Properties of Neutron Stars Described by a Relativistic Ab Initio Model

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Abstract

Properties of neutron stars are investigated by an available relativistic ab initio method, the relativistic Brueckner–Hartree–Fock (RBHF) model, with the latest high-precision, relativistic charge-dependent potentials, pvCD-Bonn A, B, C. The neutron star matter is solved within the beta equilibrium and charge neutrality conditions in the framework of the RBHF model. Compared to the conventional treatment, where the chemical potential of leptons was approximately represented by the symmetry energy of nuclear matter, the equation of state of neutron star matter in the present self-consistent calculation with pvCD-Bonn B has a striking difference above the baryon number density \( n_b = 0.55 \text{ fm}^{-3} \). However, these differences influence the global properties of neutron stars only about 1% to 2%. Then, three two-body potentials pvCD-Bonn A, B, C, with different tensor components, are systematically applied in the RBHF model to calculate the properties of neutron stars. It is found that the maximum masses of neutron stars are around 2.21–2.30 \( M_\odot \), and the corresponding radii are \( R = 11.18–11.72 \text{ km} \). The radii of a 1.4 \( M_\odot \) neutron star are predicated as \( R_{1.4} = 12.34–12.91 \text{ km} \), and their dimensionless tidal deformabilities are \( \Lambda_{1.4} = 485–626 \). Furthermore, the direct URCA process in neutron star cooling will happen from \( n_p = 0.414 \) to \( 0.530 \text{ fm}^{-3} \) with the proton fractions \( Y_p = 0.136–0.138 \). All of the results obtained from the RBHF model only with two-body pvCD-Bonn potentials completely satisfy various constraints from recent astronomical observations of massive neutron stars, gravitational wave detection (GW170817), and simultaneous mass–radius measurement.

Unified Astronomy Thesaurus concepts: Neutron stars (1108); Gravitational waves (678); Nuclear physics (2077); Neutron star cores (1107)

1. Introduction

The pioneering investigator of neutron stars was Landau, who discovered the existence of dense stars in the universe that look like a gigantic nucleus (Landau 1932). At that time, Landau was even unaware of the discovery of neutrons (Chadwick 1932). The precise concept of a neutron star, being the collapsed core from a supernova explosion, was proposed by Baade and Zwicky (Baade & Zwicky 1934). Subsequently, the static equilibrium equation to describe neutron stars from general relativity was derived by Tolman, Oppenheimer, and Volkov, giving the Tolman–Oppenheimer–Volkov (TOV) equation (Oppenheimer & Volkov 1939; Tolman 1939). Furthermore, the interior compositions of neutron stars were also discussed by Hund and Gamow in terms of the beta equilibrium condition in nuclear matter (Hund 1936; Gamow 1937). With the development of technology for the observation of X-ray pulses in the 1960s (Ciacconi et al. 1962), the radio pulse source PSR B1919+21, discovered by Bell and Hewish, was first confirmed as a neutron star (Hewish et al. 1968). In 1974, the first binary pulsar, PSR B1913+16, was found by Taylor and Hulse and is composed of two neutron stars (Hulse & Taylor 1975). Its orbit is gradually decreasing and perfectly predicted by the general theory of relativity. It is the first circumstantial evidence that gravitational waves exist (Taylor & Weisberg 1982). In 2017, a gravitational wave from a binary neutron star merger was first detected by advanced LIGO and Virgo collaborations as the GW170817 event (Abbott et al. 2017a), which was jointly confirmed by other astronomical observations later, such as gamma-ray bursts and optical transients (Abbott et al. 2017b; Goldstein et al. 2017). This opens the multimessenger astronomy era and has a far-reaching effect on astrophysics, nuclear physics, and other subjects.

Thousands of neutron stars have been observed since 1967, whose masses are mainly 1.0–2.3 \( M_\odot \) and radii are around 10 km (Lattimer & Prakash 2005; Lattimer 2012; Martinez 2015). According to a lot of theoretical investigations, a commonly accepted internal structure of a neutron star contains the following regions (Lattimer & Prakash 2004), from the exterior to interior: the atmosphere at the star’s surface formed by light elements; the outer crust consisting of free electrons and nuclei; the inner crust, where the neutrons in neutron-rich nuclei begin to drip out; the outer core formed by homogeneous nuclear matter with neutrons, protons, and leptons; and the inner core, where the exotic states of baryons and quarks may exist. Therefore, a comprehensive understanding of neutron star physics requires close collaboration between astrophysics and nuclear physics. On the other hand, the observation data of neutron stars provide strong constraints on the equation of state (EOS) of nuclear matter at high densities and poses a great challenge to present nuclear structure theories, especially with the recent precision measurements for the massive neutron stars PSR J1614-2230 (1.928 ± 0.017 \( M_\odot \); Demorest et al. 2010; Fonseca et al. 2016), PSR J0348+0432 (2.01 ± 0.04 \( M_\odot \); Antoniadis et al. 2013), and PSR J0740+6620 (2.14 ± 0.10 \( M_\odot \); Cromartie et al. 2020). In addition, the tidal deformabilities of neutron stars, which denote the deformation of a massive object influenced by an external gravitational field from another massive body, can be extracted from the observables of gravitational waves generated by a binary neutron star merger (Abbott et al. 2018; De et al. 2018; Most et al. 2018; Radice et al. 2018). It provides a new constraint on the behavior
of nuclear matter in a high-density region. Furthermore, in 2019, the Neutron star Interior Composition Explorer (NICER) collaboration obtained the first-ever map of a neutron star surface for PSR J0030+0451 and measured its mass and radii simultaneously (Raaijmakers et al. 2019). Two independent analysis groups with these data reported a mass of $1.34^{+0.15}_{-0.16} M_{\odot}$ with a radius of $12.71^{+1.13}_{-1.12}$ km (Riley et al. 2019) and a mass of $1.44^{+0.15}_{-0.14} M_{\odot}$ with a radius of $13.02^{+1.06}_{-1.06}$ km (Miller et al. 2019).

