Isovector Effects in Neutron Stars, Radii, and the GW170817 Constraint

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Abstract

An isovector–scalar meson is incorporated self-consistently into the quark–meson coupling description of nuclear matter, and its most prominent effects on the structure of neutron stars are investigated. The recent measurement of GW170817 is used to constrain the strength of the isovector–scalar channel. With the imminent measurements of the neutron star radii in the NICER mission, it is particularly notable that the inclusion of the isovector–scalar force has a significant impact. Indeed, the effect of this interaction on the neutron star radii and masses is larger than the uncertainties introduced by variations in the parameters of symmetric nuclear matter at saturation, namely the density, binding energy per nucleon, and the symmetry energy. In addition, as the analysis of GW170817 has provided constraints on the binary tidal deformability of merging neutron stars, the predictions for this parameter within the quark–meson coupling model are explored, as well as the moment of inertia and the quadrupole moment of slowly rotating neutron stars.

Key words: equation of state – gravitational waves – stars: neutron

1. Introduction

As the repositories of the densest nuclear matter in the universe, neutron stars (NSs) have long been a focus of nuclear theory studies (Glendenning 2000; Haensel et al. 2007; Lattimer 2012, 2014; Baym et al. 2018). The interest in these intriguing objects has intensified since the LIGO and Virgo observations of GW170817 (Abbott et al. 2017), an event identified as almost certainly the merger of two NSs. The GW170817 analysis has already demonstrated the potential of gravitational wave (GW) observations to yield new information, such as the limits on NS tidal deformability, which has not hitherto been accessible.

Before the observation by GW170817, but following the discovery of particularly heavy NS with masses around 2 $M_\odot$ (Demorest et al. 2010; Antoniadis et al. 2013), the astrophysics community was already making great efforts to model nuclear matter equations of state (EOS) capable of producing such heavy objects (see for example Oertel et al. 2017). This was especially challenging because such heavy stars are expected to be so dense that, under the constraint of $\beta$-equilibrium, they must contain hyperons. The EOS including hyperons are typically much softer than those containing just nucleons, leading to maximum masses that are not compatible with observations. There are several approaches used to solve this issue, such as the inclusion of repulsive three-body forces involving hyperons, or the introduction of a possible phase transition to deconfined quark matter at densities below the hyperon threshold (for more details see Vidaña 2015 and references therein).

Within the quark–meson coupling model (QMC; Guichon 1988; Guichon et al. 1996, 2018; Saito et al. 2007) NSs with masses of order 1.9 $M_\odot$ are produced with or without the inclusion of hyperons in the EOS (Rikovska-Stone et al. 2007; Stone et al. 2010; Whittenbury et al. 2014, 2016). This remarkable feature, first published three years before the first heavy NS measurement (Demorest et al. 2010), is a consequence of the fact that the self-consistent modification of the internal quark structure of hadrons in medium naturally leads to repulsive three-body forces between all baryons—see Guichon & Thomas (2004) and Guichon et al. (2018). Furthermore, these forces involve no new parameters but are a direct consequence of the underlying quark structure, through the so-called scalar polarizabilities. Here, we extend the model presented in Rikovska-Stone et al. (2007) by adding the exchange of the isovector–scalar meson $a_0(980)$, labeled $\delta$, in addition to the original isoscalar-scalar $\sigma$, isoscalar-vector $\omega$, and isovector–vector $\rho$ mesons and the pion, and investigate the effect of this modification on predictions of NS properties. We note that earlier calculations with the QMC model (without the Fock terms) have included such an interaction (see Santos et al. 2009) to study low-density instabilities in asymmetric nuclear matter, while Wang et al. (2011) used the QMC model with the isovector–scalar channel included in their Hartree–Fock calculation of properties of finite nuclei. This work extends, for the first time, the QMC model with the isovector–scalar exchange and the full Fock terms, to predict properties of high density matter in NSs.

