Effect of the symmetry energy on compact stars

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Abstract. The effect of the symmetry energy on the properties of compact stars is discussed. It is shown that, for stars with masses above 1\,M⊙, the radius of the star varies linearly with the symmetry energy slope \( L \). The hyperon-meson couplings are chosen according to experimental values of the hyperon nuclear matter potentials, and possible uncertainties are considered. It is shown that a softer symmetry energy gives rise to stars with less hyperons and smaller radius. Hyperon-meson couplings may also have a strong effect on the mass of the star.

1. Introduction
In the present work we want to understand how sensitive is the mass/radius curve of a family of stars to the symmetry energy and its slope at saturation. We study not only maximum mass configurations but also stars with a mass in the range 1.0\,M⊙ < M < 1.4\,M⊙. These stars have a central density that goes from 1.5\,\rho_0 to 2-3\,\rho_0, and, therefore, we will be testing the equation of state at suprasaturation densities. At high density the formation of hyperons is energetically favorable and, therefore, we also study the effect of the symmetry energy on the appearance of these exotic degrees of freedom [1].

The work is performed in the relativistic mean field approximation and we consider different parametrizations of the non-linear Walecka model [2], which allow us to discuss the role of the density dependence of the symmetry energy on the properties of the non-homogeneous nuclear EOS [1, 3, 4, 5, 6]. We will also present results obtained with the quark-meson-coupling (QMC) model [7, 8], an effective nuclear model that takes into account the internal structure of the nucleon explicitly. Within the QMC model, matter at low densities and temperatures is a system of nucleons interacting through meson fields, with quarks and gluons confined within MIT bags.

We consider three different hyperon-meson parametrizations: one proposed in [1] and a second one that takes into account the different binding energies of the hyperons [10, 11], and the third one starts from the QMC model and also takes into account the different binding energies of the hyperons. The results presented here have been published in part in [12] and [13].
2. Formalism

We describe hadronic matter within the framework of the relativistic non-linear Walecka model (NLWM) [2]. We include a $\rho - \omega$ meson coupling term as in [5, 6] in order to study the effect of the symmetry energy on the star properties while leaving the isoscalar channel fixed. The Lagrangian density reads

$$\mathcal{L} = \sum_{j=1}^{8} \bar{\psi}_j \left( \gamma_\mu (i \partial^\mu - g_{\omega j} \omega^\mu - g_{\rho j} \vec{\tau}_j \cdot \vec{\rho}^\mu) - m_j^* \right) \psi_j + \sum_{l=1}^{2} \bar{\psi}_l (i \gamma_\mu \partial^\mu - \hat{M}_l) \psi_l$$

$$+ \frac{1}{2} \partial_\mu \sigma \partial^\mu \sigma - \frac{1}{2} m_\sigma^2 \sigma^2 - \frac{1}{3!} k \sigma^3 - \frac{1}{4!} \lambda \sigma^4 - \frac{1}{4} \Omega_{\mu \nu} \Omega^{\mu \nu} + \frac{1}{2} m_\omega^2 \omega_\mu \omega^\mu + \frac{1}{4!} \xi g_\omega^4 (\omega_\mu \omega^\mu)^2$$

$$- \frac{1}{4} \vec{R}_{\mu \nu} \cdot \vec{R}^{\mu \nu} + \frac{1}{2} m_\rho^2 \vec{p}_\rho \cdot \vec{p}^\mu + \Lambda_\nu (g_\rho^2 \vec{p}_\rho \cdot \vec{p}^\nu) (g_\omega^2 \omega_\mu \omega^\mu),$$

$$\Omega_{\mu \nu} = \partial_\mu \omega_\nu - \partial_\nu \omega_\mu - \partial_\rho \vec{p}_\rho \cdot \vec{R}^{\mu \nu}, \quad \vec{R}_{\mu \nu} = \partial_\mu \vec{p}_\nu - \partial_\nu \vec{p}_\mu - \vec{p}_\rho \times (\vec{p}_\rho \times \vec{R}^{\mu \nu}), \quad g_{ij} \text{ are the coupling constants of mesons } i = \sigma, \omega, \rho \text{ with baryon } j, \quad m_i \text{ is the mass of meson } i \text{ and } l \text{ represents the leptons } e^- \text{ and } \mu^-.$$  

