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Nuclear matter calculations with chiral interactions

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Abstract. Using two-nucleon and three-nucleon interactions derived in the framework of chiral perturbation theory (ChPT) with and without the explicit $\Delta$ isobar contributions, we calculate the energy per particle of symmetric nuclear matter and pure neutron matter employing the microscopic Brueckner–Hartree–Fock approach. Specifically, we present nuclear matter calculations using the new fully local in coordinate-space two-nucleon interaction at the next-to-next-to-next-to-leading-order (N3LO) of ChPT with $\Delta$ isobar intermediate states (N3LO$\Delta$) recently developed by Piarulli et al.\textsuperscript{[1]} supplemented with a local N2LO three-nucleon interaction with explicit $\Delta$ isobar degrees of freedom. We show that for this combination of two- and three-nucleon interactions it is possible to obtain a good saturation point of symmetric nuclear matter. We also calculate the nuclear symmetry energy and compare our results with the available empirical constraints on this quantity.

1. Introduction

The use of effective field theory (EFT) to describe the nuclear interaction [2] is nowadays one of most powerful tools to describe nucleonic systems (for comprehensive and thorough reviews on this subject see Refs. [3, 4]). The considerable advantage of using such method lies in the fact that two-body, three-body as well as many-body nuclear interactions can be calculated perturbatively, i.e. order by order, according to a well defined scheme based on a low-energy effective QCD Lagrangian which retains the symmetries of QCD, and in particular the approximate chiral symmetry. Within this chiral perturbation theory (ChPT) the details of the QCD dynamics are contained in parameters, the so called low-energy constants (LECs), which are fixed by low-energy experimental data.

Recently Piarulli et al. [1] have developed a fully local in coordinate-space two-nucleon chiral potential which includes the $\Delta$ isobar intermediate state. This new potential represents the fully local version of the minimally non-local chiral interaction reported in Ref. [5]. It has been shown by various authors [6, 7] that a $\Delta$-full ChPT has a better convergence with respect to the $\Delta$-less ChPT. In addition, the $\Delta$-full ChPT naturally leads to three-nucleon forces (TNFs) induced by two-pion exchange with excitation of an intermediate $\Delta$ (the celebrated Fujita–Miyazawa three-nucleon force [8]).

In this paper, we present calculations of the equation of state (EOS) of symmetric nuclear matter and pure neutron matter using the local chiral potential of Ref. [1] and employing the microscopic Brueckner–Bethe–Goldstone (BBG) [9, 10, 11] many-body theory within the Brueckner–Hartree–Fock (BHF) approximation. The present work contains some of the results published in Ref. [12] and represents a development with respect to our previous works.
[13, 14] where ChPT nuclear interactions have been used in BHF calculations of nuclear matter properties.

2. Chiral nuclear interactions

Let us now focus on the specific interactions we have employed in the present work. Among the large variety of nucleon-nucleon (NN) interactions derived in the framework of ChPT, as the two-body nuclear interaction, we have used the fully local chiral potential at N3LO including ∆ isobar excitations in intermediate state (hereafter N3LO∆) recently proposed in Ref. [1]. Originally this potential was presented in Ref. [5] in a minimal non-local form. Notice that Ref. [1] reports different parametrizations of the local potential obtained by fitting the low energy NN experimental data using different long- and short-range cutoffs. In the calculations presented in this work, we use the model b described in Ref. [1] (see their Tab. II) which fits the Granada database [15] of proton-proton (pp) and neutron-proton (np) scattering data up to an energy of 125 MeV in the laboratory reference frame and has a $\chi^2/\text{datum} \sim 1.07$.

To compare with other NN interactions, we have also employed the N3LO chiral NN potential by Entem and Machleidt (EM) [16], considering two different values of the cutoff, $\Lambda = 500$ MeV and $\Lambda = 450$ MeV, employed to regularize the high momentum components of the interaction. Notice that for consistency reasons, the same value of the cutoff has been employed in each calculation, both in the two- and three-nucleon interactions. However the considered shape of the cutoff in the two-body and in the three-body interaction is in general different (see Ref. [12] for more details).

