INTERPLAY BETWEEN Δ PARTICLES AND HYPERONS IN NEUTRON STARS

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Abstract: We analyze the effects of including $\Delta(1232)$ isobars in an equation of state (EoS) for cold, β-stable neutron star matter, employing Relativistic Nuclear Mean Field Theory. The selected EoS reproduces the properties of nuclear matter and finite nuclei, and also allows for the presence of hyperons in neutron stars having masses larger than $2M_\odot$. We find that the composition and the structure of neutron stars are critically influenced by the addition of the Δ's, an observation that allows us to constraint their interaction with the meson fields sigma and omega. Imposing that the EoS is stable and ensures the existence of $2M_\odot$ neutron stars, as well as requiring agreement with data of Δ excitation in nuclei, we find that, in the absence of other mechanisms stiffening the EoS at high densities, the interaction of the Δ's with the sigma and omega fields must be stronger than that of the nucleons.

I. INTRODUCTION

Neutron stars are the most compact objects known without an horizon event [1], and their cores contain strongly interacting matter, several times denser than the matter at the center of nuclei.

The structure and properties of neutron stars primarily depend on the equation of state (EoS). Even though the EoS at saturation density can be determined from several experimental sources, the large densities at the center of these objects have not been reached experimentally, and the EoS of neutron stars' cores remains a mystery.

In order to model the structure and composition of matter in these extreme conditions, new phenomenological theories, which take into account effective particle interactions, phase transitions and general relativity, have been developed [2–5].

The composition of a neutron star is driven by the so called β-equilibrium condition, which establishes equilibrium among weak interaction processes, imposing charge neutrality and baryon number conservation [1]. A neutron star is mostly composed by neutrons, protons and electrons. However, due to the large values of the nucleon chemical potential at the large inner densities, the conversion of nucleons to hyperons is energetically favorable. The appearance of hyperonic degrees of freedom relieves the Fermi pressure exerted by baryons and makes the EoS softer, which leads to a reduction of the maximum possible mass of neutron stars below $2M_\odot$, in disagreement with recent observations [6, 7]. However, it is still possible to tune some parameters, like the couplings between the meson fields and the baryons, to fulfill the conditions imposed by recent observations. In the present work, we use as starting point the EoS of the FSU2H model [4] which reproduces faithfully the properties of finite nuclear matter at saturation density, heavy-ion collision measured parameters, the symmetry energy E_{sym} and its derivative (parameter L), and is compatible with the $2M_\odot$ limit observations.

While many studies have been conducted regarding the presence of hyperons in the core of neutron stars [8], little work has been done to study the appearance of $\Delta(1232)$ isobars, probably due to the outcome of [9], which indicated that these particles would only appear at much higher densities than the typical one in neutron star cores.

Nonetheless, recent studies [5] have pointed out that the density onset for Δ particles in neutron star matter would be around $(2-3)\rho_0$ (with $\rho_0 = 0.16$ fm^{-3} the saturation density), a density which is easily attained in neutron stars. The aims of the present work are to analyze the interplay between Δ particles and hyperons using the recently fine tuned EoS of Ref. [4] and to study the effects of such modification in the maximum masses and radii of neutron stars.

II. EQUATION OF STATE

In this section, we introduce a modified version of the EoS of the FSU2H model [4], which includes $\Delta(1232)$ degrees of freedom, to describe the core of neutron stars. For the inner and outer crust, we employ the EoS presented in [10].

As in [4], we adopt the scheme of the Relativistic Nuclear Mean Field (RMF) theory, which provides a covariant description of the EoS. In RMF theory, the interaction between baryons is mediated by the exchange of a scalar meson σ, and three vector mesosns, ω, ρ and ϕ. The Lagrangian density of the theory can be written as

$$\mathcal{L} = \sum_b \mathcal{L}_b + \mathcal{L}_\Delta + \mathcal{L}_m + \sum_{l=e,\mu} \mathcal{L}_l \quad (1)$$