The sum over $j$ in (1) extends over the octet of lightest baryons $\{n, p, \Lambda, \Sigma^-, \Sigma^0, \Sigma^+, \Xi^-, \Xi^0\}$. The coupling $k$ and $\lambda$ are the weights of the non-linear scalar terms and $\vec{t}$ is the isospin operator. Their values can be obtained from [12]. The symmetry energy on the star properties while leaving the isoscalar channel fixed. The Lagrangian density reads

$$\mathcal{L} = \sum_{j=1}^{8} \bar{\psi}_j \left( \gamma_\mu (i \partial^\mu - g_{\omega j} \omega^\mu - g_{\rho j} \vec{\tau}_j \cdot \vec{\rho}^\mu) - m_j^* \right) \psi_j + \sum_{l=1}^{2} \bar{\psi}_l (i \gamma_\mu \partial^\mu - \hat{M}_l) \psi_l$$

$$+ \frac{1}{2} \partial_\mu \sigma \partial^\mu \sigma - \frac{1}{2} m_\sigma^2 \sigma^2 - \frac{1}{3!} k \sigma^3 - \frac{1}{4!} \lambda \sigma^4 - \frac{1}{4} \Omega_{\mu \nu} \Omega^{\mu \nu} + \frac{1}{2} m_\omega^2 \omega_\mu \omega^\mu + \frac{1}{4!} \xi g_\omega^4 (\omega_\mu \omega^\mu)^2$$

$$- \frac{1}{4} \vec{R}_{\mu \nu} \cdot \vec{R}^{\mu \nu} + \frac{1}{2} m_\rho^2 \vec{p}_\rho \cdot \vec{p}^\mu + \Lambda_\nu (g_\rho^2 \vec{p}_\rho \cdot \vec{p}^\nu) (g_\omega^2 \omega_\mu \omega^\mu),$$

where $m_q^0$ is the current quark mass, and $g_\rho^2$, $g_\omega^2$ and $g_\rho^0$ denote the quark-meson coupling constants. The effective mass of a nucleon bag at rest is taken to be equal to the energy of the bag, $M_i^* = E_i^{\text{bag}}$. The equilibrium condition for the bag is obtained by minimizing the effective mass, $M_i^*$, of baryon $i$ with respect to the bag radius, see [7, 8, 9].

$$\frac{d M_i^*}{d R_i^*} = 0,$$

The energy density and pressure of hadronic matter within QMC is equal to the one obtained for NLWM with the effective mass replaced by the energy of the bag, $E_i^{\text{bag}}$. We will also include a meson nonlinear term involving the $\omega$ and $\rho$ mesons. Choosing the coupling constant $\Lambda_\nu$ adequately it is possible to soften the symmetry energy of the QMC model at large densities.

We consider two different sets of hyperon-meson couplings. For the coupling set $\Lambda$ the $\omega$ and $\rho$ meson-hyperon coupling constants are obtained using the SU(6) symmetry:

$$\frac{1}{2} g_{\omega \Xi} = g_{\omega \Xi} = \frac{1}{2} g_{\omega N}, \quad \frac{1}{2} g_{\rho \Xi} = g_{\rho \Xi} = g_{\rho N}, \quad g_{\rho \Lambda} = 0,$$

where $N$ means 'nucleon' ($g_{i N} \equiv g_i$). The coupling constants $\{g_{\sigma j}\}_{j=\Lambda, \Sigma, \Xi}$ of the hyperons with the scalar meson $\sigma$ are constrained by the hypernuclear potentials in nuclear matter to be consistent with hypernuclear data [10]. We take $V_j = x_{\omega j} V_\omega - x_{\rho j} V_\rho$, where $x_{ij} = g_{ij} / g_i$, $V_\omega \equiv g_{\omega 0} \omega_0$, and $V_\rho \equiv g_{\rho 0} \rho_0$, and $V_\sigma \equiv g_{\sigma 0} \sigma_0$ are the nuclear potentials for symmetric nuclear matter at saturation with (see Ref. [10]), $V_\Lambda = -28$ MeV, $V_\Sigma = 30$ MeV, $V_\Xi = -18$ MeV. We use these same values in QMC. In QMC the couplings of the hyperons to the $\sigma$-meson do not need to be fixed because the effective masses of the hyperons are determined selfconsistently at the bag level. We obtain $x_{\omega B}$ from the hyperon potentials in nuclear matter, $V_j = -(M_j^* - M_j) + x_{\omega j} g_{\omega 0}$, and find $x_{\omega \Lambda} = 0.743$, $x_{\omega \Sigma} = 1.04$ and $x_{\omega \Xi} = 0.346$. $x_{\rho B} = 1$ is fixed for all the baryons [13]. However, while the binding of the $\Lambda$ to symmetric
nuclear matter is well settled experimentally, the binding values of the $\Sigma^-$ and $\Xi^-$ still have a lot of uncertainties [14]. We, therefore, test the effect of the coupling to the cascade and show results also for $V_\Xi = -10$ and 0 MeV.

