesons and linear and nonlinear interaction terms for the scalar meson σ. In such a scheme the symmetry energy reads $S = S_{\text{kinetic}} + S_{\text{interaction}}$, where the interaction term $S_{\text{interaction}} = [(g_{\rho N}^2)/(8m_\rho^2)]n_B$, m_ρ is the mass of the ρ meson, and n_B is the baryon density. The coupling $g_{\rho N}$ (where the label N stands for the nucleon) is fixed by using the experimental value of the symmetry energy, the most recent estimates ranging in the interval $29 \lesssim S \lesssim 32.7$ MeV [19]. In this scheme no experimental information on the density dependence of the symmetry energy can be incorporated and in particular the L parameter is automatically fixed once a specific value of S is adopted. It turns out, that in the models introduced in Refs. [1,20], $L \sim 80$ MeV and is thus higher than the values suggested by the most recent analysis [19]. There are two ways to modify the Lagrangian adopted in the GM models in order to include the new experimental information: to introduce density-dependent couplings or to introduce nonminimal couplings also for the vector mesons; the two approaches being basically equivalent. The general form of such Lagrangians is given by

$$\begin{aligned}\mathcal{L}_{\text{octet}} &= \sum_k \bar{\Psi}_k \bigg(i\gamma_\mu \partial^\mu - m_k + g_{\sigma k}\sigma \\ &\quad - g_{\omega k}\gamma_\mu \omega^\mu g_{\rho k}\gamma_\mu \frac{\boldsymbol{\tau}_k}{2}\cdot \boldsymbol{\rho}^\mu \bigg)\Psi_k \\ &\quad + \frac{1}{2}\left(\partial_\mu\sigma\partial^\mu\sigma - m_\sigma^2\sigma^2\right) - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu \\ &\quad - \frac{1}{4}\boldsymbol{\rho}_{\mu\nu}\cdot\boldsymbol{\rho}^{\mu\nu} + \frac{1}{2}m_\rho^2\boldsymbol{\rho}_\mu\cdot\boldsymbol{\rho}^\mu + U(\sigma,\omega,\boldsymbol{\rho}), \qquad (3)\end{aligned}$$

where the index k runs over the baryon octet, m_k is the bare mass of the baryon k, $\boldsymbol{\tau_k}$ is the isospin operator and, finally, U is the mesons' potential which can contain nonlinear-interaction terms.

The mean-field Lagrangian density for the Δ isobars (to be added to the one of the baryon octet) can be then expressed as

$$\begin{aligned}\mathcal{L}_\Delta &= \overline{\psi}_{\Delta\nu}\big[i\gamma_\mu\partial^\mu - (m_\Delta - g_{\sigma\Delta}\sigma) - g_{\omega\Delta}\gamma_\mu\omega^\mu \\ &\quad - g_{\rho\Delta}\gamma_\mu I_3 \rho_3^\mu\big]\psi_\Delta^\nu, \qquad (4)\end{aligned}$$

where ψ_Δ^ν is the Rarita–Schwinger spinor[1] for the Δ isobars (Δ^{++}, Δ^+, Δ^0, Δ^-) and $I_3 = \text{diag}(3/2, 1/2, -1/2, -3/2)$ is the matrix containing the isospin charges of the Δs.

In our first analysis we adopt the GM3 model but we consider a density dependent baryon-ρ meson coupling, i.e., $g_{\rho i} = g_{\rho i}(n_0)e^{-a(n_B/n_0 - 1)}$ (see Ref. [22]). In this way we introduce a single parameter a which affects only the value of L leaving untouched the other properties of nuclear matter at saturation. In a second analysis we will adopt the more sophisticated model based on the parametrization SFHo [23,24].