Concerning the TNF, we have used the N2LO potential by Epelbaum et al. [17] in its local version given by Navratil [18]. We note that the non locality of the N2LO three-nucleon interaction depends only on the cutoff used to regularize the potential. The N2LO TNF depends on factors $c_1$, $c_3$, $c_4$, $c_D$ and $c_E$ which are the so called low energy constants. The N2LO interaction keeps the same operatorial structure both including or not the ∆ degrees of freedom [7]. We note that the constants $c_1$, $c_3$ and $c_4$ are already fixed at the two-body level by the N3LO interaction. However when including the ∆ isobar in the three-body potential, the parameters $c_3$ and $c_4$ take additional contribution from the Fujita–Miyazawa diagram. Such a diagram appears at the NLO and is clearly not present in the theory without the ∆ (see discussion in Ref. [12] about this issue). The values of the constants $c_i$ for the TNFs that we have considered in the present work are reported in Tab. 1.

The remaining parameters $c_D$ and $c_E$ are not determined by the two-body data and have to be fixed constraining some specific observables in few-nucleon systems or to reproduce the empirical saturation point of symmetric nuclear matter. In particular, for the interaction model N3LO+N2LO(450) we have set $c_D = -0.24$ and $c_E = -0.11$ in order to reproduce the binding energies of $^3$H and $^3$He and the Gamow-Teller matrix element for the $^3$H β-decay considering contributions to the axial nuclear current up to order N3LO [19]. For the interaction model N3LO+N2LO(500), we have adopted a recent constraint on $c_D$ and $c_E$ employing the same strategy of Ref. [19] but considering contributions to the axial nuclear current up to order N4LO [20]. We note that this parametrization has also the valuable property to reproduce the neutron–deuteron doublet scattering length.

Finally, for the very recent [1] interaction model N3LOΔ+N2LOΔ no calculation for few-body nuclear systems has been done so far. Thus we have fitted the LECs $c_D$ and $c_E$ to get a good saturation point for symmetric nuclear matter.

3. The Brueckner–Hartree–Fock approach with averaged three-body forces

The BHF approach is the lowest order of the BBG many-body theory [9, 10, 11]. In this theory, the ground state energy of nuclear matter is evaluated in terms of the so-called hole-line expansion, where the various terms can be represented by Goldstone diagrams grouped according
Table 1. Values of the low energy constants of the TNFs models used in the present calculations. In the first row, we report the parametrizations of the N2LO three-body force with the ∆ isobar excitations \[1\]. Notice that the values \(c_1, c_3\) and \(c_4\) have been kept fixed. In the third and in the forth rows we report the N2LO TNF parametrizations obtained in conjunction with the EM [16] N3LO two-nucleon potential with \(\Lambda = 500\) MeV (third row) and with \(\Lambda = 450\) MeV (forth row). The LECs \(c_1, c_3\) and \(c_4\) are expressed in GeV\(^{-1}\), whereas \(c_D\) and \(c_E\) are dimensionless.

| TNF    | \(c_D\) | \(c_E\) | \(c_1\) | \(c_3\) | \(c_4\) |
|-------|---------|---------|---------|---------|---------|
| N2LO∆ | -0.10   | 1.30    | -0.057  | -3.63   | 3.14    |
| N2LO500| -1.88   | -0.48   | -0.810  | -3.20   | 5.40    |
| N2LO450| -0.11   | -0.24   | -0.810  | -3.40   | 3.40    |

to the number of independent hole-lines (i.e. lines representing empty single particle states in the Fermi sea). The expansion is derived by means of the in-medium two-body scattering Brueckner G-matrix which describes the effective interaction between two nucleons in presence of the surrounding nuclear medium.

In the case of asymmetric nuclear matter with neutron density \(\rho_n\), proton density \(\rho_p\), total nucleon density \(\rho = \rho_n + \rho_p\) and isospin asymmetry \(\beta = (\rho_n - \rho_p)/\rho\) (asymmetry parameter), one has different G-matrices describing the \(nn\), \(pp\) and \(np\) in medium effective interactions. They are obtained by solving the well known Bethe–Goldstone equation \[9\]. In the present work we consider spin unpolarized nuclear matter. Spin polarized nuclear matter within the BHF approach has been considered, for example, in Ref. \[21, 22\].

We make use of the so-called continuous choice \[23\] for the single-particle potential \(U_\tau(k)\) when solving the Bethe–Goldstone equation. As shown in Refs. \[24, 25\], the contribution of the three-hole-line diagrams to the energy per particle \(E/A\) is minimized in this prescription and a faster convergence of the hole-line expansion for \(E/A\) is achieved \[24, 25, 26\] with respect to the so-called gap choice for \(U_\tau(k)\).