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with

$$\mathcal{L}_b = \bar{\Psi}_b(i\gamma_\mu\partial^\mu - m_b + g_{\sigma b}\sigma - g_{\omega b}\gamma_\mu\omega^\mu - g_{\phi b}\gamma_\mu\phi^\mu - g_{\rho b}\gamma_\mu\vec{I}_b\vec{\rho}^\mu)\Psi_b$$
$$\mathcal{L}_\Delta = \bar{\Psi}_{\Delta\nu}(i\gamma_\mu\partial^\mu - m_\Delta + g_{\sigma\Delta}\sigma - g_{\omega\Delta}\gamma_\mu\omega^\mu - g_{\rho\Delta}\gamma_\mu I_3\rho_3^\mu)\Psi_\Delta^\nu$$
$$\mathcal{L}_l = \bar{\psi}_l(i\gamma_\mu\partial^\mu - m_l)\psi_l$$
$$\mathcal{L}_m = \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \frac{1}{2}m_\sigma^2\sigma^2 - \frac{\kappa}{3!}(g_{\sigma N}\sigma)^3 - \frac{\lambda}{4!}(g_{\sigma N}\sigma)^4 - \frac{1}{4}\Omega^{\mu\nu}\Omega_{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu + \frac{\zeta}{4!}(g_{\omega N}\omega_\mu\omega^\mu)^4 - \frac{1}{4}\vec{R}^{\mu\nu}\vec{R}_{\mu\nu} + \frac{1}{2}m_\rho^2\vec{\rho}_\mu\vec{\rho}^\mu + \Lambda_\omega g_{\rho N}^2\vec{\rho}_\mu\vec{\rho}^\mu g_{\omega N}^2\omega_\mu\omega^\mu - \frac{1}{4}P^{\mu\nu}P_{\mu\nu} + \frac{1}{2}m_\phi^2\phi_\mu\phi^\mu$$

where Ψ_b and ψ_l are the baryon and lepton Dirac fields, and Ψ_Δ is the Rarita-Schwinger spinor for Δ isobars. The subscript b runs over the octet of light baryons, the subscript l takes the values $l = e, \mu$ and the subscript m runs over all the meson fields, i.e., $m = \sigma, \omega, \rho$ and ϕ. $\Omega_{\mu\nu}$, $\vec{R}_{\mu\nu}$ and $P_{\mu\nu}$ are the mesonic strength tensors of the ω, ρ and ϕ fields, respectively. κ, λ and ζ are the coupling constants of the self-interactions of σ and ω, and Λ_ω is the coupling constant of the mixed quartic isovector-vector interaction. Finally, the strong interaction couplings to a certain baryon are denoted by g and $\vec{I}_b$ denotes the isospin vector.

From the Lagrangian density in Eq. (1) and working in the so called Mean Field Approximation, which essentially consists of replacing the meson fields by their expectation values ($\bar{\sigma} = \langle\sigma\rangle$, $\bar{\rho} = \langle\rho_3^0\rangle$, $\bar{\omega} = \langle\omega\rangle$, and $\bar{\phi} = \langle\phi^0\rangle$), we can derive the energy density of the system [4],

$$\epsilon = \sum_b \epsilon_b + \sum_l \epsilon_l + \sum_\Delta \epsilon_\Delta + \frac{1}{2}m_\sigma^2\bar{\sigma}^2 + \frac{1}{2}m_\omega^2\bar{\omega}^2 + \frac{1}{2}m_\rho^2\bar{\rho}^2 + \frac{1}{2}m_\phi^2\bar{\phi}^2 + \frac{\kappa}{3!}(g_\sigma\bar{\sigma})^3 + \frac{\lambda}{4!}(g_\sigma\bar{\sigma}^4) + \frac{\zeta}{8}(g_\omega\bar{\omega})^4 + 3\Lambda_\omega(g_\rho g_\omega\bar{\rho}\bar{\omega})^2 \tag{2}$$

where $\sum_b \epsilon_b$, $\sum_l \epsilon_l$ and $\sum_\Delta \epsilon_\Delta$ are the contributions of the light baryons of the octet, the leptons and the Δ isobars, respectively. Mainly, the contribution of the particles to the energy density depend on their Fermi momentum and effective masses, defined for baryons and Δ's as $m_b^* = m_b - g_{\sigma b}\bar{\sigma}$ and $m_\Delta^* = m_\Delta - g_{\sigma\Delta}\bar{\sigma}$.

Besides, the pressure of the system can be obtained from the thermodynamic relation [4],

$$P = \sum_i \mu_i n_i - \epsilon \tag{3}$$

where n_i is the density of the different particles and μ_i the corresponding chemical potential, defined as

$$\mu_b = E_F^b + g_{\omega b}\bar{\omega} + g_{\rho b}I_{3b}\bar{\rho} + g_{\phi b}\bar{\phi}, \tag{4}$$
$$\mu_\Delta = E_F^\Delta + g_{\omega\Delta}\bar{\omega} + g_{\rho\Delta}I_{3\Delta}\bar{\rho}, \tag{5}$$
$$\mu_l = E_F^l \tag{6}$$

where E_F^b, E_F^Δ and E_F^l denote the Fermi Energies of baryons, Δ's and leptons, respectively. Thus, the EoS of the core of a neutron star strongly depends on its composition and on the couplings to the meson fields.