As is customary, for the couplings of hyperons and Δ isobars with the mesons, we introduce the ratios $x_{\sigma i} = g_{\sigma i}/g_{\sigma N}$, $x_{\omega i} = g_{\omega i}/g_{\omega N}$, and $x_{\rho i} = g_{\rho i}/g_{\rho N}$, where the index i runs over all the hyperons and Δ isobars. For simplicity, we start by fixing these ratios to 1 for the Δ isobars, as in Ref. [1]. Concerning hyperons, with the exception of the Λ, their binding energies in hypernuclei are highly uncertain; see the recent Ref. [15] and the references therein, and thus also their couplings with mesons are poorly constrained. Here, we use the parameters set of Refs. [8,25,26] obtained by reproducing the following values of the binding energies in nuclear matter U_i^N:

$$U_\Lambda^N = -28\,\text{MeV}, \quad U_\Sigma^N = 30\,\text{MeV}, \quad U_\Xi^N = -18\,\text{MeV}. \qquad (5)$$

For the coupling with vector mesons we use the SU(6) symmetry relations:

$$\tfrac{1}{3}g_{\omega N} = \tfrac{1}{2}g_{\omega\Lambda} = \tfrac{1}{2}g_{\omega\Sigma} = g_{\omega\Xi}, \qquad (6)$$

$$g_{\rho N} = \tfrac{1}{2}g_{\rho\Sigma} = g_{\omega\Xi}, \quad g_{\rho\Lambda} = 0. \qquad (7)$$

We do not introduce here the $\Lambda - \Sigma^0$ mixing that has been studied in Refs. [27–29]. The main effect of the mixing is that Σ^0 appear already at a density of about $3n_0$ [27]. Notice anyway that the fraction of Σ^0 remains well below 10^{-3} up to about $5.5n_0$ and therefore Σ^0 would play a minor role in our analysis.

III. RESULTS AND DISCUSSION

We can now study how the values of n_{crit}^B for the different baryons change as a function of the new parameter a or, equivalently, as a function of L. We limit this first discussion to the case of the Λ, Δ^-, and Ξ^- which are the first heavy baryons appearing as the density increases (notice that Σ hyperons are unfavored due to their repulsive potential).

The results are displayed in Fig. 1. One can notice the different behavior of the thresholds: the larger the value of L the larger n_{crit}^Δ and the smaller n_{crit}^Λ and $n_{\text{crit}}^{\Xi^-}$. Indeed, for growing values of L, the isospin term in Eq. (2) also increases and the Δ isobar becomes more and more isospin unfavored. Even though the Λ is not directly coupled to the ρ meson ($t_{3\Lambda} = 0$), the value of L still affects n_{crit}^Λ defined by the equation $\mu_\Lambda(k_F^\Lambda = 0) = \mu_n(n_B = n_{\text{crit}}^\Lambda)$. More explicitly this equation reads $x_{\omega\Lambda}g_{\omega N}\omega + m_\Lambda^* = g_{\omega N}\omega - \frac{1}{2}g_{\rho N}\rho + (k_{Fn}^2 + m_n^{*2})^{1/2}$. The SU(6) symmetry implies $x_{\omega\Lambda} = 2/3$ and the equation simplifies to $m_\Lambda^* = g_{\omega N}\omega/3 - \frac{1}{2}g_{\rho N}\rho + (k_{Fn}^2 + m_n^{*2})^{1/2}$, where the mean-field value ω is positive being proportional to the baryon density. The mean field ρ is proportional to the difference between protons and neutrons and it is therefore negative. Clearly larger values of $g_{\rho N}$ (or equivalently of L) imply smaller values of n_{crit}^Λ. Similarly for the Ξ^- the threshold equation reads: $\mu_{\Xi^-}(k_F^{\Xi^-} = 0) = \mu_n(n_B = n_{\text{crit}}^{\Xi^-}) + \mu_e$. Again by using SU(6), $x_{\omega\Xi^-} = 1/3$ and

[1]The right number of spin degrees of freedom is recovered by imposing two constraints on the Lorentz index ν [21].