In the TOV equation, the energy density–pressure ($\epsilon-P$) of nuclear matter must be provided by the nuclear many-body theory now, since the available experiments can only constrain the compact matter around 2–3$n_0$, where $n_0$ is the nuclear saturation density, while the central region of a neutron star usually approaches $5-8n_0$. The properties of such an ultradense object can only be obtained by predictions via existing nuclear models. Generally, there are two types of theoretical models, which can derive the reasonable EOSs to describe the properties of neutron stars properly. The first type is based on nuclear density functional theories with effective nucleon interactions, such as the Skyrme–Hartree–Fock (SHF) model (Vautherin & Brink 1972; Douchin & Haensel 2001; Dutra et al. 2012), the Gogny–Hartree–Fock (GHF) model (Gonzalez-Boquera et al. 2018), the relativistic mean-field (RMF) model (Shen et al. 1998; Shen 2002; Bao et al. 2014a; Bao & Shen 2014b), the relativistic Hartree–Fock (RHF) model (Long et al. 2006, 2007; Sun et al. 2008), and so on. The effective $NN$ potentials in these models are determined by reproducing the nuclear bulk properties around the nuclear saturation density, such as ground-state binding energies and charge radii of finite nuclei, together with the empirical saturation properties of symmetric nuclear matter. Therefore, the density functional theories have large uncertainties when their EOSs are extrapolated to a high-density region.

The other type is based on ab initio many-body models with the realistic $NN$ interaction that is obtained by fitting the $NN$ scattering data. Most of them were achieved in the non-relativistic framework, such as the Brueckner–Hartree–Fock method (Li et al. 2006; Baldo & Maieron 2007; Baldo & Burgio 2016), quantum Monte Carlo methods (Akmal et al. 1998; Carlson et al. 2015), the self-consistent Green’s function method (Dickhoff & Barbieri 2004), the coupled-cluster method (Hagen et al. 2014b, 2014a), many-body perturbation theory (Carbone et al. 2013, 2014; Drischler et al. 2014), the functional renormalization group (FRG) method (Drews & Weise 2015, 2017), the lowest-order constrained variational method (Modarres 1993), and so on. These nonrelativistic ab initio methods can simulate the saturation behavior of symmetric nuclear matter more or less with present high-precision realistic $NN$ potentials (Stoks et al. 1994; Wiringa et al. 1995; Machleidt 2001; Entem & Machleidt 2003; Epelbaum et al. 2005, 2015a, 2015b; Entem et al. 2015, 2017; Reinert et al. 2018). However, the three-body nucleon force must be included in these models to reproduce the empirical saturation properties of symmetric nuclear matter (Li et al. 2006; Hu et al. 2017; Sammarruca et al. 2018; Logoteta 2019).

There are also a few ab initio approaches that were constructed in a relativistic framework, for example, the relativistic Brueckner–Hartree–Fock (RBHF) model. The RBHF model can reasonably describe the saturation properties of symmetric nuclear matter (Brockmann & Machleidt 1990) only with two-body nuclear potentials due to the additional repulsive contributions generated from the nucleon–antinucleon excitation ($Z$-diagram). After that, the RBHF model was first applied to simulate the properties of neutron stars by Engvik et al. (Bao et al. 1994; Engvik et al. 1994), where the decay of neutrons in the star was neglected. Then, the crust structure of neutron stars was investigated by Sumiyoshi et al. (Sumiyoshi et al. 1995) with the RBHF results in the framework of the Thomas–Fermi approximation (Ogasawara & Sato 1982), where the neutron star matter with beta equilibrium and charge neutrality conditions was discussed at high density. Further developments have been done by Krastev and Sammarruca, where the integrals about the Pauli operator in the Bethe–Goldstone equation were exactly treated in asymmetric nuclear matter (Krastev & Sammarruca 2006; Sammarruca 2010). Later, Katayama and Saito exactly solved the neutron star matter in the RBHF model with Bonn potentials by considering beta equilibrium and charge neutrality conditions self-consistently for the first time and investigated the validity of the angle-average approximation (Katayama & Saito 2013).

In these investigations, two essential issues must be improved for the studies of neutron stars with the RBHF model. First, the Bonn potentials used in the previous calculations cannot describe the charge dependence of the $NN$ potential and the latest $NN$ scattering data with high precision. Second, the EOS of neutron star matter in the past was mainly achieved by the symmetry energy approximation because of the complicated treatments for the asymmetry nuclear matter in the RBHF model. Therefore, its validity for the properties of neutron stars should be discussed in detail by comparing to calculations from the exact method. Recently, we developed the charge-dependent Bonn potentials with pseudovector coupling between pion and nucleon (pvCD-Bonn; Wang et al. 2019), based on the original CD-Bonn potential (Machleidt 2001), which can describe the $NN$ scattering data with high precision. Therefore, in this work, the pvCD-Bonn potentials will be applied to study the properties of neutron stars in the RBHF model, where the neutron star matter with the beta equilibrium and charge neutrality conditions will be solved exactly. The results will be compared to those from the symmetry energy approximation. The latest high-precision, relativistic charge-dependent $NN$ potentials will be used, and the difference between the symmetry energy approximation and the exact calculation for neutron star matter in the properties of neutron stars will be clearly, obviously exhibited in the present work, in comparison with the work by Katayama and Saito (2013).

The contents are arranged as follows. The theoretical frameworks of the RBHF model and neutron star matter are reviewed in Section 2; in Section 3, the EOSs of neutron star matter will be shown. The properties of neutron stars with pvCD-Bonn potentials will be discussed. Section 4 will finally give the summaries and conclusions.

