The radius of a typical-mass neutron star and chiral effective field theory

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We calculate neutron star masses and radii from equations of state based on recent high-quality chiral nucleon-nucleon potentials up to fifth order of the chiral expansion and the leading chiral three-nucleon force. Our focus is on the radius of a 1.4 \( M_\odot \) neutron star, for which we report predictions that are consistent with the most recent constraints. We also show the full \( M(R) \) relations up to their respective maximum masses. Beyond the densities for which microscopic predictions are derived from chiral forces, the equations of state are obtained via polytropic continuations. However, the radius of a 1.4 \( M_\odot \) neutron star is nearly insensitive to the high-density extrapolation.

I. INTRODUCTION

Neutron-rich systems are associated with a variety of important and still open questions such as: the location of neutron drip lines, the thickness of neutron skins, and the structure of neutron stars. Common to these diverse situations is the equation of state (EoS) of neutron-rich matter, namely the energy per particle in isospin-asymmetric matter as a function of density (and other thermodynamic quantities if appropriate, such as temperature). In the presence of different neutron and proton concentrations, the symmetry energy emerges as an important component of the EoS and plays an outstanding role in the physics of neutron-rich systems. In fact, it is remarkable that the relation between the mass and the radius of neutron stars is uniquely determined by the EoS together with their self-gravity. In short, these compact systems are intriguing testing grounds for nuclear physics. Most recently, the detection by LIGO of gravitational waves from two neutron stars spiraling inward and merging has generated even more interest and excitement around these exotic systems. In fact, the LIGO/Virgo [1] detection of gravitational waves originating from the neutron star merger GW170817 has most recently provided new and more stringent constraints on the maximum radius of a 1.4 \( M_\odot \) neutron star, based on the tidal deformabilities of the colliding stars [2].

A main purpose of this paper is to present and discuss predictions of neutron star masses and radii based, as far as possible, on state-of-the-art nuclear forces. The focal point is the radius of a star with mass equal to 1.4 \( M_\odot \) (the most probable mass of a neutron star), which we wish to predict with appropriate quantification of the theoretical error.

When obtained microscopically, the EoS results from the application of few-nucleon forces in appropriate many-body calculations, such as, for instance, the Brueckner-Hartree-Fock approach to nuclear matter. This is in contrast to methods which obtain the EoS from phenomenological functionals parametrized in such a way as to describe selected nuclear properties.

Concerning the development of modern few-nucleon forces, recently chiral Effective Field Theory (EFT) has become established as the most fundamental and potentially model independent approach to nuclear forces. Chiral EFT is firmly based on the symmetries of low-energy quantum chromodynamics (QCD) and, furthermore, its predictions can be improved in a systematic way [3] [4]. This is not the case with forces developed, for instance, within the formerly very popular meson-exchange picture [5] [6]. Furthermore, the problem with the meson-exchange model is that three-nucleon forces (3NF) or, more generally, \( A \)-nucleon forces with \( A > 2 \) do not have a firm link with the two-nucleon force (2NF) to which they are associated.

Chiral EFT, however, is a low-energy theory and thus there are limitations to its domain of applicability. First, the chiral symmetry breaking scale, \( \Lambda \approx 1 \) GeV, sets a limit to the momentum or energy domains where pions and nucleons are the appropriate degrees of freedom. Moreover, the cutoff parameter \( \Lambda \) appearing in the regulator function suppresses high momentum components, which should play no role in the prediction of low-energy observables, to a degree which depends on the strength of the cutoff.

Central densities in compact stars can exceed several times the density of normal saturated matter, and of course high densities imply the presence of high Fermi momenta. Those are outside the reach of chiral EFT and therefore methods to extend the predictions must be employed. A reasonable guidance for how to extrapolate chiral predictions to high densities may be the consideration that, for a very large number of existing EoS, the pressure as a function of baryon density (or mass density) can be fitted by piecewise polytropes, namely functions of the form \( P = \alpha \rho^\Gamma \). (In our notation, \( \rho \) denotes the baryon density.) With this observation as a guideline, after outlining our calculations of the energy density and pressure for matter with nucleons and leptons in \( \beta \) equilibrium, see Sections [II][III], we will extend the pressure predictions obtained from the chiral EoS using polytropes, see Section [IV].