The conditions of charge neutrality and β-equilibrium[1] in the matter of the core of neutron stars impose the following conditions on the chemical potentials μ_i and particle densities, n_i,

$$\mu_i = b_i\mu_n - q_i\mu_e, \tag{7}$$
$$0 = \sum_{cb} q_i n_i + \sum_l q_l n_l, \tag{8}$$
$$n = \sum_b n_i \tag{9}$$

where b_i is the baryon number and q_i is the charge of particle i. For a given baryon density, n, the equations of motion for the meson fields and the different species have to be solved self-consistently, subjected to the restrictions presented in Eqs. (7), (8) and (9), in order to obtain the chemical potential and the corresponding density of each of the species, and the relation between the energy density and pressure (EoS) for that density.

As a final condition, we require the resulting EoS to be stable (i.e. $\frac{dP}{d\epsilon} > 0\ \forall n$) and stiff enough as to ensure the existence of neutron stars with masses larger than $2M_\odot$, in agreement with recent observations. These two restrictions will be crucial in the discussion that follows.

III. STELLAR STRUCTURE AND TOV EQUATIONS

In the present work we analyze static, spherically symmetric neutron stars described by the EoS presented in [4] for the core and the EoS of reference [10] for the inner and outer crust.

Imposing hadrodynamic equilibrium within the theory of General Relativity yields the set of differential equations known as Tolman-Oppenheimer-Volkoff

[1] We say that a neutron star is β-stable if it is stable under β-decay, i.e., if a dynamical equilibrium exists such that the number of neutrons which undergo the reaction $n \longrightarrow p + e^- + \bar{\nu}_e$ is compensated with the number of protons and electrons colliding to generate neutrons, $p + e^- \longrightarrow n + \nu_e$.

(TOV) equations,

$$\frac{dP(r)}{dr} = -\frac{G}{r^2}\left[\epsilon(r) + P(r)\right] \times$$
$$\left[M(r) + 4\pi r^3 P(r)\right]\left[1 - \frac{2GM(r)}{r}\right]^{-1} \quad (10)$$
$$\frac{dM(r)}{dr} = 4\pi\epsilon(r)r^2, \quad (11)$$

where r is the distance to the center of the star. These two equations can be integrated from the origin with initial conditions $M(0) = 0$ and an arbitrary value for the central energy density $\epsilon(0) = \epsilon_c$ until the pressure $p(r)$ becomes zero. The point R where the pressure vanishes defines both the radius and the total mass, $M(R)$, of the star.

Pressure plays a fundamental role in the determination of the stellar structure of relativistic stars, and it is ultimately responsible of the existence of a limiting mass in these kind of objects, independently of the considered EoS [2]. However, the explicit values of the limit mass and radius of neutron stars are linked to the EoS, a fact that offers a way to test the validity of the different models (and to limit the values of the parameters on which the model depends), just requiring that the resulting neutron stars have masses that could reach the maximum value observed of around $2M_\odot$ and radii smaller than 13 km. In particular, the maximum mass of a neutron star predicted by the EoS strongly depends on the stiffness of the core, which it is also known to become softer with the appearance of both hyperons [4] and Δ's [5].

IV. RESULTS AND DISCUSSION

Even though the model presented in Sec. II has been developed for the four Δ isobars, in our implementation only the Δ^- and the Δ^0 have been explicitly considered. The reason, as can be inferred from Eq. (7), is that negatively charged and neutral particles with the same rest mass are favored to appear at lower densities than those positively charged.

The EoS presented in Sec. II depends on the values of the strong interaction couplings of the different particles to the meson fields (denoted by g), and on the parameters responsible of the self-interaction of these fields (κ, λ and ζ). We employ the values of the FSU2H model [4] for these parameters, with the proviso that the introduction of the Δ degrees of freedom introduces three new free parameters, i.e., $g_{\sigma\Delta}$, $g_{\omega\Delta}$ and $g_{\rho\Delta}$. As it is customary, in the discussion that follows, we will treat the values of these parameters in terms of the ratios,

$$x_{\sigma\Delta} = \frac{g_{\sigma\Delta}}{g_{\sigma N}} \qquad x_{\omega\Delta} = \frac{g_{\omega\Delta}}{g_{\omega N}} \qquad x_{\rho\Delta} = \frac{g_{\rho\Delta}}{g_{\rho N}}. \quad (12)$$