As it is well known, within the most advanced non-relativistic quantum many-body approaches \[27\], it is not possible to reproduce the empirical saturation point of symmetric nuclear matter, \(\rho_0 = 0.16 \pm 0.01\) fm\(^{-3}\), \(E/A|_{\rho_0} = -16.0 \pm 1.0\) MeV, when using two-body nuclear interactions only. In addition, TNFs are crucial in the case of dense \(\beta\)-stable nuclear matter to obtain a stiff EOS \[28, 29\] compatible with the measured masses, \(M = 1.97 \pm 0.04\ M_\odot\) [30] and \(M = 2.01 \pm 0.04\ M_\odot\) [31] of the neutron stars in PSR J1614-2230 and PSR J0348+0432 respectively.

Within the BHF approach TNFs cannot be used directly in their original form. This is because it would be necessary to solve the three-body Faddeev equations in the nuclear medium (Bethe–Faddeev equations) \[32, 33\] and currently this is a task still far to be achieved. To circumvent this problem an effective density dependent two-body force is built starting from the original three-body one by averaging over one of the three nucleons \[34, 35\].

In the present work, we consider the in medium effective NN force derived in Ref. \[36\] (see Ref. \[12\] for more details on the average).

4. Results and discussion

In this section we present and discuss the results of our calculations for the EOS, i.e. the energy per particle \(E/A\) as a function of the density \(\rho\), for symmetric nuclear matter (SNM) and pure neutron matter (PNM) using the chiral nuclear interaction models and the BHF approach described in the previous two sections. In all the calculations performed in this work, we have considered partial wave contributions up to a total two-body angular momentum \(J_{max} = 8\).
Figure 1. (Color online) Energy per particle of pure neutron matter [panel (a)] and symmetric nuclear matter [panel (b)] as a function of the nucleonic density for the models described in the text. Continuous lines have been obtained using two- plus three-body interactions, while the dashed lines have been obtained considering only the two-body interaction. The empirical saturation point of nuclear matter $\rho_0 = 0.16 \pm 0.01 \text{ fm}^{-3}$, $E/A|_{\rho_0} = -16.0 \pm 1.0 \text{ MeV}$ is denoted by the grey box in the panel (b).

In Fig. 1 we show the energy per particle of PNM [panel (a)] and SNM [panel (b)] for the considered interaction models. The dashed lines, in both panels, refer to the calculations performed employing the two-body potential without any TNF, whereas the continuous lines refer to the calculations where the contribution of the TNFs to the energy per nucleon has been included.

Focusing first on the case of PNM (Fig. 1(a)), we note sizable differences between the three energy per nucleon curves produced by the different NN interactions. The model N3LO$\Delta$ (black upper dashed line) gives indeed a much stiffer EOS than the N3LO ones for both cutoff values, $\Lambda = 500 \text{ MeV}$ (red middle dashed line) and $\Lambda = 450 \text{ MeV}$ (blue lower dashed line). This behaviour is both due to the local form of the potential and to the inclusion of $\Delta$ isobar.

In addition, looking at Tab. 1, we see that the values of $c_1$ and $c_3$ are very similar for the considered models. Thus we expect a comparable effect of TNFs on the EOS for PNM as confirmed by our results.

The EOS for symmetric nuclear matter is shown in Fig. 1(b). When only two-body interactions are included, the models based on the EM N3LO potential [16] give unsatisfactory nuclear matter saturation properties. More specifically the model N3LO(500) (red middle dashed line) gives a saturation point ($\rho_0 = 0.41 \text{ fm}^{-3}$, $E/A|_{\rho_0} = -24.25 \text{ MeV}$), whereas the EOS curve for the model N3LO(450) (blue lower dashed line) shows no saturation point up to density of
Table 2. Nuclear matter properties at saturation point for the models described in the text. In the first column we report the model name; in the other columns we give the saturation density \( \rho_0 \) of symmetric nuclear matter, the corresponding value of the energy per particle \( E/A \), the symmetry energy, its slope parameter \( L \) and the incompressibility \( K_\infty \). All these values refer to the calculated saturation density.

| Model                  | \( \rho_0 (\text{fm}^{-3}) \) | \( E/A \) (MeV) | \( E_{\text{sym}} \) (MeV) | \( L \) (MeV) | \( K_\infty \) (MeV) |
|------------------------|-------------------------------|-----------------|-----------------------------|---------------|---------------------|
| N3LO\(\Delta\)+N2LO\(\Delta\) | 0.171                         | -15.23          | 35.39                       | 76.0          | 190                 |
| N3LO+N2LO(500)         | 0.135                         | -12.12          | 25.89                       | 38.3          | 153                 |
| N3LO+N2LO(450)         | 0.156                         | -14.32          | 29.20                       | 39.8          | 205                 |

\(~ 0.5 \text{ fm}^{-3}\). The EOS for the N3LO\(\Delta\) NN interaction [1] (black upper dashed line) has instead a very different trend. In this case the saturation point turns out to be \((0.24 \text{ fm}^{-3}, -18.27 \text{ MeV})\).