We are then in the position to solve the Tolman-Oppenheimer-Volkoff (TOV) [8] star structure equations to obtain the mass as a function of the radius for a sequence of stars differing in their central densities, up to several times normal density. We will consider stellar matter with neutrons, protons, and leptons in \( \beta \) equilibrium.

Extensive effort has been dedicated to constraining
properties of compact stars from astrophysical observations, see, for instance, Ref. [9–13]. We will compare our predictions with the most recent constraints from astrophysical data. A brief summary, conclusions, and future plans are contained in Sect. [V].

II. THE CHIRAL FORCES

As mentioned in the Introduction, at this time chiral EFT is the only path for constructing nuclear two- and many-body forces in a systematic and, ideally, model-independent way [3–4].

Chiral nucleon-nucleon (NN) potentials have been made available from leading order (LO, zeroth order) to N^3LO (fourth order) [3–4, 14–16], with the latter reproducing NN data with high precision. More recently, chiral NN potentials at N^4LO have also become available [17–18].

Chiral interactions have been applied in few-nucleon reactions [19–24], structure of light- and medium-mass nuclei [25–41], infinite matter at zero temperature [39–50] and finite temperature [51, 52], as well as other aspects of nuclear dynamics [53–59].

A. The two-nucleon forces

Next, we briefly summarize the main features of the 2NFs employed in this work. The reader is referred to Ref. [18] for a complete and detailed description.

The NN potentials span five orders of chiral EFT, from leading order (LO) to fifth order (N^4LO). The same power counting scheme and regularization procedures are applied through all orders, making this set of interactions more consistent than previous ones.

Another novel and important aspect in the construction of these new potentials is the fact that the long-range part of the interaction is fixed by the πN LECs as determined in the recent and very accurate analysis of Ref. [60]. In fact, for all practical purposes, errors in the πN LECs are no longer an issue with regard to uncertainty quantification. Furthermore, at the fifth (and highest) order, the NN data below pion production threshold are reproduced with excellent precision (χ^2/datum = 1.15).

Iteration of the potential in the Lippmann-Schwinger equation requires cutting off high momentum components, consistent with the fact that chiral perturbation theory amounts to building a low-momentum expansion. This is accomplished through the application of a regulator function for which the non-local form

\[ f(p', p) = \exp[-(p'/\Lambda)^{2n} - (p/\Lambda)^{2n}] \]  

is chosen. For the present applications in nuclear and neutron matter, we will limit ourselves to values of the cutoff parameter Λ smaller than or equal to 500 MeV, as those have been associated with the onset of favorable perturbative properties [61].

B. The three-nucleon forces

Three-nucleon forces make their first appearance at the third order of the chiral expansion (N^3LO). At this order, the 3NF consists of three contributions [19]: the long-range two-pion-exchange (2PE) graph, the medium-range one-pion exchange (1PE) diagram, and a short-range contact term. We apply these 3NFs by way of the density-dependent effective two-nucleon interactions derived in Refs. [62]. They are expressed in terms of the well-known non-relativistic two-body nuclear force operators and can be conveniently incorporated in the usual NN partial wave formalism and the conventional Brueckner-Hartree-Fock theory.

The LECs c_D and c_E which appear within the three-nucleon sector are constrained so as to reproduce the A = 3 binding energies and the Gamow-Teller matrix element of tritium β-decay, following an established procedure which has been recently revisited in Ref. [63].

The complete 3NF set at orders higher than three is very complex, which is why including only the leading 3NF is a common practice. However, there is one important component of the 3NF where complete calculations up to N^4LO are in fact possible, namely the 2PE 3NF. In Ref. [64] it has been shown that the 2PE 3NF mathematical structure is nearly the same at N^2LO, N^3LO, and N^4LO. Thus, the three orders of 3NF contributions can be added up and parametrized in terms of effective c_i LECs. We will follow this scheme in the present calculations. The reader is referred to Refs. [61] for a detailed description of the EoS based on the newest potentials [18].

We note that, although many 3NF contributions are possible, the 2PE 3NF is of paramount significance (and the first 3NF to be calculated [65]). The prescription briefly outlined above allows to include this very important 3NF component up to the highest orders being considered.

III. CALCULATION OF THE EOS IN β-EQUILIBRATED MATTER

We calculate the EoS of symmetric nuclear matter and pure neutron matter and thus the symmetry energy. The calculations are performed with the interactions as described in the previous section. We use the non-perturbative particle-particle ladder approximation, which generate the leading order in the traditional hole-line expansion.