While NS masses can be determined reasonably accurately, the situation regarding their size is much less satisfactory. A number of techniques have been used to put broad limits on their radii, with values typically in the range 6–15 km (Ozel & Freire 2016). A comprehensive recent update can be found in the work of Steiner et al. (2018) and references therein. These limits do not constrain the EOS strongly enough, and many different models of dense matter are still allowed. However, a great deal of anticipation surrounds the NICER experiment (Gendreau et al. 2016), which aims to measure the radii of NSs with an accuracy of order 5% (Watts et al. 2016). In anticipation of results from NICER, as well as future observations of NS mergers, with GW170817 yielding its own constraint, our aim is to investigate to what extent the QMC model with the isovector–scalar interaction can provide reliable predictions for the radii of NS, with realistic error estimates. As the first positive sign we will show that the
comparision of the QMC model predictions with the recent GW measurement already suggests an upper bound on the strength of the isovector–scalar coupling in this model.

The isovector–scalar exchange has been extensively explored in relativistic mean field models in the Hartree approximation (see, for example, Kubis & Kutscher 1997; Liu et al. 2002; Menezes & Providencia 2004; Roca-Maza et al. 2011; Singh et al. 2014). The isovector–isoscalar meson δ has also been included in the chiral mean field model Beckmann et al. (2002). The Dirac–Brueckner–Hartree–Fock model (Sammarrauca et al. 2012), including six nonstrange bosons with masses below 1 GeV, π, ρ, ω, σ, and δ, was also applied to nuclear matter and NSs and the results were compared with the outcome of chiral effective field theory. The main conclusions of these investigations, relevant for nuclear matter, are that the effects of the isovector–scalar channel are almost negligible in symmetric nuclear matter, but significant in matter with high asymmetry and thus relevant for modeling NSs. Predictions for the EOS, the density dependence of the symmetry energy and its slope, the split of the proton and neutron effective mass, and the composition of asymmetric matter, namely the proton fraction and the hyperon thresholds, have been reported as a function of the isovector–scalar coupling strength, leading to estimates of its value.

In Section 2 we describe the model used in this work. Fixed and variable parameters of the model are summarized in Section 3, followed by Section 4 containing our main results. Conclusions can be found in Section 5.

2. Theoretical Model

The QMC model (Guichon 1988; Saito & Thomas 1994; Guichon et al. 1996) is based on the hypothesis that baryons, consisting of bags containing three confined, valence quarks, interact among themselves by the exchange of mesons that couple directly to the nonstrange quarks. For vector mesons the mean fields simply shift the baryon energies, as in other relativistic models. On the other hand, a mean scalar field modifies the effective mass of the confined quarks, leading to a change in the valence quark wave functions. This in turn leads to the modification of the scalar field coupling to the hadron and hence, in order to find the effective baryon mass in medium, one must solve the entire problem self-consistently (Guichon et al. 1996; Rikovska-Stone et al. 2007). There is immense interest in looking for evidence of these changes in baryon structure (Cloet et al. 2009, 2016). However, for the present purpose, the essential result of the model is that the effective baryon mass in medium no longer has a simple linear dependence on the mean scalar field.

Within the QMC model, the internal structure of a nucleon, or in general a baryon, is described by the MIT bag model (Chodos et al. 1974), within which the effective in medium baryon mass with the flavor content $N_u$, $N_d$, $N_s$ is given as

$$M_B^* = \frac{\Omega_u N_u + \Omega_d N_d + \Omega_s N_s}{R_B} - \frac{Z_0}{R_B} + \Delta E_M + BV_B.$$  

Here, $\Omega_i$ is the quark’s lowest energy eigenvalue in the bag, taking into account the interaction with the mean scalar field, $Z_0$ is the so-called zero-point parameter that corrects the energy for gluon fluctuations and center of mass effects, $\Delta E_M$ is the hyperfine color interaction (DeGrand et al. 1975), which is also modified by the applied scalar field (Guichon et al. 2008), while $B$ is the bag constant, and $V_B$ the volume of the bag.

The effective mass can be written as

$$M_B^* = M_B - g_{\sigma B}(\sigma, \delta) - g_{\delta B}(\sigma, \delta) \frac{\tau \cdot \delta}{2},$$

where the functions $g_{\sigma B}(\sigma, \delta)$ and $g_{\delta B}(\sigma, \delta)$ are fitted to reproduce Equation (1) for each baryon, as a function of the strength of the isoscalar ($\sigma$) and isovector ($\delta$) scalar fields. Thus, while in practice $g_{\sigma N}$, $g_{\delta N}$, $g_{\sigma p}$, and $g_{\delta p}$ (the couplings to the nucleon, $B = N$ in free space) are treated as parameters, these are directly related to the underlying coupling constants of the mesons to the quarks. These, in turn, allow calculation of the couplings to all of the hyperons with no new parameters.