In order to show how results are sensitive to the hyperon couplings we consider set B defined as proposed in [1] with $x_\sigma = 0.8$ and equal for all the hyperons. We obtain the fraction $x_\omega$ with $V_j = V_\Lambda = -28$ MeV, and take the same value for all the hyperons. For the hyperon-$\rho$-meson coupling we consider $x_\rho = x_\sigma$.

Figure 1. Left panel: Equation of state for symmetric nuclear matter and different NLWM models. The enclosed area represents experimental data according to Danielewicz et al., [15]. Right panel: the corresponding symmetry energy.

3. Results

Within the NLWM, we will consider the following parametrizations, see Fig. 1: NL3 [3], with a quite large symmetry energy and incompressibility at saturation and which was fitted in order to reproduce the ground state properties of both stable and unstable nuclei; FSU [5] and IUFSU [6], which were accurately calibrated to simultaneously describe the GMR in $^{90}$Zr and $^{208}$Pb, and the IVGDR in $^{208}$Pb and still reproduce ground-state observables of stable and unstable nuclei. FSU is very soft at high densities. GM1 and GM3 [1] are generally used to describe stellar matter, with a symmetry energy not so hard as the one of NL3, and NL$\rho$ [4], which has at high densities, a behavior between GM1 and GM3.

In order to study the effect of the isovector channel in the star properties we also consider a modified version of the IUFSU parametrization: we keep the isoscalar channel and change $g_\rho$ and $\Lambda_\rho$ keeping the symmetry energy fixed at the density $0.12$ fm$^{-3}$. We generate a set of models, from set 1 to set 7, that differ in their value of the symmetry energy and corresponding slope at saturation but have the same isoscalar properties. The set 1 is the parametrization IUFSU, $L = 47$ MeV. The other parametrizations have a larger symmetry energy and a larger slope $L$ at saturation. The maximum value of $L$ we have considered (for set 7, $L = 99$ MeV) is within the experimental values obtained from isospin diffusion in heavy ion reactions [16] and corresponds to a symmetry energy slightly softer than NL$\rho$ (see Fig. 1). Values of $L$ below 47 MeV would give unacceptable EOS because they would predict that neutron matter is bound.
Figure 2. Strangeness fraction for different NLWM models with hyperon set A (left panel) and set B (right panel).

Figure 3. Strangeness content for the modified IUFSU models, with set A and set B for the hyperon-meson couplings.

The effect of the symmetry energy on the strangeness fraction is seen in Figs. 2: the strangeness content is sensitive to the model and the meson-hyperon couplings. In general, the softer the EOS the larger the strangeness onset density and the smaller the strangeness content. A large meson-hyperon vector coupling, as occurs in set B, hinders the formation of hyperons. However, we should point out that when comparing different models we are comparing not only the effect of the density dependence of the symmetry energy but also the density dependence of the isoscalar channel, namely the incompressibility and effective mass. This explains why FSU, a softer EOS, has a smaller strangeness content than IUFSU, a model with a softer symmetry energy than FSU above saturation density. In Fig. 3 we show the strangeness content for the modified IUFSU models, using set A and set B for the hyperon couplings. We conclude that the smaller the symmetry energy the smaller the hyperon content.

Cooling of the star by neutrino emission can occur relatively fast if the direct Urca process, \( n \to p + e^- + \bar{\nu}_e \), is allowed [17]. The direct Urca (DU) process takes place when the proton fraction exceeds a critical value \( x_{DU} \) [17]. Cooling rates of neutron stars seem to indicate that this fast cooling process does not occur and, therefore, a constraint is set imposing that the direct Urca process is only allowed in stars with a mass larger than \( 1.5 M_\odot \), or a less restrictive limit, \( 1.35 M_\odot \) [18]. Since the onset of the direct Urca process is closely related with the density dependence of the symmetry energy, this constraint gives information on the isovector channel of the EOS.