2. Theoretical Framework

2.1. Relativistic Brueckner–Hartree–Fock Model for Nuclear Matter

In the nuclear medium, the motion of a single nucleon satisfies the Dirac equation with the species of isospin
\[ \tau (\tau = p, n), \]
\[ (\alpha \cdot p + \beta M_\tau + \beta U_\tau)(p, s) = E_\tau u_\tau(p, s), \]
\[ \text{where } p, s \text{ denote the momentum and spin of the nucleon, respectively. Its solution, } u_\tau(p, s), \text{ is a Dirac spinor normalized by } u_\tau^\dagger(p, s)u_\tau(p, s) = 1. \]
\[ \text{Due to the translational and rotational symmetries of infinite nuclear matter, the single-nucleon potential can be approximately decomposed into (Brockmann & Machleidt 1990)} \]
\[ U_\tau \approx U_{\tau,s} + \beta U_{\tau,v}, \]
\[ \text{where the scalar potential } U_{\tau,s} \text{ and time component of the vector potential } U_{\tau,v} \text{ are weakly momentum-dependent and are regarded as constants at a fixed baryon density. Furthermore, the spatial components of the vector potential are also neglected in this work. Here it should be emphasized that there are two schemes to treat the self-energy components in the RBHF model. The first one neglects the momentum dependence of the scalar potential and the time component in the vector potential, and eliminates the spatial components of the vector potential we have done in this work, which can easily extract the scalar potential and vector potential from the single-nucleon potential. The second way projects the effective interaction to five Lorentz covariants and adopts them to calculate the self-energy in a relativistic Hartree–Fock framework (Katayama & Saito 2013). There, the vector component of the vector potential is kept, which provides much fewer contributions to the self-energy compared to the scalar potential and the time component of the vector potential, as shown in Figure 2 of Katayama & Saito (2013). In the future, we will clearly discuss its role in neutron star matter.} \]

As a result, the potentials \( U_{\tau,s} \) and \( U_{\tau,v} \) can be absorbed by the effective mass \( M_\tau^* \) and effective energy \( E_\tau^* \), respectively:
\[ M_\tau^* = M_\tau + U_{\tau,s}, \quad E_\tau^* = E_\tau - U_{\tau,v}. \]

Therefore, the Dirac equation in the nuclear medium, Equation (1), can be rewritten as
\[ (\alpha \cdot p + \beta M_\tau^*)u_\tau(p, s) = E_\tau^* u_\tau(p, s) \]
with a plane wave solution \( u_\tau(p, s)\),
\[ E_\tau^* = \sqrt{p^2 + M_\tau^{*2}}, \quad u_\tau(p, s) = \frac{1}{\sqrt{E_\tau^* + M_\tau^*}} \left( \frac{\sigma \cdot p}{2M_\tau^*} \right). \]

In the mean-field approximation, the single-nucleon potential \( U_\tau \) represents the average interaction of one nucleon generated by other nucleons. Because of the medium effect, the realistic NN potential \( V_{t=0}(q', q) \) should be replaced by effective \( G \) matrices in a nuclear many-body system in the RBHF model, which can be obtained by solving the in-medium Blankenbecler–Sugar (BbS) equation. It was reduced from the Bethe–Salpeter equation,
\[ G_{\tau=0} (q', q|P) = V_{\tau=0} (q', q) + \int \frac{d^3k}{(2\pi)^3} V_{\tau=0} (q', k) \]
\[ \times \frac{2W_k}{W_0 + W_k} \frac{Q_{\tau=0} (k, P)}{W_0 - W_k} G_{\tau=0} (k, q|P), \]
where \( q', k, \) and \( q \) denote the initial, intermediate, and final relative momenta, respectively. Here, \( W_0, W_k, \) and \( W_q \) are their corresponding effective energies and \( P \) is the center-of-mass (c.m.) momentum. The Pauli operator
\[ Q_{\tau=0} (k, P) = \begin{cases} 1 & \text{if } (|P + k| > k_F^2) \text{ and } (|P - k| > k_F^2), \\ 0 & \text{otherwise}. \end{cases} \]
can prevent the nucleon above the Fermi surface from scattering into the Fermi sea in a nuclear medium according to the Pauli exclusion principle, where \( k_F^2 \) denotes the Fermi momentum of nucleon \( \tau \).

From the Dirac equation in a nuclear medium, Equation (4), the expectation value of the single-particle potential for nucleon \( \tau \) with momentum \( p \) can be expressed by
\[ U_\tau (p) = \frac{M_\tau^*}{E_\tau^*} \langle p, s | \beta U_{\tau,s} | p, s \rangle + \frac{M_\tau^*}{E_\tau^*} U_{\tau,v} + U_{\tau,v}. \]

On the other hand, this single-nucleon potential can be evaluated through the effective NN potential \( G \) matrices in the mean-field approximation:
\[ U_\tau (p) = \sum_{\tau,s} \sum_{p' \leq k_F^2} d^3p' \frac{d^3p}{(2\pi)^3} \]
\[ \times \langle ps, p's' | G_{\tau=0} | ps, p's' - p's', ps \rangle. \]

Hence, the scalar and vector potential \( U_{\tau,s} \) and \( U_{\tau,v} \) can be obtained in a self-consistent way by iterative evaluations of Equations (6), (8), and (9) until their convergence.