In practice it is sufficient to make an expansion up to terms quadratic in the meson field. So we write

$$M_B^*(\sigma, \delta) = M_B - g_{\sigma B} w_{\sigma B}^2 \sigma - t_{\sigma B} g_{\sigma} \delta$$

$$+ w_{\delta B}^2 \sigma^2 - \frac{w_{\delta B}^2}{2} + \lambda_B \sigma^2 \delta,$$

where $t_{\sigma B}$ and $t_{\delta B}$ are, respectively, the isospin and the isovector projection of a baryon, and $w_{\sigma B}^2$, $w_{\delta B}^2$, $\lambda_B$ are weight parameters that we fit to reproduce the result of Equation (1). The expression for the energy density, including the full exchange Fock terms, derived in Rikovska-Stone et al. (2007), which arise from single pion exchange, and the meson mean field equations, can be found in Appendix A. These equations are solved self-consistently, minimizing the energy density subject to the constraints of charge neutrality, $\beta$-equilibrium, and baryon number conservation.

3. Input Parameters

The QMC model has two fixed parameters, the bag radius, set to $R_B = 0.8$ fm and the mass of the scalar meson $\sigma$, $m_\sigma = 700$ MeV, which is not well known experimentally. The masses of the pion, $\omega$, $\rho$, and $\delta$, and of the baryon octet, were taken from the experiment. The bag constant, strange quark mass, and the color interaction strength, $\alpha_c$, are fitted within the model to reproduce the bare mass of the free nucleon and the $\Lambda$-hyperon, as well as to fulfill the stability condition $\partial_{\rho_\sigma} M_B^* = 0$.

The variable parameters, the coupling constants $G_i$, for the mesons $\phi = (\sigma, \omega, \rho, \delta)$, to the nucleon are defined as $G_i = g_i^2/m_i^2$. These are obtained by fitting to the empirical properties of symmetric nuclear matter, the saturation density, $\rho_0$, the binding energy per particle, $E$, and the symmetry energy, $S$, at saturation. The values $\rho_0 = 0.16$ fm$^{-3}$, $E = -15.8$ MeV, and $S = 30$ MeV were chosen as “standard” in this work. In order to probe the effects of a change in nuclear matter parameters on the nuclear matter EOS and, consequently, the NS gravitational mass and radius, six combinations of the parameters, deviating from the standard values, were constructed to form additional EOSs. Fits labeled $\rho_0^\pm$, $\rho_0^\pm$ deviate by $\pm 0.01$ fm$^{-3}$ from the standard value of the saturation density, as detailed in Table 1. We also allow variations of the symmetry energy and binding energy of $\pm 2$ MeV around the standard fit value. For clarity, we refrain from showing the results for fits other than the standard and $\rho_0^\pm$, $\rho_0^\pm$.
as all results for other parameter variations were found to lie between the results for $\rho_0^\text{nm}$ fits.

The range within which each parameter is varied defines the uncertainty band in $\rho_0$, $S$, and $\varepsilon$ around the standard EOS. Each set has been used to determine the three couplings $G_{\sigma}$, $G_{\omega}$, and $G_{\rho}$. The coupling $G_{\delta}$ was kept constantly equal to 3.0 fm$^2$ during this procedure. However, when examining the isovector effects, $G_{\delta}$ was also varied about the central value of 3.0 fm$^2$ (taken from the one-boson-exchange potential of Haidenbauer et al. 1992). The couplings $G_{\sigma}$, $G_{\omega}$, and $G_{\rho}$ were also obtained for two other choices of the $\delta$-nucleon coupling, $G_{\delta} = 0$ and 6.0 fm$^2$ (denoted $2G_{\delta}$) and these are shown in Appendix B.

### 4. Results

By varying the nuclear matter parameters over the specified ranges we can define an uncertainty band regarding the variation in $\rho_0$, $S$, and $\varepsilon$ parameters around the standard EOS, as given in Figure 1. In order to calculate the $M$–$R$ curves shown in Figures 2 and 3, the solution of the Tolman–Oppenheimer–Volkoff (TOV) equations using the QMC model to describe the NS core is matched to the low-density EOS that accounts for the NS crust. In order to describe the crust we have used the EOS developed by Hempel & Schaffner-Bielich (2010) and Hempel et al. (2012), which was also recently used by Marques et al. (2017) to augment their EOS of an NS core based on the relativistic mean field model with the density dependent interaction DD2Y, including the full baryon octet. This choice is similar to that of the QMC model and we regard it as sufficiently realistic for the purpose of this work. In particular, for stars of mass above $1.4M_\odot$ the crust occupies only the outer 20% or less of the radial profile of the star.