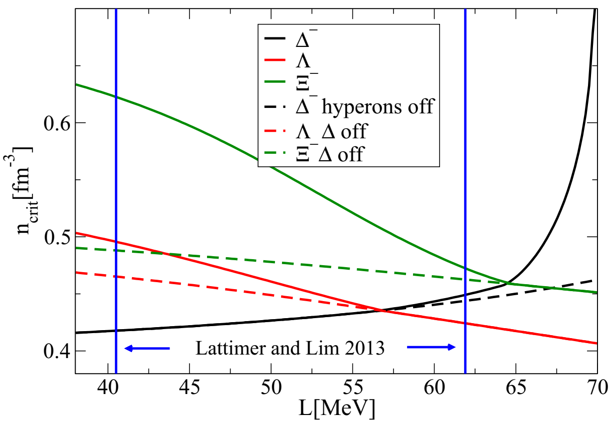

FIG. 1. (Color online) Threshold densities of hyperons and Δs as functions of the L parameter for $x_{\sigma\Delta} = x_{\omega\Delta} = x_{\rho\Delta} = 1$ within the modified GM3 model. The continuous lines refer to the case in which all the degrees of freedom are included in the computation of the equation of state and the dashed lines refer to the case in which either hyperons or Δs are artificially switched off. The vertical lines indicate the range of allowed values of L, as found in Ref. [19].

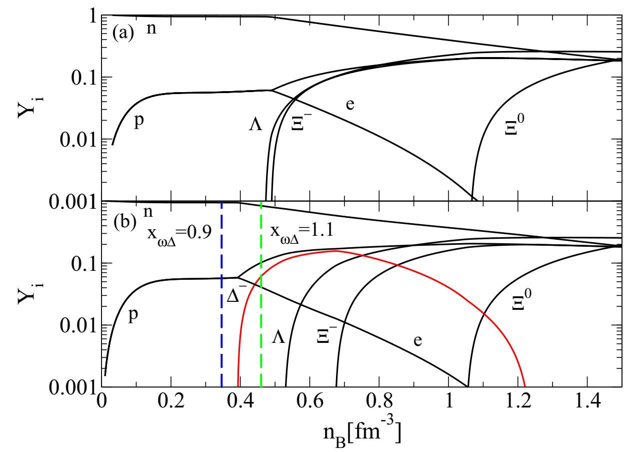

FIG. 2. (Color online) Particles fractions as functions of the baryon density within the SFHo model: only (a) hyperons and (b) hyperons and Δs for $x_{\sigma\Delta} = x_{\omega\Delta} = x_{\rho\Delta} = 1$. The red line indicates the fraction of the Δ^- which among the four Δs are the first to appear. The blue and the green vertical lines indicate the onset of the formations of Δ^- for $x_{\omega\Delta} = 0.9$ and $x_{\omega\Delta} = 1.1$, respectively.

$x_{\rho\Xi^-} = 1$, and the threshold reads $\frac{2}{3} g_{\omega N}\omega + (k_{Fn}^2 + m_n^{*2})^{1/2} + \mu_e = m_{\Xi^-}^*$.

Larger values of L imply larger amounts of protons and electrons, thus μ_e increases as a function of L and the appearance of the Ξ^- is favored. Note that the interplay between L and the hyperon content of neutron stars has been studied in detail in Refs. [31–33]. Our results are compatible with those studies.

Finally, for the Δ^-, $\mu_{\Delta^-}(k_F^{\Delta^-}) = \mu_n(n_B = n_{\rm crit}^{\Delta^-}) + \mu_e$ and the threshold conditions (assuming all the ratios $x_{i\Delta} = 1$) reads $g_{\rho N}\rho + (k_{Fn}^2 + m_n^{*2})^{1/2} + \mu_e = m_{\Delta^-}^*$ and, contrary to the case of the Λ and Ξ^-, larger values of L lead to larger values of μ_e but, at the same time, also to larger values of the (negative) quantity $g_{\rho N}\rho$. Notice that this term is twice as large but with the opposite sign of the similar term appearing in the equation for the Λ. The L dependence of $n_{\rm crit}^{\Delta^-}$ is therefore dominated by $g_{\rho N}\rho$.

