

# Single particle potentials of asymmetric nuclear matter in different spin-isospin channels<sup>\*</sup>

ZUO Wei(左维)<sup>1,2;1)</sup> GAN Sheng-Xin(甘胜鑫)<sup>1,2</sup> U. Lombardo<sup>3</sup>

<sup>1</sup> Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China

<sup>2</sup> Graduate University of Chinese Academy of Sciences, Beijing 100049, China

<sup>3</sup> Department of Physics and Astrophysics, Catania University, Via Santa Sofia 64, I-95123, Italy

**Abstract:** We investigate the neutron and proton single particle (s.p.) potentials of asymmetric nuclear matter and their isospin dependence in various spin-isospin  $ST$  channels within the framework of the Brueckner-Hartree-Fock approach. It is shown that in symmetric nuclear matter, the s.p. potentials in both the isospin-singlet  $T=0$  channel and isospin-triplet  $T=1$  channel are essentially attractive, and the magnitudes in the two different channels are roughly the same. In neutron-rich nuclear matter, the isospin-splitting of the proton and neutron s.p. potentials turns out to be mainly determined by the isospin-singlet  $T=0$  channel contribution which becomes more attractive for the proton and more repulsive for the neutron at higher asymmetries.

**Key words:** single particle potential, asymmetric nuclear matter, contribution from various spin-isospin channels, symmetry potential, Brueckner-Hartree-Fock approach

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## 1 Introduction

One of the main aims of nuclear physics is to determine the equation of state (EOS) of nuclear matter and constrain effective nucleon-nucleon (NN) interactions. Nucleon single particle (s.p.) potentials, especially their isospin dependence in asymmetric nuclear matter are basic inputs for the dynamic simulations of heavy ion collisions and are expected to play an important role in constraining nucleon-nucleon (NN) effective interactions in asymmetric nuclear matter [1]. The phenomenological NN effective interactions such as the Skyrme and Skyrme-like interactions play an important role in predicting the properties of finite nuclei [2–8], nuclear matter and neutron stars [9–12], nucleus-nucleus interaction potential [13, 14] and fission barriers [15]. The parameters of the effective interactions are usually constrained by the ground state properties of stable nuclei and/or the saturation

properties of nuclear matter, and thus they are shown to be quite successful for describing nuclear phenomena related to a nuclear system not far from the normal nuclear matter density ( $\rho_0 = 0.17 \text{ fm}^{-3}$ ) at small isospin-asymmetries. However, as soon as the density deviates from the normal nuclear matter density and the isospin-asymmetry becomes large, the discrepancy among the predictions of the Skyrme-Hartree-Fock (SHF) approach by adopting different Skyrme parameters can be extremely large [16, 17]. As for the isospin dependence of nucleon single-particle properties, different Skyrme parameters may lead to an opposite isospin splitting of the neutron and proton effective masses in neutron-rich nuclear matter even at densities around  $\rho_0$  [18]. In order to improve the predictive power of the Skyrme interaction at high densities and large isospin asymmetries, some work was done in recent years to constrain the Skyrme parameters by fitting the bulk properties of asymmetric

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1) E-mail: zuowei@impcas.ac.cn

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nuclear matter obtained by the SHF approach to those predicted by microscopic many-body theories. For example, in Ref. [19], Chabanat et al. proposed a number of sets of Skyrme parameters by reproducing the equation of states (EOSs) of symmetric nuclear matter and pure neutron matter predicted by the microscopic variational approach [20]. In Ref. [21], the authors constructed the LNS parameters for the Skyrme interaction by fitting to the EOS of asymmetric nuclear matter and the neutron/proton effective mass splitting in neutron-rich matter around saturation density obtained within the Brueckner-Hartree-Fock (BHF) approach extended to include a microscopic three-body force (TBF) [22, 23]. Although these recent parametrizations of Skyrme interaction can reproduce fairly well the EOSs of symmetric nuclear matter and pure neutron matter predicted by microscopic approaches (variational method and BHF approach), the deviation from the microscopic results is shown to become significantly large even for symmetric nuclear matter as soon as the EOS decomposes into different spin-isospin channels [18], and what is more, the single particle (s.p.) properties (especially their isospin and momentum dependence) obtained by the Skyrme-Hartree-Fock calculation could be significantly different from the predictions of microscopic approaches.

In Ref. [32], we investigated the EOS of asymmetric nuclear matter and its isospin dependence in various spin-isospin  $ST$  channels within the framework of the microscopic BHF approach. In the present paper, we shall extend our work to study the proton and neutron s.p. potentials in different spin-isospin channels for a deeper understanding of the mechanism of the isospin dependence of the nuclear matter properties and to provide more elaborate microscopic constraints for effective NN interactions. We shall discuss particularly the isovector part and the isospin dependence of the neutron and proton s.p. potentials in asymmetric nuclear matter in different spin-isospin  $ST$  channels.