The overall repulsive effect introduced by the inclusion of TNFs produces a significant improvement of the calculated SNM saturation point (see the continuous lines in Fig. 1(b)) with respect to the results described above for the case with no TNFs.

These results clearly show that in the case of \(\Delta\)-full chiral nuclear interactions the contribution to the energy per particle generated by the TNFs is strongly reduced in comparison to the case where the EOS is obtained from \(\Delta\)-less chiral interactions.

In Tab. 2 we report the calculated values of the saturation points of SNM for the interaction models considered in the present work. All the models, with the exception of the N3LO+N2LO(500) one, provide satisfactory saturation points.

The energy per nucleon of asymmetric nuclear matter can be accurately reproduced [37, 38, 39] using the so called parabolic (in the asymmetry parameter \(\beta\)) approximation

\[
\frac{E}{A}(\rho, \beta) = \frac{E}{A}(\rho, 0) + E_{\text{sym}}(\rho)\beta^2
\]

where \(E_{\text{sym}}(\rho)\) is the nuclear symmetry energy [40]. Using Eq. (1), the symmetry energy can be calculated as the difference between the energy per particle of pure neutron matter (\(\beta = 1\)) and symmetric nuclear matter (\(\beta = 0\)).

The symmetry energy, calculated within this prescription, is plotted as function of the nucleon density \(\rho\) in Fig. 2. The symmetry energy calculated with the new local chiral potential of Ref. [1] (continuous line in Fig. 2) is systematically above the other curves and has a larger slope with respect to the one calculated with the N3LO+N2LO interaction model. In the same figure, we show \(E_{\text{sym}}\) (triangles) as obtained from recent calculations [41] of asymmetric neutron-rich matter with two- and three-body interactions determined respectively at N3LO and N2LO of the chiral perturbation theory. The results of Ref. [41] confirm the validity of the quadratic approximation (Eq.(1)) for describing the EOS highly asymmetric matter. The two bands in Fig. 2 represent the constraints on the symmetry energy obtained by Danielewicz and Lee [42] using the excitation energies to isobaric analog states (IAS) in nuclei (black-dashed band labeled IAS) and with the additional constraints from neutron skin thickness \(\Delta r_{np}\) of heavy nuclei [43, 44] (red-dashed band labeled IAS+\(\Delta r_{np}\)).

The symmetry energy obtained in the present work for the N3LO\(\Delta\)+N2LO\(\Delta\) interaction model is in a very good agreement with the experimental constraints [42] reported in Fig. 2, whereas \(E_{\text{sym}}\) as calculated with the N3LO+N2LO model (with both \(\Lambda = 500 \text{ MeV}\) and \(450 \text{ MeV}\)) lies slightly below the IAS+\(\Delta r_{np}\) red-dashed region.

In Tab. 2 we report the symmetry energy and the so called slope parameter

\[
L = 3\rho_0 \left. \frac{\partial E_{\text{sym}}(\rho)}{\partial \rho} \right|_{\rho_0}
\]
Figure 2. (Color on line) Nuclear symmetry energy as a function of the nucleonic density for the three interaction models used in the present work. The triangles labeled DSS represent the results of Ref. [41]. The black-dashed band, labeled IAS, represents the constraints on the symmetry energy obtained in Ref. [42] using the excitation energies of isobaric analog states (IAS) in nuclei. The additional constraints from neutron skin thickness $\Delta r_{np}$ of heavy nuclei give the more limited region covered by the red-dashed band labeled IAS+$\Delta r_{np}$ [41].

at the calculated saturation density $\rho_0$ (second column in Tab. 2) for the interaction models considered in the present work. As we can see our calculated $E_{sym}(\rho_0)$ and $L$ are in a satisfactory agreement with the values obtained by other BHF calculations with two- and three-body interactions (see e.g. [45, 46]) and with the values extracted from various experimental data, $E_{sym}(\rho_0) = 29.0 – 32.7$ MeV, and $L = 40.5 – 61.9$ MeV, as summarized in Ref. [47].