Then the binding energy per nucleon at baryon density \( n_b = n_p + n_n \) and the asymmetry factor \( \alpha = \frac{n_p - n_n}{n_b} \) are evaluated by
\[ E \left( n_b, \alpha \right) = \frac{1}{n_b} \sum_{\tau, s} \int d^3p d^3p' d^3p'' d^3p''' \]
\[ \times \frac{M_\tau^*}{(2\pi)^3} \frac{M_\tau^*}{(2\pi)^3} \frac{M_\tau^*}{(2\pi)^3} \frac{M_\tau^*}{(2\pi)^3} \frac{M_\tau^*}{(2\pi)^3} \]
\[ \times \frac{1}{2} \frac{1}{2} \frac{1}{2} \frac{1}{2} \frac{1}{2} \frac{1}{2} \frac{1}{2} \frac{1}{2} \frac{1}{2} \frac{1}{2} \frac{1}{2} \]
\[ \times \frac{d^3p}{(2\pi)^3} \frac{d^3p'}{(2\pi)^3} \frac{d^3p''}{(2\pi)^3} \frac{d^3p'''}{(2\pi)^3} \]
\[ \times \langle ps, p's' | G_{\tau=0} | ps, p's' - p's', ps \rangle. \]

Equations (9) and (10) are calculated in the nuclear matter rest frame, and the \( G \) matrix will be decomposed into the \( |LSJ \rangle \) representation. The explicit solid angles of Pauli operator \( Q \) in these integrals are used instead of their averaged values (Alonso & Sammarruca 2003), while the angular integrals about the center-of-mass momentum \( P \) are exactly worked out (Tong et al. 2018).

### 2.2. Neutron Star Matter

In this work, we concentrate on the discussion of the core matter of a neutron star, which is regarded as the beta equilibrium nuclear matter with electron \( (e) \) and muon \( (\mu) \). The beta equilibrium matter is established on the chemical
equilibrium conditions between nucleons and leptons:
\[ \mu_i + \mu_p = \mu_\nu. \]

Furthermore, the whole system should be of charge neutrality
\[ n_p = n_e + n_\nu, \]
with \( \mu_i, \mu_p, \) and \( \mu_\nu \) being the chemical potentials of leptons, protons, and neutrons.

### 2.2.1. Symmetry Energy Approximation

In principle, the chemical potential of a particle is obtained by taking the derivative of the total energy with respect to its number density. However, in the conventional investigations of neutron stars with the RBHF model, the EOSs of neutron star matter were generally obtained based on the symmetry energy approximation, due to the complicated and time-consuming calculation for neutron-rich matter (Alonso & Sammarruca 2003; Krastev & Sammarruca 2006; Tong et al. 2020).

The binding energy per nucleon of asymmetric nuclear matter can be written as
\[ E(n_b, \alpha) = E_0(n_b) + E_{\text{sym}}(n_b)\alpha^2, \]
where the symmetry energy in the RBHF model can be extracted from the energy differences between the symmetric nuclear matter and pure neutron matter:
\[ E_{\text{sym}}(n_b) = E(n_b, 1) - E(n_b, 0). \]

Therefore, the total energy per nucleon in neutron star matter with nucleons and leptons can be written as
\[ E_{\text{tot}} = E_0 + E_{\text{sym}}(Y_e - Y_\nu)^2 + Y_p M_p + Y_n M_n + \frac{\varepsilon_e}{n_b} + \frac{\varepsilon_\nu}{n_b}, \]
where \( Y_i \) is the particle fraction
\[ Y_i = \frac{n_i}{n_b} \quad (i = n, p, \nu). \]

According to the thermodynamic definition, the chemical potential for each particle \( i \) is
\[ \mu_i = \frac{\partial E_{\text{tot}}}{\partial Y_i}. \]

Through the beta equilibrium condition (11), the chemical potential of leptons can be related to the symmetry energy at a fixed baryon density:
\[ \mu_i = M_n - M_p + 4(1 - 2Y_\nu)E_{\text{sym}}(n_b). \]

Furthermore, the charge neutrality condition (12) implies
\[ Y_p = Y_e + Y_\nu. \]

After solving Equations (18) and (19) simultaneously, the proper particle fractions \( Y_i \) for nucleons and leptons at a given baryon density \( n_b \) can be obtained in neutron star matter. Then the corresponding total energy density \( \varepsilon_{\text{tot}} \) and the pressure \( P \) for the beta equilibrium matter can be easily obtained from Equations (15) and
\[ P = -\frac{\partial E_{\text{tot}}}{\partial (1/n_b)} = n_b \frac{\partial \varepsilon_{\text{tot}}}{\partial n_b} - \varepsilon_{\text{tot}}. \]

### 2.2.2. Self-consistent Method

In this work, the total energy of asymmetric nuclear matter will be directly obtained by solving Equations (11) and (12) regularly. The chemical potential of nucleons in the mean-field approximation is given by
\[ \mu_i = E_i^F = \sqrt{k_i^2 + M_i^2} + U_{cv}, \]
where \( U_{cv} \) is the vector potential, and the effective nucleon mass \( M_i^2 \) is related to the scalar potential. Both of them are dependent on the asymmetry factor \( \alpha \).

The leptons are treated as the noninteracting Fermi gas, whose chemical potential at zero temperature corresponds to its Fermi energy:
\[ \mu_\nu = E_\nu^F = \sqrt{k_\nu^2 + m_\nu^2}, \]

Its energy density is given by
\[ \varepsilon_i = \frac{1}{\pi^2} \int_0^{k_i} dp \cdot p^2 \sqrt{p^2 + m_i^2} = \frac{k_i E_i^F}{4\pi^2} - \frac{k_i E_i^F m_i^2}{8\pi^2} - \frac{m_i^4}{8\pi^2 \ln \left( \frac{E_i^F + k_i^2}{m_i^2} \right)}. \]

Finally, once the beta equilibrium and charge neutrality conditions are solved, the energy density of the beta equilibrium matter can be exactly expressed by the proton fraction \( Y_p \):
\[ \varepsilon_{\text{tot}} = n_b [E(n_b, 1 - 2Y_p) + Y_p M_p + (1 - Y_p) M_n] + \varepsilon_e + \varepsilon_\nu. \]
Neutron Star Properties