The effect of the symmetry energy and the hyperon content on the onset density of the
nucleon direct Urca process is seen in figures 4 as function of the slope $L$ for the IUFSU and modified versions in the left panel, and for NL3, GM1, GM3, NL$\rho$, FSU and IUFSU models in the right panel. We conclude that: a) for matter without hyperons the larger the $L$ the smaller the neutron-proton asymmetry above the saturation density and, therefore, the smaller the direct Urca onset density; b) the larger the slope the smaller the onset density because a larger $L$ corresponds to a harder symmetry energy and, therefore, larger fractions of protons are favored; c) generally, for a low value of $L$ the presence of hyperons decreases the onset density. However, the effect of the inclusion of hyperons depends on the hyperon-meson coupling.

![Figure 4. Onset of the direct Urca process in stellar matter for the modified IUFSU models (left panel) and NLWM (right panel), for nohyperon matter (red triangles), hyperon coupling set A (green squares) and hyperon coupling set B (blue stars).](image)

Integrating the Tolman-Volkoff-Oppenheimer [20] equations we have obtained the mass-radius curves for the families of stars from the EOS without hyperons and from the EOS with the meson-hyperon sets A and B.

All the models except FSU are able to describe the mass of pulsar J1614-2230 [21] if hyperons are not included [12]. However, only IUFSU and FSU satisfy the constraints set by the an empirical EOS obtained from a heterogeneous set of seven neutron stars with well-determined distances [19]. The properties of the set of relativistic mean field (RMF) models chosen are reflected on the star properties: the harder models like NL3 and GM1 predict larger masses and radius, the softest EOS, FSU, the smallest mass, the smaller the $L$ the smaller the radius [12]. This last property is clearly seen in the left panel of Fig. 5 were the radius of maximum mass stars (squares), 1.4 $M_\odot$ stars (circles) and 1.0$M_\odot$ stars (triangles) are plotted as a function of the symmetry energy slope for nucleonic stars. The full symbols are for the modified IUFSU models and the empty ones for the NL3, GM1, GM3, NL$\rho$, FSU models. The modified IUFSU models show that if the isoscalar channel is left unchanged the radius decreases if $L$ decreases. This reduction is larger for 1.0$M_\odot$ stars (more than 1 km for $45 < L < 100$ MeV) but even for the maximum mass configurations there is still a 0.5 km difference. The set of RMF models chosen also show the same trend. However, since the isoscalar properties differ among the models, and they also affect the radius, the linear behavior is not present.
Figure 5. Star radius dependence on the slope of the symmetry energy for stars with maximum mass (squares), 1.4 \( M_\odot \) (circles), 1 \( M_\odot \) (triangles): no-hyperons (left panel) with hyperons, coupling A (middle panel) with hyperons, coupling B (right panel). The empty symbols are for the set of different models considered with hyperon coupling A. The full symbols are for the modified IUFSU models.

Figure 6. Mass/radius curves using set A (left panel) and set B (right panel) for the hyperon couplings.

Including hyperons in the EOS makes the EOS softer at large densities and the mass of the maximum mass stars is smaller [22]. This is seen in Fig. 6 were the mass-radius curves obtained with hyperon-meson coupling set A and B are plotted, respectively, in the left and right panels. We conclude that it is important to have correct couplings since the star masses are sensitive to the hyperon couplings. For set A only the NL3 model is able to describe the PSR J1316-2230 a star with a mass \( 1.97 \pm 0.4 \ M_\odot \) [21], while within set B NL3, GM1, GM3 and NL\( \rho \) are able to describe this star. The trend discussed above between the star radius and \( L \) is still present in these stars, see the empty symbols in the middle and right panels of Fig. 5. This trend is confirmed by the modified IUFSU models, full symbols in the middle and right panels of Fig. 5. Stars with 1.0 and 1.4 \( M_\odot \) contain no hyperons, or only a small fraction and therefore their radius do not different from the results obtained for np matter. Maximum mass stars, however, do have hyperons and their radius depends on the hyperon couplings chosen: for set A radius is larger and the maximum mass is smaller than the corresponding quantities predicted by set B. None of the modified IUFSU models with hyperons is able to describe the PSR J1614-2230. We also conclude that the mass of the maximum mass configuration is quite insensitive to the
symmetry energy slope [12].