The incompressibility $K_\infty$ of symmetric nuclear matter at saturation density is given by:

$$K_\infty = 9\rho_0^2 \frac{\partial^2 E/A}{\partial \rho^2} \bigg|_{\rho_0}.$$  \hspace{1cm} (3)

The incompressibility $K_\infty$ is usually extracted from experimental data of giant monopole resonance (GMR) energies in medium-mass and heavy nuclei. This analysis gives $K_\infty = 210 \pm 30$ MeV [48] or more recently $K_\infty = 240 \pm 20$ MeV [49]. Recently the authors of Ref. [50] performed a re-analysis of GMR data finding $250 \text{ MeV} < K_\infty < 315$ MeV. The incompressibility $K_\infty$, at the calculated saturation point for the various interaction models used in the present work, is reported in the last column of Tab. 2. These calculated values for $K_\infty$ are rather low when compared with the empirical values extracted from GMR in nuclei. This is a common feature with many other BHF nuclear matter calculations with two- and three-body interactions (see e.g. [46].
5. Summary
The EOS of nuclear matter is a basic ingredient for the description of a large variety of physical and astrophysical phenomena [11, 51, 52, 53, 54, 55]. In this work we have investigated the EOS of symmetric nuclear matter and pure neutron matter using three interaction models fully derived in chiral effective field theory and using the microscopic Brueckner–Hartree–Fock many-body approach. In particular, we have tested the new fully local chiral potential at order N3LO which includes the ∆ isobar contributions in the intermediate states of the NN interaction [1]. We have also considered two versions of the N3LO chiral NN potential by Entem and Machleidt [16], which differ in the value of the cutoff employed in the calculations. All the two-nucleon interactions have been supplemented with TNFs required to satisfactorily reproduce the empirical saturation point of symmetric nuclear matter. Our results for various nuclear matter properties at saturation density are in good agreement with the available experimental data except for the incompressibility $K_\infty$ which is underestimated with respect to the highly uncertain empirical value [48, 49, 50]. A remarkable agreement has been found between our calculated symmetry energy and the recent experimental constraints for the low density behavior of this quantity obtained [42] using the excitation energies to isobaric analog states in nuclei with the additional constraints from neutron skin thickness of heavy nuclei [43, 44]. In addition, we have found that the inclusion of the ∆ isobar in the NN potential diminishes the strength of the TNF needed to get a good saturation point of symmetric nuclear matter. In conclusion, the chiral nuclear interaction models considered in this work provide solid basis both for the physics light nuclei and low density nuclear matter.