From Figure 2 we see the fairly dramatic change in radius for a typical NS as $G_{\delta}$ is varied. That this is considerably larger than the variation associated with the choice of nuclear matter parameters may be seen in Figure 3.

Next we examine the effect that the introduction of the $\delta$-meson has on NS structures. The gravitational mass of the NS, obtained by solving the TOV equations (Oppenheimer & Volkoff 1939) using the standard EOS, is shown in Figure 2 as a function of the corresponding radius for three different values of $G_{\delta}$. We observe that the $\delta$ coupling strength has a sizable effect on the radius, while changing the maximum mass by less than 0.15 $M_\odot$.

It is especially interesting to observe that, for the standard choice of nuclear matter parameters (standard fit in Table 1), the presence of the $\delta$ meson shifts the $M$–$R$ curve toward larger radii. By centering our search around $G_{\delta} = 3.0$ fm$^2$, one sees clearly that the value of this coupling produces transverse shifts of the whole $M$–$R$ diagram that exceed the spread arising from variations in the nuclear matter parameters, which is shown in Figure 3. For NSs with gravitational masses around 1.5 $M_\odot$, the inclusion of the isovector channel results in radius changes of the order of 0.5 km. The recent LIGO–Virgo joint analysis of the GW170817 data (Abbott et al. 2018) constrains the NS radius (90% confidence level) to the black box, given in Figure 2. This upper limit on the radius is consistent with other

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**Table 1**

| EOS        | NM Parameters | QMC Couplings |
|------------|---------------|---------------|
|            | $\rho_0$ (fm$^{-3}$) | $S$ (MeV) | $\varepsilon$ (MeV) | $G_{\sigma}$ (fm$^3$) | $G_{\omega}$ (fm$^3$) | $G_{\rho}$ (fm$^3$) | $G_{\delta}$ (fm$^3$) | $L_0$ (MeV) | $K_0$ (MeV) |
| Std. Fit   | 0.16          | 30           | −15.8          | 6.39          | 4.27            | 10.0            | 3.0            | 63.7          | 282          |
| $\rho_0^\text{nm}$ | 0.17          | 30           | −15.8          | 5.93          | 3.81            | 9.46            | 3.0            | 62.6          | 284          |
| $\rho_0^\text{t}$  | 0.15          | 30           | −15.8          | 6.88          | 4.59            | 10.64           | 3.0            | 62.4          | 280          |

Note. The value of $K_0$ does not change significantly for different values of $G_{\delta}$, while the slope, $L_0$, for the cases with $G_{\delta} = 0$ and 6 fm$^2$ have, respectively, a decrease and an increase of 10 MeV.
recent work (Raithel et al. 2018; Most et al. 2018; Annala et al. 2018) and suggests that within the QMC model the strength of the isovector–scalar sector is most likely to be $G_\delta \lesssim 6.0 \text{ fm}^2$.

Next we demonstrate the effect of the isovector–scalar channel on two macroscopic properties of NSs, the moment of inertia, $I$, and the tidal deformability, $\Lambda$. As we see in Figure 4, the variation of this parameter with the strength of the $\delta$ coupling is relatively weak. Furthermore, we have verified the universality of the relation between the moment of inertia, the Love number and the quadrupole moment (Hartle 1967; Hartle & Thorne 1968), supporting the proposal that this is independent of the EOS (Yagi & Yunes 2013). Given that there is also interest in the moment of inertia calculated within the model, we show in Figure 5 the results of the calculation using the slow-rotation Hartle–Thorne approximation (Hartle 1967) and an explicit comparison with the work carried out in Zhao & Lattimer (2018). It is clear that the moment of inertia calculated in the present model is consistent with the constraint region proposed there.