As a demonstration of the order-by-order pattern in our latest EoS [61], we show in Fig. [1] the energy per particle in neutron matter across all five orders of the chiral perturbation expansion and for two values of the
and then obtain the corresponding energy densities. Baryon density and charge neutrality. The resulting set energy per particle subjected to the constraints of fixed gies per baryon. We then proceed to minimize the total last two are the relativistic electron and the muon ener-

tal energy density, above the third (N

\[ \rho = \sum n, p \] for neutrons \[ Y_p \] for protons in \( \beta \) equilibrium with electrons and muons is given by:

\[ \epsilon_{\text{tot}} = \epsilon_0 + \epsilon_{\text{sym}} (Y_n - Y_p)^2 + \sum_{i=n,p} Y_i m_i + \epsilon_e + \epsilon_\mu . \tag{2} \]

The first three terms on the right-hand side are the baryon contributions with their rest energies \( (Y_i, i = n, p) \), stands for the neutron(proton) fraction), while the last two are the relativistic electron and the muon energies per baryon. We then proceed to minimize the total energy per particle subjected to the constraints of fixed baryon density and charge neutrality. The resulting set of equations allow to solve for the various lepton fractions and then obtain the corresponding energy densities.

The pressure is related to the energy density through

\[ P(\rho) = \rho^2 \frac{d(\epsilon_{\text{tot}}/\rho)}{d\rho} . \tag{3} \]

In Fig. 1 we show the calculated pressure in \( \beta \)-stable matter at the third, fourth, and fifth orders of the 2NF together with the leading 3NF.

**IV. CONTINUING THE EOS TO HIGH DENSITY**

In this section, we perform continuation to high-density of the microscopic EoS. We employ our microscopic predictions up to about \( 2\rho_0 \), a choice which calls for some explanations. Since we are dealing with a perturbative expansion in the parameter \( Q/\Lambda \), we rely on arguments based on the size of the expansion parameter for typical momenta of the system under consideration. Smooth regulators can, of course, impact momenta lower than the highest momentum, which, for neutron-rich matter around twice normal density (with our predicted proton fractions), is approximately 400 MeV, still lower than, although close to \( \Lambda \sim 450 - 500 \) MeV. On the other hand, the \( r.m.s. \) momentum of nucleons in nuclear matter is approximately 55% of the Fermi momentum \( \langle p \rangle \). Thus, on statistical grounds, we should be safe from cutoff artifacts.

We then attach polytropes having different adiabatic indices, \( P(\rho) = \alpha \rho^\Gamma \), ensuring, of course, continuity of the pressure. The range of the polytropic index is taken to be between 1.5 and 4.5 (based on guidelines from the literature \[7\]), and these extensions are calculated up to about \( 3\rho_0 \). At this density, every polytrope is again joined continuously with a set of polytropes spanning the same range. In this way, we can cover a large set of possibilities, with the EoS being “softer” or “stiffer” in one density region or the other, as it would be the case if phase transitions (most likely to non-hadronic degrees of freedom) were to take place.

This procedure, and the corresponding spreading of the pressure, is demonstrated in Fig. 3. Note that only combinations of \( \Gamma_1 \) and \( \Gamma_2 \) which can support a maximum mass of at least \( 1.97 M_\odot \), are retained, to account for the observation of a pulsar with a mass of \( 2.01 \pm 0.04 M_\odot \) \[69\]. The \( M(R) \) relations are shown in Fig. 4 again for those polytropic extensions consistent with a maximum mass of at least \( 1.97 M_\odot \).

Causality constraints impose limitations on the allowed values of \( \Gamma_i \) and those are enforced in Fig. 5. That is, one must require that the speed of sound in stellar matter is less than the speed of light. We recall that this condition can be expressed as \( dP/d\epsilon < 1 \), where \( \epsilon \) is the total energy density. It has been pointed out, however, that the relation \( v_s = c \sqrt{dP/d\epsilon} \) holds exactly if stellar matter is not dispersive (in the presence of dispersion, the phase velocity of sound waves would not be well defined). Therefore, it is not entirely clear how strong a constraint the above relations poses on the EoS \[70\].