Also, from Fig. 1, one can notice that, at high values of L, larger than about 65 MeV, the threshold of the Δ^- increases very rapidly with L. This corresponds to the values of L for which the Ξ^- appears before the Δ^- thus completely suppressing those particles. Indeed, within the GM3 model, for which $L \sim 80$ MeV, the Δ^- do not appear at all as already found in Ref. [1]. Similarly, one can notice that, if the isobars are formed before the hyperons, which happens below $L \sim 56$ MeV, $n_{\rm crit}^{\Lambda}$ and $n_{\rm crit}^{\Xi^-}$ are shifted to larger densities, as already noticed in Ref. [8]. Similar results have been found in Ref. [1], where two cases are analyzed, corresponding to a finite and to a vanishing value of $g_{\rho N}$, with the result that in the case of $g_{\rho N} = 0$ the isobars are favored. The blue lines mark the range of the values of L indicated by the analysis of Ref. [19]: the recent constraints on L imply that, at densities close to three times n_0, both the hyperons and the isobars must be included in the equation of state and, for the lower allowed values of L, the isobars appear even before the hyperons. Finally, let us stress that all the previous analyses are based on a rather conservative choice for the couplings between Δs and mesons. If higher values of $x_{\sigma\Delta}$ and or lower values for $x_{\omega\Delta}$ are adopted, $n_{\rm crit}^{\Delta}$ can result in being smaller than $n_{\rm crit}^{\Lambda}$ and $n_{\rm crit}^{\Xi^-}$ for all the acceptable values of L.

Let us turn now to the more sophisticated model for the equation of state proposed in Refs. [23,24]; here we adopt the parametrization called SFHo for which $S = 32$ MeV (very close to the GM3 value) and $L = 47$ MeV. We have added in their Lagrangian hyperons [assuming SU(6) symmetry] and Δ resonances (assuming $x_{\sigma\Delta} = x_{\rho\Delta} = 1$ and three different values for $x_{\omega\Delta}$).

Results for the particles' fractions as functions of the baryon density in β-stable matter are displayed in Fig. 2. In the upper panel, we include only hyperons: the Λ and the Ξ^- appear at a density of about 0.5 fm^{-3} and then the Ξ^0 appear at a density of about 1.1 fm^{-3}. In the lower panel we include also the Δ isobars. In agreement with what was found from the previous analysis, for small values of L the Δs appear at densities relevant for neutron stars and actually, in the SFHo model, they appear even before the hyperons with the Δ^- formed at a density of about 0.4 fm^{-3}. The appearance of these particles delays the appearance of hyperons in agreement with the results of Fig. 1. It is important to remark that, within the SFHo model, even using $x_{\omega\Delta} = 1.1$, the Δ^- appear before hyperons.

Let us now discuss the uncertainties on the couplings between Δs and mesons. 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. [34], from QCD sum rules, it has been found that $x_{\omega\Delta}$ is significantly smaller than 1. In the many-body analysis of Ref. [35], the real part of the Δ self-energy has been evaluated to be about −30 MeV at $n_B = 0.75 n_0$. Notice that this self-energy is relative to that of the nucleon and the total potential felt by the Δ is the sum of its self-energy and of the nucleon potential, a number of the order of −80 MeV [36]. Also phenomenological analysis have been performed of data from electron-nucleus [30,37,38], photoabsorption [39] and pion-nucleus scattering [40,41]. When discussing pion scattering data, a value for the real part of the Δ-nucleus potential of −30 MeV is extracted [40]. Since pions interact mainly with the nuclear surface, larger values are expected for the binding at n_0.