Measurement of the moment of inertia of highly relativistic double pulsar systems, such as PSR J0737-3039, may be within reach after a few years of observation and yield a result with about 10% accuracy (Steiner et al. 2013). Given that the masses of both stars in that system are already accurately determined by observations, a measurement of the moment of inertia of even one NS would enable accurate estimates of the radius of the star and the pressure of matter in the vicinity of 1–2 times the nuclear saturation density. This, in turn, would provide strong constraints on the equation of state of NSs and the physics of their interiors. Our calculations show little sensitivity to the variation in nuclear matter parameters, except for the region of compactness between 0.15 and 0.16 [$M_\odot \text{ km}^{-1}$] where they differ slightly from the results reported in Zhao & Lattimer (2018). In the compactness region between 0.10 and 0.15 they are in agreement of the lower bound of the Zhao & Lattimer (2018) analysis. We illustrate the contribution of the low-density region to the moment of inertia in Figure 6, showing that, for stars with masses greater than $1 M_\odot$, the low-density region contributes less than 10% of the total, going below 5% for masses $\gtrsim 1.4 M_\odot$ for all fits and all values of the $\delta$ coupling.

Using the signal from GW170817, a restriction was placed on the binary tidal deformability, $\tilde{\Lambda}$, namely that it should lie

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**Figure 3.** Mass vs. radius diagrams for the variations of nuclear matter parameters shown in Table 1 for the standard $\delta$ coupling strength. The symbols are as defined in Figure 1.

**Figure 4.** Tidal deformability as a function of the mass. The width of the curves illustrates the relatively small dependence on the choice of nuclear matter parameters. The bar at $M = 1.4 M_\odot$ shows the constraints derived in Abbott et al. (2018).

**Figure 5.** Moment of inertia of the star vs. the ratio $M/R$, compared with the region preferred in the analysis of Zhao & Lattimer (2018).

**Figure 6.** Fraction of the total contribution to the moment of inertia coming from the crust. The colors indicate the value of $G_\delta$, while the width of each curve indicates the effect of the variation of nuclear matter parameters.
inside the window $80 < \bar{\Lambda} < 640$ (Zhao & Lattimer 2018), while the masses of the stars in the binary system were in the window $(1.36 < m_1 < 1.6) \times (1.17 < m_2 < 1.36)$. This constraint is indicated by the red box in Figure 7, where we compare the present model calculations for the different strengths of the $\delta$ meson coupling $G_\delta$. Calculations of such quantities were performed following the work of Hartle & Thorne (1968), Zhao & Lattimer (2018), and Postnikov et al. (2010). Clearly, the QMC model results overlap the constraint region and constrain the NS masses and the values for $\bar{\Lambda}$ even further. The measurement does not rule out the model with double the delta coupling $2G_\delta$ but, as we can see in Figure 2, it does tend to give values for the radius which are in some tension with the preferred region.

5. Conclusion

The QMC model, where the quark structure of the baryons adjusts self-consistently to the mean scalar fields generated in medium, has been extended to include the isovector–scalar meson, $\delta$. The self-consistent change in structure leads to repulsive three-body forces between all baryons (nucleons and hyperons), without additional parameters. Because of these forces the model still (see Rikovska-Stone et al. 2007) yields maximum NS masses of the order $\gtrsim 1.9 M_\odot$. The major effect of the $\delta$ meson on NS properties is to increase their radii (see Figure 2), with the effect being considerably larger than the effect of varying the saturation properties of symmetric nuclear matter (see Figure 3).

We have studied the moment of inertia ($I$) and tidal deformability ($\Lambda$) of NSd over a wide range of masses. In the case of the moment of inertia, our results are consistent with the constraint suggested by Zhao & Lattimer (2018) on the variation of $I/\mathcal{M}R^2$ versus $\mathcal{M}/R$. Our results also support the universal relation between $I$, the Love number, and $\Lambda$, suggesting that it is indeed independent of the EOS used.

Following the NS merger observed recently by LIGO and Virgo, we also explored the dependence of the binary tidal deformability, $\bar{\Lambda}$, on the parameters of the model as well as the masses of the stars involved. The results of our analysis tend to favor the larger radius end of the constrained region in Figure 2, while being consistent with the binary tidal deformability constraints reported in Abbott et al. (2018) and Lattimer & Schutz (2005).