We now proceed to estimate the value and the uncertainty for the radius of a \( 1.4 M_\odot \) star. To that end, we first average all values of the radius separately at \( N_2 \)LO and \( N^3 \)LO. The error from the high-density continuation at \( N_2 \)LO is then combined in quadrature with the truncation error, estimated as the difference between the average radii at the two highest orders. More precisely,
say that averaging over all polytropic solutions gives, at the two successive orders $N^{3\text{LO}}$ and $N^{4\text{LO}}$, 

$$R^{N^{3\text{LO}}} = X + \epsilon^{(3)}_u - \epsilon^{(3)}_l$$

and

$$R^{N^{4\text{LO}}} = Y + \epsilon^{(4)}_u - \epsilon^{(4)}_l ,$$

respectively. Then, we estimate the truncation error at $N^{3\text{LO}}$ to be

$$\Delta = |X - Y| + \epsilon_u - \epsilon_l ,$$

where

$$\epsilon_u = \sqrt{\epsilon^{(3)}_u^2 + \epsilon^{(4)}_u^2}, \quad (6)$$

and

$$\epsilon_l = \sqrt{\epsilon^{(3)}_l^2 + \epsilon^{(4)}_l^2}. \quad (7)$$

Equations (6-7) provide our estimate for the allowed range of the truncation error. For the radius of the 1.4 $M_\odot$ star, this procedure yields

$$R^{N^{3\text{LO}}} = (10.8 − 12.8) \text{ km} .$$

Table I shows the the radius and the central density of the 1.4 $M_\odot$ neutron star when the microscopic pressure is extended via polytropes with adiabatic indices as shown. The microscopic part of the predictions are obtained at $N^{3\text{LO}}$ with $\Lambda=450$ MeV. (Very similar values are found with $\Lambda=500$ MeV.) Clearly, the radius is nearly insensitive to the polytropic extension at the larger density, and changes only moderately due to variations of the first polytropic index between 1.5 and 4.5. In other words, the uncertainty reported in Eq. 5 is relatively small given the huge uncertainty introduced in the pressure by the polytropic continuation. Note that the central densities we predict for the average-mass star are typically in the order of, and can exceed $3 \rho_0$, as can be seen from Table I. These densities are at or above the one marked by the yellow line in Fig. 3, where the spreding of the pressure is as large as a factor of 4. Clearly, this indicates that the radius responds to pressures at much lower than central densities. This is line with earlier observations [71] which found “...remarkable empirical correlation... between the radii of 1 and 1.4 $M_\odot$ normal stars and the matter’s pressure at fiducial densities of 1, 1.5 and 2$\rho_0$...”. With our present observations, we wish to stress the point that the radius of the average-mass star bears the signature of the microscopic theory, being nearly insensitive to the phenomenological continuations.

Although masses of neutron stars can be and have been measured with high precision, simultaneous measurements of radii are much more problematic. Some techniques do exist, such as those based on photospheric radius expansion [72]. Current observations have begun to determine the M(R) relation. In Ref. [12], using data from both accreting sources and bursting sources, the authors determine the radius of a 1.4 $M_\odot$ neutron star to be between 10.4 and 12.9 km. Furthermore, from their Bayesian analysis of several EoS parametrized so as to be consistent with a baseline data set (see Ref. [12] and references therein), they also determine the M(R) relation for a range of neutron star masses. Our predictions are well within this constraint, shown in Fig. 4 as the shaded purple area. Most recently, from LIGO/Virgo measurements the radius of a 1.4 $M_\odot$ neutron star was determined to be between 11.1 and 13.4 km [1, 2].

Before closing this section, we take note of some other works aimed at incorporating aspects of chiral dynamics in the development of EoS suitable for astrophysical phenomena, such as Refs. [73, 75]. In the latter reference, the authors calculate neutron star masses and radii with mean-field models whose parameters are made consistent with a chiral EoS at low to moderate densities. Constraints from chiral EFT on neutron star tidal deformabilities were investigated in Ref. [76].
FIG. 3: Spreading of the pressure from extension with polytropes as explained in the text. The top, middle, and bottom rows show the results at $N^2\text{LO}, N^3\text{LO},$ and $N^4\text{LO},$ respectively. Left and right: $\Lambda=450$ MeV and 500 MeV, respectively. The vertical coordinate axis and the vertical yellow line mark are located at the two matching points. Only the combinations of polytropes which can support a maximum mass of at least 1.97 $M_\odot$ are retained. See text for more details.