The mass and radius of a cold, spherical, static, and relativistic star should be described by the TOV equation (Tolman 1939; Oppenheimer & Volkov 1939):

$$\frac{dP}{dr} = \frac{\left[ (r^2 + 2M(r)) [M(r) + 4\pi r^3 P(r)] \right]}{r[r - 2M(r)]},$$

$$\frac{dM}{dr} = 4\pi r^2 \varepsilon(r).$$

These differential equations can be solved numerically with a given central pressure $P_c$ and $M(0) = 0$. The $R$ for $P(R) = 0$ denotes the radius of the neutron star, and $M(R)$ is its mass. Recently, with the development of astronomical observations, another property of neutron stars, the tidal deformability, can be extracted from the gravitational wave detectors in the binary neutron star merger (Abbott et al. 2018) and is defined as

$$\Lambda = \frac{2}{3} k_2 C^{-5}.$$

Actually, it represents the quadrupole deformation of a compact star in the external gravitational field generated by another compact star. Here, $C = M/R$ is the compactness parameter, and the second Love number $k_2$ (Hinderer 2008; Hinderer et al. 2010) is defined as

$$k_2 = \frac{8C^5}{3}(1 - 2C)^2[2 - y_R + 2C(y_R - 1)]$$

$$\times \{6C[2 - y_R + C(5y_R - 8)]$$

$$+ 4C^3[13 - 11y_R + C(3y_R - 2) + 2C^2(1 + y_R)]$$

$$+ 3(1 - 2C)^2[2 - y_R + 2C(y_R - 1)]\ln(1 - 2C)\}^{-1}.$$

where $y_R = y(R)$ is a solution of the following differential equation:

$$r \frac{dy(r)}{dr} + y^2(r) + y(r) F(r) + r^2 Q(r) = 0.$$

Note that $F(r)$ and $Q(r)$ are functions of mass, radius, energy density, and pressure:

$$F(r) = \left[ 1 - \frac{2M(r)}{r} \right]^{-1} \left[ 1 - 4\pi r^2 \varepsilon(r) - P(r) \right],$$

$$Q(r) = \left\{ 4\pi \left[ 5\varepsilon(r) + 9P(r) + \frac{\partial P}{\partial \varepsilon}(r) \right] - \frac{6}{r^2} \right\} \times \left[ 1 - \frac{2M(r)}{r} \right]^{-1}$$

$$- \left[ \frac{2M(r)}{r^2} + 2 \times 4\pi r P(r) \right] \times \left[ 1 - \frac{2M(r)}{r} \right]^{-2}.$$

This differential equation for the second Love number $k_2$ can be solved together with the TOV equation and the initial condition $y(0) = 2$.

Results and Discussion

3.1. Comparisons between the Symmetry Energy Approximation and the Self-consistent Method

First, the binding energies per nucleon of symmetric nuclear matter and pure neutron matter as functions of density from high-precision pvCD-Bonn A, B, C potentials (Wang et al. 2019) are calculated within the RBHF model and are shown in Figure 1. The saturation property from the pvCD-Bonn A potential mostly approaches the empirical data shown as the

![Figure 2](image-url)

Figure 2. Chemical potentials of electron and proton fractions of neutron star matter as a function of baryon density from the self-consistent method and symmetry energy approximation. “Exact” and “Approx” represent the self-consistent method and symmetry energy approximation, respectively. Panel (a) shows results for lepton chemical potentials, while panel (b) shows the corresponding proton fractions.
gray block, which generates the smallest D-state probability and corresponds to the weakest tensor component. For the pvCD-Bonn A, B, C potentials, the saturation densities and binding energies are 0.192, 0.158, 0.139 fm\(^{-3}\) and -16.82, -12.91, -10.72 MeV, respectively, which can form a "Coester band" such as those from Bonn potentials. The equations of state of pure neutron matter from the three pvCD-Bonn potentials are almost identical, since the tensor force plays a negligible role for the \(T=1\) case. The symmetry energy of nuclear matter can be approximately expressed by the differences of the binding energies between the pure neutron matter and the symmetric nuclear matter.

Then, the results from the symmetry energy approximation and the self-consistent method in neutron star matter are compared with the same \(NN\) potential, pvCD-Bonn B. The BbS equation is solved in the \(|LSJ|\) partial wave representation. The total angular momentum \(J\) is summed up to \(J=8\). In panel (a) of Figure 2, the chemical potentials of electrons obtained from these two schemes are shown as functions of baryon density. They are almost identical below \(n_b = 0.55\) fm\(^{-3}\). With the density further increasing, the differences between the two schemes are more obvious. At \(n_b = 1.0\) fm\(^{-3}\), the chemical potential of electrons from the self-consistent method is about 320 MeV, while that from the symmetry energy approximation is 290 MeV. There is about 10\% difference between them.

In panel (b) of Figure 2, the proton fractions from two schemes are exhibited. They show behaviors analogous to the chemical potentials in panel (a), since the chemical potential of a lepton is determined by its Fermi momentum, which is related to the proton fraction due to the charge neutrality condition shown in Equation (12). Similarly, above the baryon density 0.55 fm\(^{-3}\), the proton fraction of the self-consistent method becomes obviously larger than that of the symmetry energy approximation. At \(n_b = 1.00\) fm\(^{-3}\), the self-consistent method predicts the proton fraction as \(Y_p = 0.26\), while it is about \(Y_p = 0.20\) in the symmetry energy approximation. There is about 20\% difference between the two schemes. In addition, the proton fraction from the symmetry energy approximation is approaching a saturation value slowly, which is similar to the results from Krastev and Summarruca (2006).