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References
[1] Piarulli M, Girlanda L, Schiavilla R, Kievsky A, Lovato A, Marcucci L E, Pieper S C, Viviani M and Wiringa R B 2016 Phys. Rev. C 94 054007
[2] Weinberg S 1979 Physica A 96 327; 1990 Phys. Lett. B 251 288; 1991 Nucl. Phys. B 363 3; 1992 Phys. Lett. B 259 114
[3] Epelbaum E, Hammer H-W and Meißner U G 2009 Rev. Mod. Phys. 81 1773
[4] Machleidt R and Entem D R 2011 Phys. Rep. 503 1
[5] Piarulli M, Girlanda L, Schiavilla R, Navarro Perez R, Amaro J E and Ruiz Arriola E 2015 Phys. Rev. C 91 024003
[6] Kaiser N, Gersten dörfer S and Weise W 1998 Nucl. Phys. A 637 395
[7] Krebs H, Epelbaum E and Meißner U G 2007 Eur. Phys. J. A 32 127
[8] Fujita J and Miyazawa H 1957 Prog. Theor. Phys. 17 360
[9] Day B D 1967 Rev. Mod. Phys. 39 719
[10] Baldo M, Bombaci I, Giansiracusa G, Lombardo U, Mahaux C and Sartor R 1990 Phys. Rev. C 41 1748
[11] Baldo M and Burgio G F 2012 Rep. Progr. Phys. 75 026301
[12] Logoteta D, Bombaci I and Kievsky A 2016 Phys. Rev. C 94 064001
[13] Logoteta D, Vidaña I, Bombaci I and Kievsky A 2015 Phys. Rev. C 91 064001
[14] Logoteta D, Bombaci I and Kievsky A 2016 Phys. Rev. C 94 064001
[15] Navarro Pérez R, Amaro J E and Ruiz Arriola E 2013 Phys. Rev. C 88 064002; Erratum 2015 Phys. Rev. C 91 029901
[16] Entem D R and Machleidt R 2003 Phys. Rev. C 68 041001(R)
[17] Epelbaum E, Nogga A, Glöckle W, Kamada H and Meißner U G and Witala H 2002 Phys. Rev. C 66 064001
[18] Navratil P 2007 Few-Body Syst. 41 117
[19] Marcucci I, E, Kievsky A, Rosati S, Schiavilla R and Viviani M 2012 Phys. Rev. Lett. 108 052502
[20] Baroni A, Girlanda L, Kievsky A, Marcucci L E and Viviani M 2016 Phys. Rev. C 94 024003.
[21] Vidaña I and Bombaci I 2002 Phys. Rev. C 66 045801
[22] Bombaci I, Poli A, Ramos A, Rios A and Vidaña I 2006 Phys. Lett. B 632 638
[23] Jeukenne J P, Lejeunne A and Mahaux C 1976 Phys. Rep. 25 83
[24] Song H Q, Baldo M, Giansiracusa G and Lombardo U 1998 Phys. Rev. Lett. 81 1584
[25] Baldo M, Giansiracusa G, Lombardo U and Song H Q 2000 Phys. Lett. B 473 1
[26] Baldo M, Bombaci I, Giansiracusa G and Lombardo U 1990 J. Phys. G: Nucl. Part. Phys. 16 L263
[27] Bombaci I, Fabrocini A, Polls A and Vidaña I 2005 Phys. Lett. B 609 232
[28] Baldo M, Bombaci I and Burgio G F 1997 Astron. and Astrophys. 328 274
[29] Akmal A, Pandharipande V R and Ravenhall D G 1998 Phys. Rev. C 58 1804
[30] Demorest P, Pennucci T, Ransom S, Roberts M and Hessels J 2010 Nature 467 1081
[31] Antoniadis J et al. 2013 Science 340 1233232
[32] Bethe H A 1965 Phys. Rev. 138 804B
[33] Rajaraman R and Bethe H A 1967 Rev. Mod. Phys. 39 745
[34] Loiseau B A, Nogami Y and Ross C K 1971 Nucl. Phys. A 401 601
[35] Grangé P, Lejeune A, Martzolff B and Mathiot J-F 1989 Phys. Rev. C 40 1040
[36] Holt J W, Kaiser N and Weise W 2010 Phys. Rev. C 81 024002
[37] Bombaci I and Lombardo U 1991 Phys. Rev. C 44 1892
[38] Zuo W, Bombaci I and Lombardo U 1999 Phys. Rev. C 60 024605
[39] Zuo W, Bombaci I and Lombardo U 2014 Eur. Phys. J. A 50 12
[40] Eur. Phys. J. A 50 (2) 2014, Topical Issue on Nuclear Symmetry Energy, edited by Li B A, Ramos A, Verde G and Vidaña I
[41] Drischler C, Somà A and Schwenk A 2014 Phys. Rev. C 89 025806
[42] Danielewicz P and Lee J 2014 Nucl. Phys. A 922 1
[43] Roca-Maza X et al. 2013 Phys. Rev. C 87 034301
[44] Zhang Z and Chen L-W 2006 Phys. Rev. C 74 047304
[45] Li Z H, Lombardo U, Schulze H-J, Zuo W, Chen L W and Ma H R 2006 Phys. Rev. C 74 047304
[46] Li Z H and Schulze H-J 2008 Phys. Rev. C 78 028801
[47] Lattimer J M 2014 Gen. Rel. Grav. 46 1713
[48] Blaizot J P, Gogny D and Grammaticos B 1976 Nucl. Phys. A 265 315
[49] Sholmo S, Kowalewicz V K and Colò G 2006 Eur. Phys. J. A 30 23
[50] Stone J R, Stone N J and Moszkowski S A 2014 Phys. Rev. C 89 044316
[51] Oertel M, Hempel M, Klähn T and Typel S 2017, Rev. Mod. Phys. 89 015007
[52] Logoteta D, Providencia C, Vidaña I and Bombaci I 2012 Phys. Rev. C 85 055807
[53] Logoteta D, Bombaci I, Providencia C and Vidaña I 2012 Phys. Rev. D 85 023003
[54] Logoteta D and Bombaci I 2013 Phys. Rev. D 88 063001
[55] Bombaci I and Logoteta D 2013 Monthly Notices of the Royal Astronomical Society 433 L79