Even though the couplings of the Δ isobars with the meson fields at high densities are poorly constrained due to the lack of experimental observations, some information is available to restrict their values. According to [5], it has been possible to establish that the Δ's inside a nucleus feel an attractive potential and, given that the quark content of these particles is essentially up and down quarks, we don't expect these parameters to significantly differ from those of nucleons. No information is available for $x_{\rho\Delta}$, but studies in electromagnetic excitations of the Δ baryon within the framework of quantum hadrodynamics established the following constraint[11]:

$$0 \lesssim x_{\sigma\Delta} - x_{\omega\Delta} \lesssim 0.2 \quad (13)$$

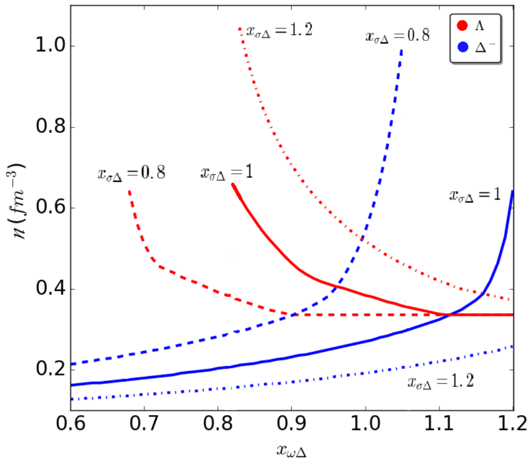

Figure 1: Threshold densities of Λ and Δ^- particles as function of $x_{\omega\Delta}$ for three different values of $x_{\sigma\Delta}$, fixing $x_{\rho\Delta} = 1$.

For these reasons, in the present work we analyze the effect that the values of these parameters have in the composition and structure of neutron stars for a relatively small range of values close to $x_{\sigma\Delta} = x_{\omega\Delta} = x_{\rho\Delta} = 1$. First of all, we notice that, in the present model, the EoS is fairly independent of the value of $x_{\rho\Delta}$ for the analyzed range of values $x_{\rho\Delta} \in [0.5, 2.0]$. Thus, for the following discussions we set $x_{\rho\Delta} = 1$, though the results we present hold for any value of $x_{\rho\Delta}$ within the studied range. The dependence of the EoS on the values of the ratios $x_{\sigma\Delta}$ and $x_{\omega\Delta}$ is, by far, more interesting.

In Fig. 1, we study the dependence of the onset density, i.e., the lowest density at which a particle first appears, of the Δ^- (which appears at the lowest density among the Δ's, since it can replace a neutron and an electron at the top of their Fermi seas) and the Λ (which is the hyperon that first appears, owing to its lowest mass and to the fact that the Σ^- feels a repulsive interaction) as a function of the value of $x_{\omega\Delta}$, for three different values of $x_{\sigma\Delta}$ and taking $x_{\rho\Delta} = 1$.

For small values of the ratio $x_{\omega\Delta}$, the Δ^- appears at smaller densities than the hyperon Λ, delaying its appearance, in agreement with the outcome of reference [5]. As the value of $x_{\omega\Delta}$ increases, the onset density of the Δ^- also increases and that of the Λ decreases, leading to the existence of a value of $x_{\sigma\Delta}$ and $x_{\omega\Delta}$ such that both Δ^-

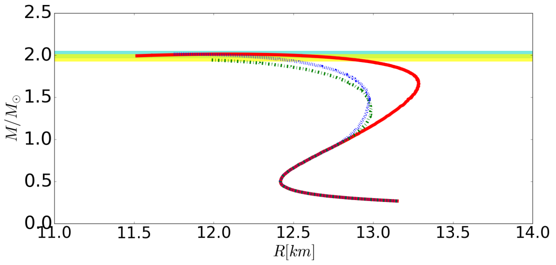

Figure 2: Mass versus radius profile for hyperonic neutron stars in the FSU2H model without including Δ's (solid red line) and for the modified model (which includes Δ isobars degrees of freedom), taking $x_{\sigma\Delta} = x_{\omega\Delta} = x_{\rho\Delta} = 1$ (dot-dashed green line) and $x_{\sigma\Delta} = x_{\omega\Delta} = 1.15$, $x_{\rho\Delta} = 1$ (dotted blue line). The horizontal shaded regions represent the masses $M = 1.97 \pm 0.04 M_\odot$ in the pulsar PSR J1614-2230 (yellow band) and $M = 2.01 \pm 0.04 M_\odot$ in the pulsar PSR J0348+0432 (blue band).

and Λ appear at the same density. For larger values of $x_{\omega\Delta}$, the hyperon Λ appears before the Δ^-, at an onset density of 0.336 fm^{-3}, which is the onset density for this particle in the FSU2H model without Δ's [4].