To solve the TOV equation, the EOS must cover full regions of the neutron star from outer crust to the core. In the present work, we just concentrate on a discussion of the core region in the neutron star EOS within the RBHF model. Therefore, the outer crust applies the Baym–Pethick–Sutherland (BPS) EOS (Baym et al. 1971), while the inner crust uses the EOS with RMF interaction and the self-consistent Thomas–Fermi method for the pasta phase. The RMF interaction is adopted as the TM1 parameterization with symmetry energy slope \(L = 60\) MeV (Bao et al. 2014a; Bao & Shen 2014b), which is close to those from the pvCD-Bonn potentials A, B, C (\(L = 80, 57, 45\) MeV, respectively).

In panel (a) of Figure 3, the energy densities and pressures as functions of baryon density derived from the self-consistent method and symmetry energy approximation are shown. The energy densities given by the two schemes are almost the same, while the corresponding pressures reveal differences above the density 0.55 fm\(^{-3}\). This can be easily understood from the
thermodynamic self-consistency condition \( \sum n_i \mu_i = \varepsilon + P \). In panel (b), the pressure as a function of energy density is given. There, the distinction between the two methods is more obvious. Furthermore, the crust–core transition density from the symmetry energy approximation is smaller than that from the self-consistent method.

When these complete EOSs in panel (b) of Figure 3 are applied in the TOV equation, the mass–radius relation of neutron stars can be obtained and plotted in Figure 4. The maximum neutron star mass and the corresponding radius are 2.28 \( M_\odot \) and 11.52 km from the self-consistent method, while they are 2.25 \( M_\odot \) and 11.27 km from the symmetry energy approximation. Their mass–radius relations have a few differences above 1.0 \( M_\odot \). At a fixed radius, the mass of a neutron star from the self-consistent method is larger than that from the symmetry energy approximation, since the EOS of the former is a bit stiffer in the energy density region \( \varepsilon = 500–950 \text{ MeV}/\text{fm}^3 \), as shown in panel (b) of Figure 3.

In the neutron star cooling process, the direct URCA (DURCA) reaction

\[
n \rightarrow p + e + \bar{v}_e, \quad p + e \rightarrow n + \nu_e \tag{31}
\]

plays a very important role, which requires the conservation of momenta for nucleons and leptons: \( k^p_f + k^\ell_f = k^p_i \). With this equation, the threshold density of the DURCA process can be predicted. If a muon does not appear, this threshold density corresponds to \( Y_p = 1/9 \) (Lattimer et al. 1991). In the calculations of the RBHF model, the DURCA process happens after the muon’s appearance. The threshold densities are predicted as \( n_b = 0.477 \text{ fm}^{-3} \) and \( Y_p = 0.137 \) from the self-consistent method, while the predictions from the symmetry approximation are \( n_b = 0.464 \text{ fm}^{-3} \) and \( Y_p = 0.136 \). This is consistent with the astronomical observations, which does not allow the DURCA process to be too early.

Finally, the properties of neutron stars from two schemes with pvCD-Bonn B potential are listed in Table 1, such as the threshold density of the DURCA process, the maximum mass, the central density, the radius, the density, and tidal deformability at 1.4 \( M_\odot \). It can be found that the results from the symmetry energy approximation are consistent with those from the self-consistent method. Their differences are smaller than 3% for these global properties of neutron stars. Therefore, the symmetry energy approximation is a very good approach to treating the time-consuming calculations in neutron stars. It is worth noting that when we treat the physical processes in the central region of a neutron star, especially related to particle fractions, the self-consistent method should be more reliable.

\[\text{Table 1}
\]

| \( n_b,\text{URCA} \) | \( Y_p,\text{URCA} \) | \( M_{\text{max}} \) | \( R_{\text{max}} \) | \( n_{b,\text{max}} \) | \( R_{1.4} \) | \( n_{b,1.4} \) | \( k_{2,1.4} \) | \( \Lambda_{1.4} \) |
|------------------|------------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Exact            | 0.477            | 0.137          | 2.28           | 11.52          | 0.914          | 12.74          | 0.391          | 0.098          | 580            |
| Approx.          | 0.464            | 0.136          | 2.25           | 11.27          | 0.949          | 12.69          | 0.392          | 0.098          | 578            |

Note. \( n_b,\text{URCA} \) and \( Y_p,\text{URCA} \) are the baryon density and proton fraction, respectively, for the DURCA process thresholds. \( R_{\text{max}} \) and \( n_{b,\text{max}} \) are the radius and central baryon density for the neutron star with maximum mass \( M_{\text{max}} \). \( R_{1.4} \), \( n_{b,1.4} \), \( k_{2,1.4} \), and \( \Lambda_{1.4} \) represent the radius, central baryon density, second Love number, and dimensionless tidal deformability of a neutron star with mass 1.4 \( M_\odot \), respectively. The units of mass, radius, and central density are solar mass, km, and \( \text{fm}^{-3} \).

\[\text{3.2. Neutron Star Properties from Self-consistent Calculations with pvCD-Bonn A, B, C Potentials}
\]

In this subsection, the properties of neutron stars will be investigated and be compared in the framework of the self-consistent method with pvCD-Bonn A, B, C potentials. The most significant difference among these three potentials is the strength of their tensor forces, which will play an important role in the symmetry energy and influence the proton fractions in neutron star matter. The strengths of tensor forces in pvCD-Bonn A, B, C
potentials gradually increase with different coupling constants and cutoffs in the one-pion exchange component, similar to the Bonn potentials \(^{(Brockmann & Machleidt 1990)}\). The strengths of tensor forces can be represented by the \(D\)-state probability of deuterons, \(P_{D}\), which is strongly correlated with the saturation properties of nuclear matter, that is, the Coester band. In other words, a larger \(P_{D}\) indicates a stronger tensor force, which generates a smaller symmetry energy \(E_{\text{sym}}\) at a given baryon density. The \(D\)-state probabilities \(P_{D}\) of pvCD-Bonn A, B, C potentials are 4.2\%, 5.5\%, and 6.1\%, respectively.