The EOS obtained with the QMC model are displayed in Fig. 7. We have considered QMC with nucleons and hyperons [9] and different values of the coupling parameter $\Lambda_v$ and QMC with $\Lambda_v = 0$ with protons and neutrons only. We also include the empirical EOS obtained by Steiner et al. [19]. These results however, should still be considered with care because there are many uncertainties involved. The agreement of the calculated EOS with the empirical one when hyperons are included is defined by the hyperon-meson interaction and the $\Lambda_v$ coupling, or, equivalently, by the symmetry energy. The QMC pn EOS agrees with the constraints. However, the inclusion of hyperons with the hyperon couplings obtained for the hyperon nuclear potentials taking $V_\Lambda = -28$ MeV, $V_\Sigma = 30$ MeV and $V_\Xi = -18$ MeV makes the EOS too soft. Increasing $\Lambda_v$ makes the EOS harder bringing the EOS closer to the constraints defined by the empirical EOS. Increasing $\Lambda_v$ corresponds to decreasing the symmetry energy at supersaturation densities, giving rise to a softer pn EOS at high densities and, therefore, hinders the onset of hyperons. So the larger $\Lambda_v$ the smaller the hyperon fraction in the star and the harder the EOS.

The effect of a less attractive $V_\Xi$ potential is also clear: the EOS becomes harder because the onset of hyperons occurs at larger densities. We conclude that any mechanism that hinders the formation of hyperons makes the EOS harder.

The mass/radius curve for stars with a mass larger than $1 M_\odot$ and the corresponding properties of maximum mass stars are shown in Fig. 8.

![Figure 7](image1.png)  
**Figure 7.** Equation of state for QMC and different values of $V_\Xi$ and of the $\Lambda_v$ coupling.

![Figure 8](image2.png)  
**Figure 8.** Mass/radius curve for the families of compact stars obtained with the EOS of Fig. 7.

![Figure 9](image3.png)  
**Figure 9.** Strangeness content in the models represented in Fig. 7.

First let us discuss the effect of the symmetry energy and the hyperon couplings on the mass/radius curve. A larger $\Lambda_v$ gives rise to a softer EOS and, therefore, a smaller radius. It is seen that when going from $\Lambda_v = 0$ to 0.1 the radius of stars with a mass $M = 1 - 1.5 M_\odot$ decreases by $\sim 0.3$ Km. A similar effect was obtained with the NLWM [12, 13]. However, within the NLWM models the maximum mass did not depend on $L$, while in the framework of the QMC model there is a clear effect of almost $0.1 M_\odot$ if $\Lambda_v$ increases from 0 to 0.1. This is mainly due to the smaller strangeness fraction inside the star.

The reduction of the attractiveness of $V_\Xi$ has a similar effect on the maximum mass of the star, i.e., the mass increases $\sim 0.2 M_\odot$ if $V_\Xi$ increases from -18 to 0 MeV.

We conclude that there is still quite a large uncertainty on the coupling of hyperons to nuclear matter and, therefore, there is still room for a very massive star such as the recently measured pulsar J1614-2230 with a mass $M = 1.97 \pm 0.04$ [21], even including hyperons in the EOS. This, however, is a particularly massive star.
4. Conclusions
We have tested three different hyperon-meson parametrizations, using information from hypernuclei to fix the couplings. We took advantage of the fact that QMC predicts the hyperon effective masses without being necessary to fix the hyperon-σ couplings, in one of the parametrizations.

It was shown that both the symmetry energy and the hyperon couplings have a strong effect on the mass and radius of the star. A softer symmetry energy gives rise to smaller stars. Also the hyperon fraction is affected: softer symmetry energy corresponds to a smaller hyperon fraction [12, 13]. Within QMC the density dependence of the symmetry energy has also an effect on the maximum star mass, effect not observed in NLWM models.

It was also shown that the hyperon nuclear interaction defines the amount of strangeness in the star, and, therefore, has a strong influence on the maximum mass allowed. Even including hyperons in the QMC EOS we could explain the mass of the pulsar J1614-2230 if the cascade nuclear potential is set to be very little attractive. More data on hypernuclei is needed to constrain the hyperon-meson couplings.

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