The results of Fig. 1 can be interpreted within the framework of the Relativistic Nuclear Mean Field Theory, since large values of $g_{\sigma\Delta}$ reduce the chemical potential of the Δ^-, thus favoring the appearance of Δ's at smaller densities, and large values of $g_{\omega\Delta}$ increase their energy, contributing to the opposite effect [see Eq. (5)].

We note that the range of possible values for the ratios $x_{\omega\Delta}$ and $x_{\sigma\Delta}$ are limited by the appearance of instabilities in the EoS, i.e., regions where the $\frac{dP}{d\epsilon} < 0$, and the experimental constraint of Eq. (13) [11]. In fact, we have observed that a positive difference close to the value 0.2 in $x_{\sigma\Delta} - x_{\omega\Delta}$ leads to instabilities in the EoS. Demanding stability, we have been able to further constrain the values of these ratios to fulfill the relation

$$x_{\omega\Delta} \gtrsim 1.14 x_{\sigma\Delta} - 0.286 \qquad (14)$$

Next, we analyze the effect of including Δ's on the structure of neutron stars. In Fig. 2 we display the M-R relation obtained for the FSU2H model (without inclusion of Δ's) and for the EoS in which we consider strength ratios of $x_{\sigma\Delta} = x_{\omega\Delta} = 1$ (for which the $2M_\odot$ limit is not fulfilled) and $x_{\sigma\Delta} = x_{\omega\Delta} = 1.15$. In accordance with [5], we notice that the inclusion of Δ isobars softens the EoS at high densities, thus dramatically reducing the maximum mass until it falls below the observational limit $2M_\odot$ for $x_{\sigma\Delta} \approx x_{\omega\Delta} \approx 1$. However, we also notice that the EoS becomes stiffer if we consider a more intense interaction of the Δ's with the meson fields than that of the nucleons. Regarding the radii, we observe that, for values of $x_{\sigma\Delta}$ and $x_{\omega\Delta}$ which fulfill the $2M_\odot$ condition, we obtain very compact stars, with radii smaller than 12 km in all the cases. This result falls within the range for realistic radii of canonical neutron stars mentioned in [4].

In Figs. 3 and 4 we compare the particle fractions as function of the baryon density for the FSU2H model

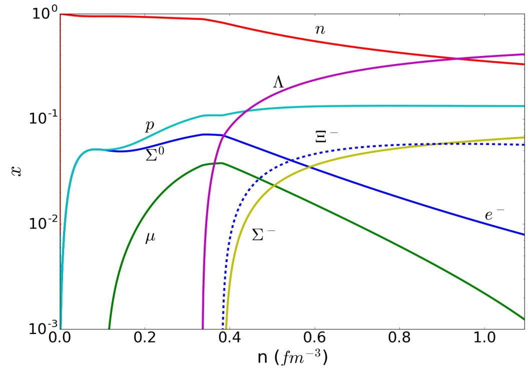

Figure 3: Particle fractions as a function of the baryonic density (in fm^{-3}) within the FSU2H model including hyperons.

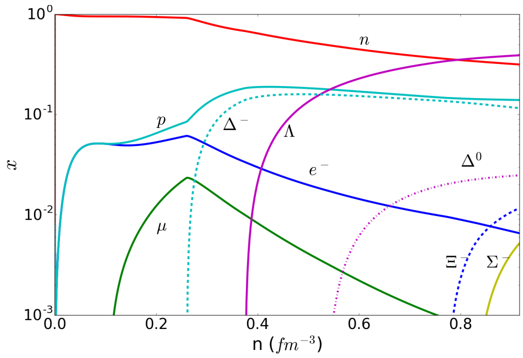

Figure 4: Particle fractions as a function of the baryonic density (in fm^{-3}) within the FSU2H model including hyperons and Δ's for $x_{\sigma\Delta} = 1.15$, $x_{\omega\Delta} = 1.15$ and $x_{\rho\Delta} = 1$.

without including Δ isobar degrees of freedom (Fig. 3) and for the case $x_{\sigma\Delta} = 1.15$, $x_{\omega\Delta} = 1.15$ and $x_{\rho\Delta} = 1$ (Fig. 4) which fulfill the $2M_\odot$ mass limit, clearly showing the delay in the appearance of the hyperons caused by the Δ's. It is also interesting to notice that the Δ^- partially replaces the role of the Σ^- and Ξ^- in compensating the positive charge of the protons, which leads to a decrease of the fraction of Σ^- and Ξ^- in the equilibrium composition when Δ's are considered (Fig. 4).