## 2 Theoretical approaches

Our present investigation is based on the Brueckner theory [24]. The Brueckner approach for asymmetric nuclear matter and its extension to include a microscopic TBF can be found in Refs. [22, 25]. Here we simply give a brief review for completeness. The starting point of the BHF approach is the reaction  $G$ -matrix, which satisfies the following isospin depen-

dent Bethe-Goldstone (BG) equation,

$$G(\rho, \beta, \omega) = v_{\text{NN}} + v_{\text{NN}} \times \sum_{k_1 k_2} \frac{|k_1 k_2\rangle Q(k_1, k_2) \langle k_1 k_2|}{\omega - \epsilon(k_1) - \epsilon(k_2)} G(\rho, \beta, \omega), \quad (1)$$

where  $k_i \equiv (\vec{k}_i, \sigma_i, \tau_i)$ , denotes the momentum, the  $z$ -component of spin and isospin of a nucleon, respectively.  $v_{\text{NN}}$  is the realistic NN interaction, and  $\omega$  is the starting energy. The asymmetry parameter is defined as  $\beta = (\rho_n - \rho_p)/\rho$ , where  $\rho$ ,  $\rho_n$ , and  $\rho_p$  denote the total, neutron and proton number densities, respectively. In solving the BG equation for the  $G$ -matrix, the continuous choice [26] for the auxiliary potential  $U(k)$  is adopted since it provides a much faster convergence of the hole-line expansion than the gap choice [27]. Under the continuous choice, the auxiliary potential describes the BHF mean field felt by a nucleon during its propagation in nuclear medium [28].

The BG equation has been solved in the total angular momentum representation [25]. By using the standard angular-averaging scheme for the Pauli operator and the energy denominator, the BG equation can be decoupled into different partial wave  $\alpha = \{JST\}$  channels [29], where  $J$  denotes the total angular momentum,  $S$  the total spin and  $T$  the total isospin of a two-particle state.

For the NN interaction, we adopt the Argonne  $V_{18}$  ( $AV_{18}$ ) two-body interaction [30] plus a microscopic based on the meson-exchange current approach [31]. The parameters of the TBF model have been self-consistently determined so as to reproduce the  $AV_{18}$  two-body force by using the one-boson-exchange potential model [22]. The TBF contains the contributions from different intermediate virtual processes such as virtual nucleon-antinucleon pair excitations, and nucleon resonances (for details, see Ref. [31]). The TBF effects on the EOS of nuclear matter and its connection to the relativistic effects in the DBHF approach have been reported in Ref. [22].

The TBF contribution has been included by reducing the TBF to an equivalently effective two-body interaction via a suitable average with respect to the third-nucleon degrees of freedom according to the standard scheme [31]. The effective two-body interaction  $\tilde{v}$  can be expressed in  $r$ -space as [22]

$$\langle \vec{r}_1 \vec{r}_2 | \tilde{v} | \vec{r}'_1 \vec{r}'_2 \rangle = \frac{1}{4} \text{Tr} \sum_n \int d\vec{r}_3 d\vec{r}'_3 \phi_n^*(\vec{r}'_3) (1 - \eta(r'_{23}))$$

$$\begin{aligned} &\times(1-\eta(r'_{13}))W_3(\vec{r}'_1\vec{r}'_2\vec{r}'_3|\vec{r}_1\vec{r}_2\vec{r}_3)(1-\eta(r_{13})) \\ &\times(1-\eta(r_{23}))\phi_n(r_3), \end{aligned} \quad (2)$$

where the trace is taken with respect to the spin and isospin of the third nucleon. The function  $\eta(r)$  is the defect function. Since the defect function is directly determined by the solution of the BG equation [31], it must be calculated self-consistently with the  $G$  matrix and the s.p. potential  $U(k)$  [22] at each density and isospin asymmetry. It is evident from Eq. (2) that the effective force  $\tilde{v}$  rising from the TBF in the nuclear medium is density dependent. A detailed description and justification of the method can be found in Ref. [31].

### 3 Results and discussion

In Fig. 1 we display the neutron (the dash-dotted curves) and proton (the dashed curves) s.p. potentials in various spin-isospin channels of  $ST = 00, 10, 01, 11$ , and  $T = 0, 1$  at a density of  $\rho = 0.17 \text{ fm}^{-3}$  and an isospin-asymmetry of  $\beta = 0.6$ . Shown in Fig. 2 are the results for  $\rho = 0.34 \text{ fm}^{-3}$ . In the two figures, the s.p. potentials in symmetric nuclear matter are also plotted (solid lines) for comparison. It is seen