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Appendix A

Expressions for the Energy Density

The expression for the energy density is

$$\epsilon_{\text{Hartree}} = \frac{m_0^2}{2} \sigma^2 + \frac{m_0^2}{2} \omega^2 + \frac{m_0^2}{2} b^2 + \frac{m_0^2}{2} \delta^2$$

$$+ \frac{1}{\pi^2} \sum_B k^2 \left( \frac{k^2}{k^2 + M_B^2(\sigma, \delta)} \right) dk$$

$$+ \frac{1}{\pi^2} \sum_L k^2 \left( \frac{k^2}{k^2 + m_l^2} \right) dk,$$

with sums over full baryon octet $B = (n, p, \Lambda, \Sigma^{0,+}, \Xi^{0,-})$ and leptons $L = (e^-, \mu^-)$.

The meson mean field equations are given by the following

$$m_0^2 \sigma = \sum_B (-\partial_r M_B^2(\sigma, \delta))$$

$$\times \frac{1}{\pi^2} \int_0^{k_B} k^2 \left( \frac{M_B^2(\sigma, \delta)}{k^2 + M_B^2(\sigma, \delta)} \right) dk$$

$$m_0^2 \omega = \sum_B n_B g^B_\omega \times \left( 1 + \frac{\delta}{3} \right) = \sum_B n_B g^B_\omega$$

$$m_0^2 b = \sum_B n_B g^B_\rho \times \Gamma_B = \sum_B n_B g^B_\rho$$

$$m_0^2 \delta = \sum_B (-\partial_r M_B^2(\sigma, \delta))$$

$$\times \frac{1}{\pi^2} \int_0^{k_B} k^2 \left( \frac{M_B^2(\sigma, \delta)}{k^2 + M_B^2(\sigma, \delta)} \right) dk.$$

The Fock terms are

$$\epsilon_{\text{Fock}} = \frac{1}{(2\pi)^6} \sum_{B,k_1,k_2} \frac{\partial_r M_B^2(\sigma, \delta)}{\left( k_1 - k_2 \right)^2 + m_B^2}$$

$$\times \left[ \frac{M_B^2(\sigma, \delta)}{k_1^2 + M_B^2(\sigma, \delta)} \right] \left[ \frac{M_B^2(\sigma, \delta)}{k_2^2 + M_B^2(\sigma, \delta)} \right]$$

$$+ \frac{1}{(2\pi)^6} \sum_{B',B''} \frac{\partial_r M_B^2(\sigma, \delta)}{\left( k_1 - k_2 \right)^2 + m_B^2}$$

$$\times \left[ \frac{M_B^2(\sigma, \delta)}{k_1^2 + M_B^2(\sigma, \delta)} \right] \left[ \frac{M_B^2(\sigma, \delta)}{k_2^2 + M_B^2(\sigma, \delta)} \right]$$

$$- \frac{1}{(2\pi)^6} \sum_{B,k_1,k_2} \frac{g^B_\omega}{\left( k_1 - k_2 \right)^2 + m_B^2}$$

$$- \sum_{B',B''} \left( 1 \right) \frac{g^B_\omega}{\left( k_1 - k_2 \right)^2 + m_B^2}.$$
where
\[ I_{\text{rot}} = \delta_{\text{rot}} + (\delta_{\text{rot}} + \delta_{\text{rot}}) \Omega_{B} \] (9)
and
\[ Z_{\text{rot}} = \partial_{\delta} M_{R}^{\delta} (\sigma, \delta) \frac{\partial_{\delta} M_{R}^{\delta}}{\sigma, \delta} \times \delta_{\text{rot}} \]
\[ + g_{\delta}^{B} (\delta, \sigma) g_{\delta}^{R} (\delta, \sigma) \times (\delta_{\text{rot}} + \delta_{\text{rot}}) \Omega_{B} \]

Appendix B
Parameter Sets for Different \( G_{\delta} \)
In Table 2 we summarize the parameters used in the calculations.

Appendix C
Summary of Equations Used to Calculate Neutron Star Properties
The TOV equations are
\[ \frac{dP}{dr} = -\left( \frac{\epsilon (r) + P (r) (m (r) + 4\pi r^{3} P (r))}{r (r - 2m (r))} \right) \]
\[ \frac{dm}{dr} = 4\pi r^{2} \epsilon (r), \]
which are solved together with initial conditions \( P (r = 0) = \rho \) and \( m(R) = 0 \) to produce the mass-radius relation from the boundary value \( m (R) = M \).