V. SUMMARY AND CONCLUSIONS

We calculated $M(R)$ relations for neutron star sequences using, as a starting point, EoS for neutron-rich matter obtained in Brueckner-Hartree-Fock calculations based on modern high-quality chiral few-nucleon forces. For densities above approximately twice normal density, we extrapolated the microscopic predictions using a family of polytropes whose range of adiabatic index is suggested by empirical analyses.

With regard, specifically, to the radius of a 1.4 $M_\odot$ neutron star, a central issue in this paper, we observe that our microscopic predictions up to about $2\rho_0$, along with considerations of theoretical error, essentially determine the radius of a 1.4 $M_\odot$ star. Our predictions fall between 10.8 and 12.8 km.
FIG. 4: The mass vs. radius relation for a neutron star at the indicated chiral order. Left: $\Lambda=450$ MeV; Right: $\Lambda=500$ MeV. The various curves are obtained with the polytropic extension as explained in the text. The purple curves are obtained extending the predictions at N$^4$LO, while the red and the green curves are obtained extending the predictions at N$^3$LO and at N$^2$LO, respectively. The lavender shaded area is the constraint from Ref. [12].

The simultaneous detection of gravitational and electromagnetic signals from the merger of two compact stars has recently begun a new era of “multimessenger astronomy”. In Ref. [2], it is concluded with 90% confidence from LIGO/Virgo measurements and otherwise very robust assumptions that the radius of a 1.4 $M_\odot$ is bound between 11.1 and 13.4 km. Our chirally constrained predictions are in agreement with these constraints, which we find encouraging.

The quest for a unified microscopic approach to neutron-rich systems, able to reach out to central densities of maximum-mass stars, remains an exceedingly complex task. Hopefully, a combination of theoretical, observational, and phenomenological efforts will help us move towards a more complete picture of the EoS.

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TABLE I: Adiabatic indices, $\Gamma_1$ and $\Gamma_2$, of the extension polytropes at the two matching densities, along with the radius and the central density of the 1.4 $M_\odot$ neutron star. The microscopic part of the predictions are obtained at N$^3$LO with $\Lambda=450$ MeV.

| $\Gamma_1$ | $\Gamma_2$ | R (km) | $\rho$ (fm$^{-3}$) |
|-----------|-----------|--------|-------------------|
| 1.5       | 3.5       | 10.98  | 0.684             |
| 1.5       | 4.0       | 11.09  | 0.640             |
| 1.5       | 4.5       | 11.17  | 0.612             |
| 2.0       | 3.5       | 11.36  | 0.611             |
| 2.0       | 4.0       | 11.42  | 0.585             |
| 2.0       | 4.5       | 11.45  | 0.567             |
| 2.5       | 3.0       | 11.66  | 0.567             |
| 2.5       | 3.5       | 11.68  | 0.548             |
| 2.5       | 4.0       | 11.70  | 0.536             |
| 2.5       | 4.5       | 11.71  | 0.528             |
| 3.0       | 3.0       | 11.92  | 0.501             |
| 3.0       | 3.5       | 11.92  | 0.498             |
| 3.0       | 4.0       | 11.92  | 0.496             |
| 3.0       | 4.5       | 11.92  | 0.494             |
| 3.5       | 2.5       | 12.07  | 0.457             |
| 3.5       | 3.0       | 12.06  | 0.457             |
| 3.5       | 3.5       | 12.06  | 0.456             |
| 3.5       | 4.0       | 12.06  | 0.456             |
| 3.5       | 4.5       | 12.06  | 0.455             |
| 4.0       | 2.0       | 12.16  | 0.429             |
| 4.0       | 2.5       | 12.16  | 0.429             |
| 4.0       | 3.0       | 12.16  | 0.429             |
| 4.0       | 3.5       | 12.16  | 0.429             |
| 4.0       | 4.0       | 12.16  | 0.429             |
| 4.0       | 4.5       | 12.16  | 0.429             |
| 4.5       | 1.5       | 12.23  | 0.411             |
| 4.5       | 2.0       | 12.23  | 0.411             |
| 4.5       | 2.5       | 12.22  | 0.411             |
| 4.5       | 3.0       | 12.22  | 0.411             |
| 4.5       | 3.5       | 12.22  | 0.411             |
| 4.5       | 4.0       | 12.22  | 0.411             |
| 4.5       | 4.5       | 12.22  | 0.411             |

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