that in symmetric nuclear matter, the s.p. potentials in the isospin-singlet  $T = 0$  channel and in the isospin-triplet  $T = 1$  channel are attractive and are compatible in magnitude. One may notice that the contributions in the two even channels ( $ST = 10$  and  $ST = 01$ ) are considerably larger in magnitude than those in the two odd channels ( $ST = 00$  and  $ST = 11$ ). Consequently, the attraction in both the  $T = 0$  and  $T = 1$  channels mainly comes from the two even channels. In asymmetric nuclear matter, the neutron and proton s.p. potentials will split (i.e. become different) with respect to their common values in symmetric nuclear matter. It can be seen that the splitting of the proton and neutron s.p. potentials is much larger in the isospin-singlet  $T = 0$  channel than that in the isospin-triplet  $T = 1$  channel. Thus the splitting is dominated by the isospin-singlet  $T = 0$  channel. This result is consistent with the prediction for the EOS of asymmetric nuclear matter in [23, 25] where it is shown that the isovector part of the EOS of asymmetric nuclear matter is determined by the contribution from the  $T = 0$  channel. As the isospin-asymmetry increases, the proton potential in the  $ST = 10$  channel becomes more attractive and the neutron one in the  $ST = 10$  becomes less attractive. The isospin-asymmetry dependence of the proton and neutron

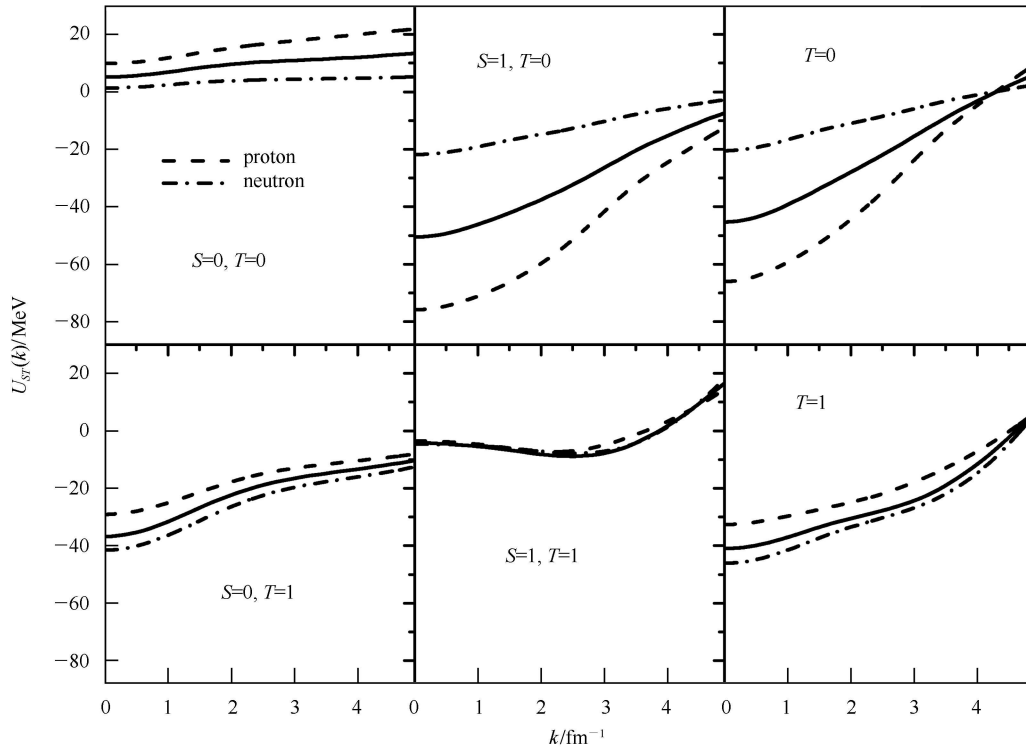


Fig. 1. Decomposition of the neutron (the dash-dotted curves) and proton (the dashed curves) s.p. potentials into various spin-isospin  $ST$  channels in asymmetric nuclear matter at density  $\rho = 0.17 \text{ fm}^{-3}$  and isospin-asymmetry  $\beta = 0.6$ . The results for symmetric matter are also shown by the solid curves for comparison.