The moment of inertia equations read as
\[ \frac{d\nu}{dr} = 2 \frac{m (r) + 4\pi r^{3} P (r)}{r (r - 2m (r))} \]
\[ e^{\nu (r = R)} = 1 \]
\[ - \frac{2M}{R} \]
\[ \frac{dF}{dr} = -4r^{2} \omega (r) \frac{d\omega}{dr} = \frac{16 \pi r^{4} (P (r) + \epsilon (r)) e^{-\nu (r)/2} \omega (r)}{\sqrt{1 - 2m (r)/r}} \]
\[ \frac{d\omega}{dr} = \frac{F}{r^{4} e^{\nu (r)/2} e^{\lambda (r)/2}} = \frac{Fe^{\nu (r)/2}}{r^{4} \sqrt{1 - 2m (r)/r}} \]

with the crustal moment of inertia calculated via
\[ \Delta I = \frac{8 \pi}{3} \int_{R - \Delta}^{R} r^{4} (\epsilon (r) + P (r)) e^{-\nu (r)/2} \omega (r) \frac{d\omega}{dr} \]
\[ \Omega = \frac{2}{3} k_{2}^{T} \beta^{-5}, \]
\[ \Lambda_{T} = 16 \frac{(12q + 1) \Lambda_{T} + (12 + q) q \Lambda_{T}^{2}}{13 (1 + q)^{2}}, \]

Finally, the tidal deformability equations read as
\[ \frac{dy}{dr} = -\frac{1}{r} (y^{2} + r^{2} Q + y e^{\lambda (r)}) \times [1 + 4 \pi r^{2} (P (r) - \epsilon (r))] \]
\[ Q = 4 \pi e^{\lambda (r)} \left( 5 \epsilon (r) + 9 P (r) + \frac{\epsilon (r) + P (r)}{c_{s}^{2} (r)} \right) - 6 \frac{e^{\lambda (r)}}{r^{2}} - \left( \frac{du^{2}}{dr} \right)^{2}, \]

with \( c_{s}^{2} = \frac{dP}{d\epsilon} \) and initial condition \( y (r = 0) = 2 \).

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Table 2
Fit Parameters for Different Choices of \( \delta \) Couplings and Nuclear Matter Parameters

| EOS            | NM Parameters | No \( \delta \) Couplings | Double \( \delta \) Couplings |
|----------------|---------------|---------------------------|-----------------------------|
|                | \( \rho_{0} \) (fm\(^{-3}\)) | \( S \) (MeV) | \( \delta \) (MeV) | \( G_{c} \) (fm\(^{3}\)) | \( G_{\tau} \) (fm\(^{3}\)) | \( G_{\text{norm}} \) (fm\(^{3}\)) | \( G_{e} \) (fm\(^{3}\)) | \( G_{\text{norm}} \) (fm\(^{3}\)) |
| Std. Fit       | 0.16          | 30                        | -15.8                       | 6.11                       | 2.74                       | 10.03                       | 0.0                        | 6.57                       | 5.33                       | 9.99                       | 6.0                        |
| \( \rho_{0} \) | 0.17          | 30                        | -15.8                       | 5.67                       | 2.35                       | 9.5                         | 0.0                        | 6.12                       | 4.94                       | 9.45                       | 6.0                        |
| \( \rho_{0} \) | 0.15          | 30                        | -15.8                       | 6.63                       | 3.08                       | 10.69                       | 0.0                        | 7.08                       | 5.77                       | 10.61                      | 6.0                        |
Erratum: “Isovector Effects in Neutron Stars, Radii, and the GW170817 Constraint” (2019 ApJ, 878, 159)

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1. Saturation Density

In the published article, we estimate the systematic error in our model due to the uncertainties on nuclear matter parameters. The results are correct, however, the definitions of \(\rho_0^+\) and \(\rho_0^-\) are flipped. The correct definition is \(\rho_0^+ = 0.15 \text{ fm}^{-3}\), which tends to increase the maximum mass, and \(\rho_0^- = 0.17 \text{ fm}^{-3}\), which tends to lower the maximum mass. All other results and plots are correct with this corrected definition. This tendency is well known, as was first pointed out by Haensel et al. (1981) and, with the corrected definitions of \(\rho_0^\pm\), we verify it.

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