More recently a global analysis of pion-nucleus scattering and of pion photoproduction has been performed in Ref. [41] where the experimental data are described by assuming a Δ potential equal to the nucleon potential. From the data analysis of electron-nucleus scattering, either density or momentum dependent potentials have been deduced. In Ref. [37] the binding potential is parametrized as $-75 n_B(r)/n_0$ MeV. In Ref. [38] they obtain an optical potential which, at a momentum of about 400 MeV (quite typical for electron scattering), gives a binding in agreement with the one of Ref. [37]. Electromagnetic excitations of the Δ baryon have also been analyzed within a relativistic quantum hadrodynamics scheme with the result that $0 \lesssim x_{\sigma\Delta} - x_{\omega\Delta} \lesssim 0.2$ [30]. The conclusion one can draw from all these analyses is that the potential of the Δ in the nuclear medium falls within the range $-30\ \mathrm{MeV} + V_N \lesssim V_\Delta \lesssim V_N$ where V_N is the nucleon potential.

In the relativistic mean-field model the potential of the Δ (which coincides with the binding energy of the lowest Δ level) is given by $V_\Delta = x_{\omega\Delta} g_{\omega N}\omega - x_{\sigma\Delta} g_{\sigma N}\sigma$, where the mean fields are calculated at n_0 [20]. By fixing a value for V_Δ a relation between $x_{\sigma\Delta}$ and $x_{\omega\Delta}$ is obtained, as shown in Fig. 3 together with the experimental constraints on $x_{\sigma\Delta} - x_{\omega\Delta}$ [30]. New analyses, and possibly new experiments, aiming at a better determinations of these couplings would be extremely important. Notice also that no information is available for $x_{\rho\Delta}$ which in principle could be extracted by analyzing scattering on neutron rich nuclei.

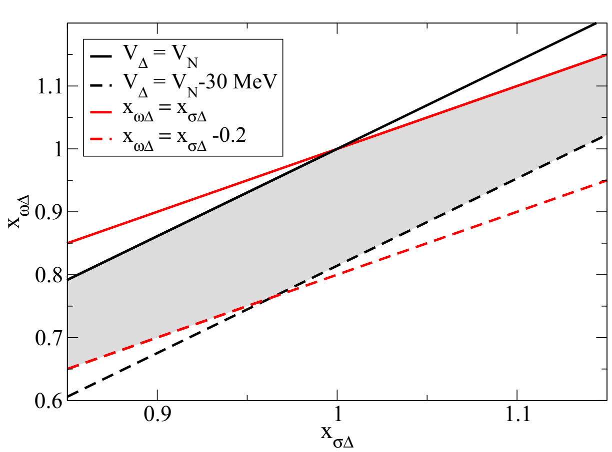

FIG. 3. (Color online) Relation between the coupling ratios $x_{\omega\Delta}$ and $x_{\sigma\Delta}$, within the SFHo model, for two values of the potential V_Δ as obtained from pion and electron scattering and from photoabsorption on nuclei. Also displayed are the experimental constraints on the difference between $x_{\omega\Delta}$ and $x_{\sigma\Delta}$ [30]. The shaded area corresponds to the region in which all constraints are satisfied.