Based on Equations \((11)\), \((12)\), and \((21)\), the particle fractions \(Y_{i}\) for beta equilibrium matter can be calculated in the RBHF model self-consistently with these three pvCD-Bonn potentials, which are plotted as a function of baryon density in Figure 5. The onset densities for muons from pvCD-Bonn A, B, C potentials are 0.15 fm\(^{-3}\), 0.17 fm\(^{-3}\), and 0.18 fm\(^{-3}\), respectively. The muon appears earliest in the pvCD-Bonn A potential, because it has the strongest symmetry energy and generates the largest proton fraction. The threshold densities of the DURCA process in neutron star matter obtained from pvCD-Bonn A, B, C potentials are 0.41 fm\(^{-3}\), 0.48 fm\(^{-3}\), and 0.53 fm\(^{-3}\), respectively, with the same DURCA proton fractions \(Y_{p} = 0.14\), after considering the Fermi momentum conservation of nucleons and leptons. Actually, the DURCA threshold density can be simply estimated as inversely proportional to the symmetry energy at a given density.

When the particle fractions are fixed, the pressure and energy density of neutron star matter can be obtained from Equations \((20)\) and \((24)\). They are shown in panel (a) of Figure 6 as functions of baryon density. As mentioned before, in the present work, the RBHF model is only applied to calculate the uniform matter in the core part. In the low-density region, we adopt the BPS EOS and that from the self-consistent Thomas–Fermi method. The matching points of the crust and core EOSs are chosen where both the energy densities and pressures are the same. The corresponding crust–core transition densities are 0.077 fm\(^{-3}\), 0.092 fm\(^{-3}\), and 0.100 fm\(^{-3}\), respectively, for the pvCD-Bonn A, B, and C potentials.

Within these EOSs, the mass–radius relations of neutron stars can be generated from the TOV equation in Equation \((25)\). In Figure 7, the maximum masses of neutron stars are predicted as 2.21 \(M_{\odot}\), 2.28 \(M_{\odot}\), 2.30 \(M_{\odot}\) from the pvCD-Bonn A, B, C potentials, respectively, which are consistent with the available observations about massive neutron stars, such as PSR J1614-2230, PSR J0348+0432, and PSR J0740+6620. The stiffer...
EOS leads to a larger maximum neutron star mass, so the pvCD-Bonn C potential produces the heaviest neutron star. The corresponding radii are 11.18, 11.54, and 11.72 km. Due to the different strengths of tensor forces in pvCD-Bonn potentials, the core densities of neutron stars at maximum mass are quite distinguished. It is 0.97 fm\(^{-3}\) for the pvCD-Bonn A potential and is about 10% larger than the one from the pvCD-Bonn C potential. Therefore, these three mass–radius curves from pvCD-Bonn potentials in the high-mass region have obvious differences that are due to their tensor components. In the lower mass region, these relations are quite different, where the proton fractions are rather small. This is because the crust EOSs from the Thomas–Fermi method are adopted in the low-density region, and the crust–core transition densities have some differences, as shown in Figure 6.

Recently, the mass and radius of PSR J0030+0451 were observed simultaneously by NICER. Miller et al. estimated that its mass is 1.44\(^{+0.15}_{-0.12}\)M\(_{\odot}\) with radius 13.02\(^{+1.24}_{-1.06}\) km (Miller et al. 2019). In the present calculations from the RBHF model, the radii of a 1.4 M\(_{\odot}\) neutron star are 12.34 km (pvCD-Bonn A), 12.77 km (pvCD-Bonn B), and 12.91 km (pvCD-Bonn C), which are completely consistent with the constraint from NICER. The confidence intervals for 68% and 95% about the relations between mass and radius from the NICER analysis are also shown. It can be found that the results from the three pvCD-Bonn potentials are properly located in these confidence intervals, especially those from the pvCD-Bonn B potential, which completely coincide with the central values of the NICER data shown as the star symbol in Figure 7.

In 2017, the gravitational wave from the binary neutron star merger was detected by advanced LIGO and Virgo collaborations as the GW170817 event, which provided new constraints for the tidal deformabilities of neutron stars of intermediate neutron mass. The tidal deformability represents the quadrupole deformation of a compact star in an external gravitational field from another star within a binary star system, which is related to the second Love number \(k_2\). This \(k_2\) and dimensionless tidal deformability \(\Lambda\) from the pvCD-Bonn potentials are shown in Figure 8. Panel (a) presents the second Love number \(k_2\) as a function of the neutron star mass. It first increases with neutron star mass and reaches its maximum value around 0.13 at \(M = 0.8M_{\odot}\), then rapidly decreases in the high-mass region. The second Love numbers \(k_2\) at 1.4\(M_{\odot}\) from the pvCD-Bonn A, B, C potentials are 0.096, 0.098, and 0.099, respectively.

The dimensionless tidal deformabilities \(\Lambda\) as functions of neutron star mass are plotted in panel (b) of Figure 8. It decreases with neutron star mass dramatically, since it is strongly dependent on the compactness parameter \(C = M/R\), as shown in Equation (26). The initial estimation for \(\Lambda\) at 1.4\(M_{\odot}\) was less than 800 from GW170817. The revised analysis from LIGO and Virgo collaborations showed \(\Lambda_{1.4} = 190^{+350}_{-120}\) (Abbott et al. 2018). Furthermore, there are also many works to constrain the \(\Lambda_{1.4}\) with the observational data from the gravitational wave detector. The values of \(\Lambda_{1.4}\) are 485, 580, and 626 from pvCD-Bonn A, B, C potentials, respectively, which are very similar to results from Bonn A, B, C potentials by Tong et al. (Tong et al. 2020) and are consistent with the constraint of gravitational waves.