In Fig.5, we summarize the constraints which the strength ratios $x_{\sigma\Delta}$ and $x_{\omega\Delta}$ must fulfill to ensure the existence of neutron stars compatible with the analyzed stability criterion and compatible with the observational results. Even though there is a range of values for the parameters $x_{\sigma\Delta}$ and $x_{\omega\Delta}$ in which all the constrains are satisfied (green region), we notice that it implies the interaction between Δ's and the meson fields σ and ω must be 10-20% larger than that of the nucleons.

V. CONCLUSIONS

In this work we analyze the effect of the inclusion of Δ isobars in the EoS of the core of neutron stars, taking as a starting point the model FSU2H presented in [4]. We

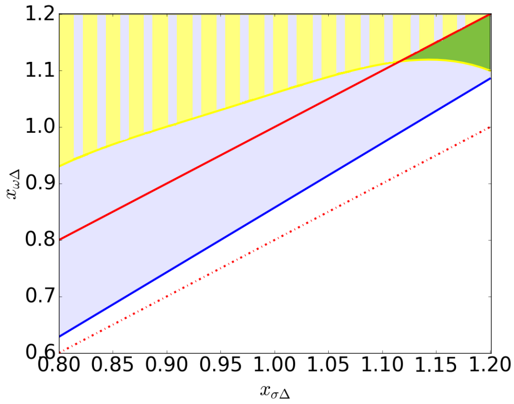

Figure 5: Relation between the coupling ratios $x_{\omega\Delta}$ and $x_{\sigma\Delta}$ ($x_{\rho\Delta} = 1$) within the FSU2H model which lead to stable EoS (region above the blue line) and to maximum masses higher than $2M_{\odot}$ with stable EoS (region above the yellow line). The experimental constraints on the difference between $x_{\omega\Delta}$ and $x_{\sigma\Delta}$ [11] (region in between the solid and dot-dashed red lines) are also shown. The green shaded area corresponds to the region where all the constraints are satisfied.

also analyze the interplay between these particles and the meson fields (parametrized in the values of $x_{\sigma\Delta}, x_{\omega\Delta}$ and $x_{\rho\Delta}$).

Even though the resulting EoS is fairly independent of the value of $x_{\rho\Delta}$, we have found that both the composition and the structure of neutron stars depend on the values of $x_{\sigma\Delta}$ and $x_{\omega\Delta}$, allowing us to further constraint the values of these parameters to ensure the existence of neutron stars with masses larger than $2M_{\odot}$ with a stable EoS, while fulfilling the experimental relation between $x_{\sigma\Delta}$ and $x_{\omega\Delta}$ presented in [11].

However, in order to fulfill all the restrictions, we find that $x_{\sigma\Delta} \gtrsim 1.11$ and $x_{\omega\Delta} \gtrsim 1.11$, which would indicate a stronger interaction of the Δ's with the meson fields than that of the nucleons. Also, contrary to our initial guess that the Δ's essentially behave as the nucleons, we notice that the values $x_{\sigma\Delta} = x_{\omega\Delta} = 1$ give rise to a too soft EoS and, consequently to neutron stars with masses smaller than $2M_{\odot}$. Thus, it would be interesting to study if there are alternative mechanisms to further stiffen the EoS at high densities, which would enlarge towards lower values of $x_{\sigma\Delta}$ and $x_{\omega\Delta}$ the region where all constraints are fulfilled.

Finally, we notice that, in agreement with the outcome of [5], the inclusion of Δ's with strength ratios in the range where all the constraints are satisfied, delays the appearance of hyperons in the core of cold, β-stable neutron stars. Since the appearance of new particles in the core of neutron stars is accompanied by a softening in the EoS and, consequently, by a reduction of the maximum mass, the appearance of Δ's was expected to add its effect to that of hyperons, further reducing the maximum mass. However, the fact that the appearance of Δ's delays the appearance of hyperons leads to a smoother softening, allowing for the existence of neutron stars with masses higher than $2M_{\odot}$.

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