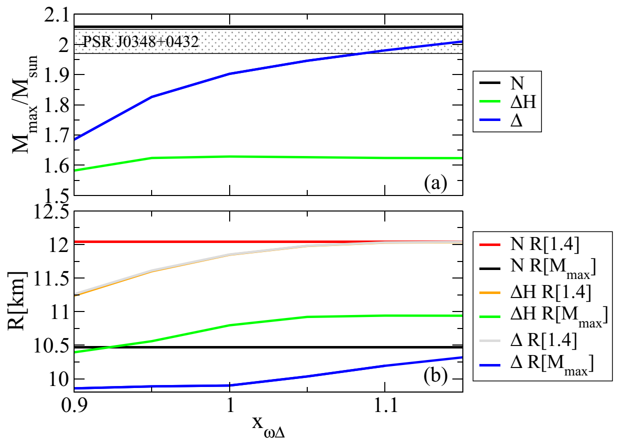

FIG. 4. (Color online) Properties of hadronic stars (with and without hyperons within the SFHo model) as functions of $x_{\omega\Delta}$. (a) Maximum masses, (b) radii of the $1.4M_\odot$ stellar configurations and the radii of the maximum-mass configurations. The labels N, Δ and ΔH in the legend stand for purely nucleonic stars, for hadronic stars with only Δs, and for hadronic stars in which Δs and hyperons are present, respectively.

Let us now analyze the effect of including Δs on the structure of neutron stars. We calculate the equation of state of β-stable matter by use of the SFHo model for different values of $x_{\omega\Delta}$ at fixed values of $x_{\sigma\Delta} = x_{\rho\Delta} = 1$ (similar results are found by varying $x_{\sigma\Delta}$). From the upper panel of Fig. 4 one can notice that the inclusion of the Δ dramatically reduces the maximum mass: if $x_{\omega\Delta} \lesssim 1$ as indicated by the experimental data, the maximum mass does not satisfy the $2M_\odot$ limit [11]. Concerning the radii, we notice that, if only Δ resonances are included, the maximum-mass configurations are very compact, with a radius $R \lesssim 10.5$ km. Concerning hyperons, the implementation of additional repulsion between them, as in Refs. [2,12], would shift the green curves towards the blue ones which correspond to the case in which hyperons are not present at all.

A comment regarding the reliability of our equation of state is in order: we adopt a model belonging to the class of quantum hadrodynamics models which, as shown in Ref. [42], beyond the mean-field approximation are inconsistent. Possible solutions for including loop corrections have been proposed in Refs. [43,44]. Although still this represents an open issue, this class of models is commonly used as a guideline in the absence of any *ab initio* technique to investigate matter at very large densities. Our result could be very important for the physics of compact stars and it would be interesting to investigate whether similar outcomes are obtained, for instance, in nonrelativistic microscopic calculations.

IV. CONCLUSION

The main result of our work is that, by combining constraints on the value of L and on the value of the Δ potential in nuclear matter, we obtain an early appearance of Δ isobars in β-stable matter, at a density of the order of $2n_0$ to $3n_0$. This is strongly at variance with the results of Ref. [1] where

Δs did not appear even at the center of the most massive neutron stars. The interplay between Λ and Δ resonances takes place at relatively low densities. At those densities the use of relativistic mean-field models, whose parameters are fit to reproduce saturation properties, is probably still reliable. In our work we also analyze the problem of the maximum mass of compact stars and we find that the formation of Δ^- makes it difficult to reach the $2M_\odot$ limit. This apparent conflict between calculations suggesting the early appearance of new resonances and astrophysical measurements could be solved in two ways. The first is based on the existence of a mechanism which stiffens the equation of state at high density while still allowing the production of resonances at low densities: this could be related to many body correlations, such as the ones studied, e.g., in Ref. [18] or to the existence of a multipomeron exchange potential generating a universal many-body repulsion, as proposed in Ref. [45]. Another possibility is based on a change from hadronic to quark degrees of freedom motivated by many analyses indicating that the equation of state of quark matter can be rather stiff [46–49]. Quark matter can occupy just the center of the most massive compact stars, such as, e.g., in Refs. [47,50–52]. Alternatively stars made entirely of quark matter could exist [53]. In particular, the scenario of two coexisting families of compact stars, hadronic stars and stars containing quark matter, has been extensively discussed in the literature; see, for instance, Refs. [8,54–57]. In Ref. [8] it was shown that hadronic stars can be very compact but light (due to the formation of delta resonances and hyperons) while quark stars can be very heavy. The two $2M_\odot$ stars would therefore be interpreted as quark stars in that scenario.

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