**Table 2**

Neutron Star Properties from pvCD-Bonn and Bonn Potentials

| Potential   | \(n_b\)\(_{\text{DURCA}}\) | \(Y_p\)\(_{\text{DURCA}}\) | \(M_{\max}\) | \(R_{\max}\) | \(n_b\)\(_{\max}\) | \(R_{1.4}\) | \(n_{6.14}\) | \(k_{2,1.4}\) | \(\Lambda_{1.4}\) |
|-------------|-----------------|-----------------|-------------|-------------|-----------------|---------|-------------|-------------|--------------|
| pvCD-Bonn A | 0.414           | 0.136           | 2.21        | 11.18       | 0.970           | 12.34   | 0.425       | 0.096       | 485          |
| pvCD-Bonn B | 0.477           | 0.137           | 2.28        | 11.54       | 0.921           | 12.77   | 0.392       | 0.098       | 580          |
| pvCD-Bonn C | 0.530           | 0.138           | 2.30        | 11.72       | 0.880           | 12.91   | 0.376       | 0.099       | 626          |
| Bonn A      | 0.416           | 0.135           | 2.22        | 11.29       | 0.950           | 12.48   | 0.412       | 0.092       | 522          |
| Bonn B      | 0.463           | 0.136           | 2.22        | 11.36       | 0.941           | 12.58   | 0.403       | 0.100       | 559          |
| Bonn C      | 0.514           | 0.137           | 2.23        | 11.42       | 0.932           | 12.63   | 0.397       | 0.110       | 605          |

---

**Figure 8.** Second Love number and dimensionless deformabilities obtained by the RBHF model within the pvCD-Bonn A, B, C potentials.
In the present gravitational wave detection, it is very difficult to distinguish the corresponding masses of two neutron stars in a merger process, while their chirp mass, defined as \( M = (M_1 M_2)^{3/5}(M_1 + M_2)^{-1/5} \), can be exactly extracted from the gravitational wave signal. The chirp mass in GW170817 was measured as \( M = 1.44 \pm 0.02 \, M_\odot \) (Abbott et al. 2017a). Therefore, we assume that the mass of one neutron star is in the range from 1.170 \( M_\odot \) to 1.365 \( M_\odot \), while the other star has 1.365 \( M_\odot \) to 1.600 \( M_\odot \) with the constraint of chirp mass. The corresponding dimensionless tidal deformabilities are named as \( \Lambda_1 \) and \( \Lambda_2 \). Their confidence intervals for 50% and 90% from GW170817 observations are plotted as the shadow areas in Figure 9. The correlations between \( \Lambda_1 \) and \( \Lambda_2 \) calculated by the RBHF model with different pvCD-Bonn potentials are completely located within these constraints.

In addition to the event GW170817, another gravitational wave event, GW190425, was considered as a possible binary neutron star merger (Pozanenko et al. 2019; Abbott et al. 2020), while it is also possibly a neutron–black hole merger. The total mass of the binary system in GW190425 is around 3.4 \( M_\odot \), with chirp mass \( M = 1.44 \pm 0.02 \, M_\odot \). If both components in this binary system are regarded as neutron stars, according to results of the \( M-\Lambda \) relation in the present framework, the joint tidal deformabilities for each component can be predicted in Figure 10. It can be found that the tidal deformabilities in GW190425 are much smaller than those in GW170817 since the neutron star masses of the former are larger.

Finally, the numerical details of neutron star properties, such as threshold of DURCA process, maximum mass, central density, and the radii and tidal deformability at 1.4 \( M_\odot \), obtained by pvCD-Bonn A, B, C potentials together with Bonn A, B, C potentials in the framework of the self-consistent method, are collected in Table 2. In the available ab initio calculations (Brockmann & Machleidt 1990; Li et al. 2006) in nuclear matter, it was found that the saturation properties of symmetric nuclear matter from different \( NN \) potentials have linear correlations with their \( D \)-state probabilities; that is, a larger \( P_D \) potential generated a smaller saturation density and larger saturation binding energy. It is also called the “Coester band.” In Figure 11, the tidal deformabilities of 1.4 \( M_\odot \) from the pvCD-Bonn and Bonn potentials are shown as a function of their \( D \)-state probabilities. The larger value of \( P_D \) leads to a larger tidal deformability. Furthermore, there is also a linear correlation between the \( D \)-state probabilities of neutron star potentials with the systematic calculations.
probability of NN potential and the tidal deformability of a neutron star, since the tensor force still provides some contributions in neutron star matter, where the proton fraction is about 10%–20%.

4. Summaries and Perspectives

A relativistic ab initio method, the relativistic Brueckner–Hartree–Fock model, was applied to study the properties of neutron stars with the latest relativistic, high-precision nucleon–nucleon (NN) potentials: pvCD-Bonn A, B, C. These three potentials can completely describe the NN scattering phase shifts and include different components of tensor force. The neutron star matter in the present framework was considered as the composition of protons, neutrons, electrons, and muons with beta equilibrium and charge neutrality conditions.

Due to the complicated and time-consuming nature of the RBHF model for asymmetric nuclear matter in the past available investigations of neutron stars within the RBHF model, the total energy of neutron star matter was approximately given by the binding energy of symmetric nuclear matter and symmetry energy, named as the symmetry energy approximation. In the present framework, the equations of state of neutron star matter were solved under the beta equilibrium and charge neutrality conditions self-consistently. It was found that the global properties of a neutron star, such as maximum mass, radius, and tidal deformability, from the two schemes are almost identical for the pvCD-Bonn B potential. Their different tensor components had a few in

the equation of state of neutron star matter. The neutron superfluidity and cooling process in neutron stars will also be investigated in the future.

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