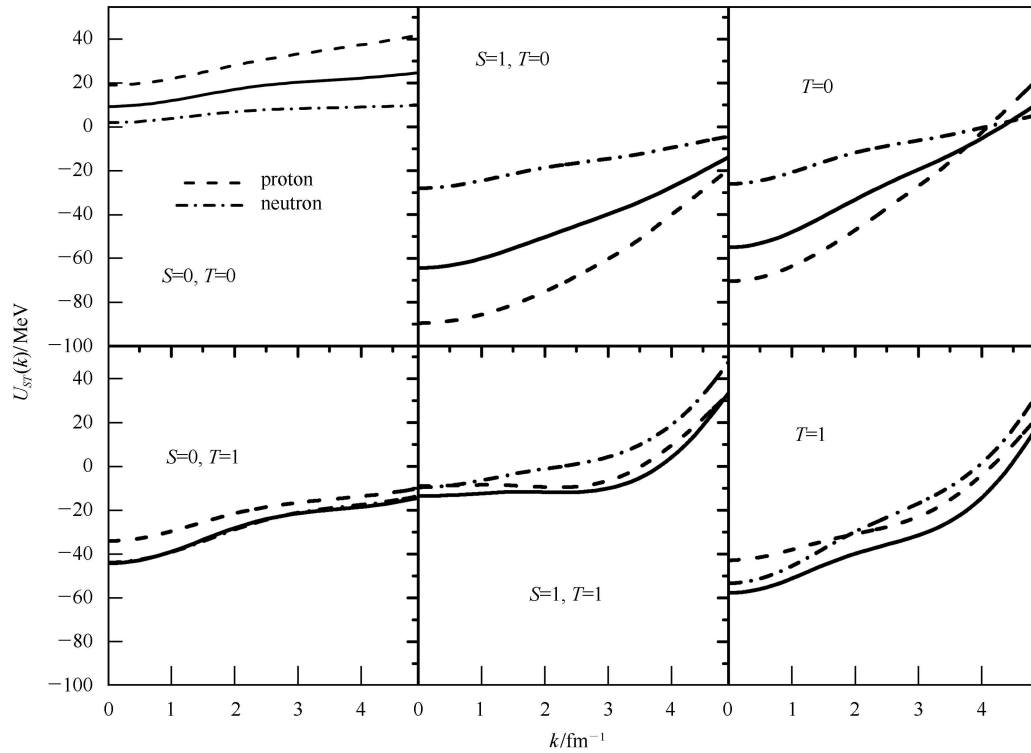


Fig. 2. The same as Fig. 1 but for a density  $\rho = 0.34 \text{ fm}^{-3}$ .

potentials in the  $ST = 00$  channel turns out to be opposite to that in the  $ST = 10$  channel. The isospin dependence of the proton and neutron potentials in the two isospin-triplet ( $ST = 01$  and  $ST = 11$ ) channels is quite weak. At densities around the nuclear saturation density  $\rho = 0.17 \text{ fm}^{-3}$ , the attraction decreases for the proton s.p. potential and increases for the neutron s.p. potential slightly in the  $T = 1$  channel as the asymmetry increases. At a high density ( $\rho = 0.34 \text{ fm}^{-3}$ ), the attraction in the  $T = 1$  channel becomes slightly smaller for both proton and neutron at a higher asymmetry. It is also seen from Fig. 1 and Fig. 2 that the isospin dependence of the neutron and proton s.p. potentials in the  $T = 0$  channel becomes weaker as the momentum increases, which responds for the repaid decreasing of nuclear symmetry potential as a function of momentum [23].

To see more clearly the isospin dependence of the s.p. potentials in asymmetric nuclear matter, we show in Fig. 3 the contribution to nuclear symmetry potential from different  $ST$  channels at two densities  $\rho = 0.17 \text{ fm}^{-3}$  and  $0.34 \text{ fm}^{-3}$ . The symmetry potential is defined as:  $U_{\text{sym}} = (U_n - U_p)/(2\beta)$ . It describes the isovector part of the neutron and proton s.p. potentials in neutron-rich nuclear matter and is crucial for predicting the isospin observables in heavy ion collisions at medium and high energies [1, 23]. Symmetry potential is defined as:  $U_{\text{sym}} = (U_n - U_p)/2\beta$ .

It describes the isovector part of the s.p. potential and is crucial for predicting the isospin observables in heavy ion collisions at medium and high energies [1]. The symmetry potential in the isospin-singlet channel ( $T = 0$ ) is shown to be positive, while that in the isospin-triplet channel  $T = 1$  is negative. From Fig. 3, one may see again that the contribution from the  $T = 0$  channel is much larger in magnitude than that from the  $T = 1$  channel especially at low momenta, which indicates that the momentum-dependence of the isovector part of nucleon s.p. potential in neutron-rich nuclear matter is governed by the contribution from the  $T = 0$  channel. The positive symmetry potential in the isospin-singlet  $T = 0$  channel implies that it is repulsive to neutrons and attractive to protons in the momentum range considered here. In the  $T = 0$  channel, the contribution from the odd partial wave  $ST = 00$  channel is negative, while the contribution from the even partial wave  $ST = 10$  channel is positive. At relatively low momenta, the contribution from the  $ST = 10$  channel turns out to be much larger in magnitude than that in the  $ST = 00$  channel. As a consequence, the contribution from the even partial wave  $ST = 10$  channel dominates the symmetry potential in the  $T = 0$  channel and it determines the total symmetry potential to a large extent. It is also noticed that the symmetry potential in the  $T = 0$  channel is almost independent

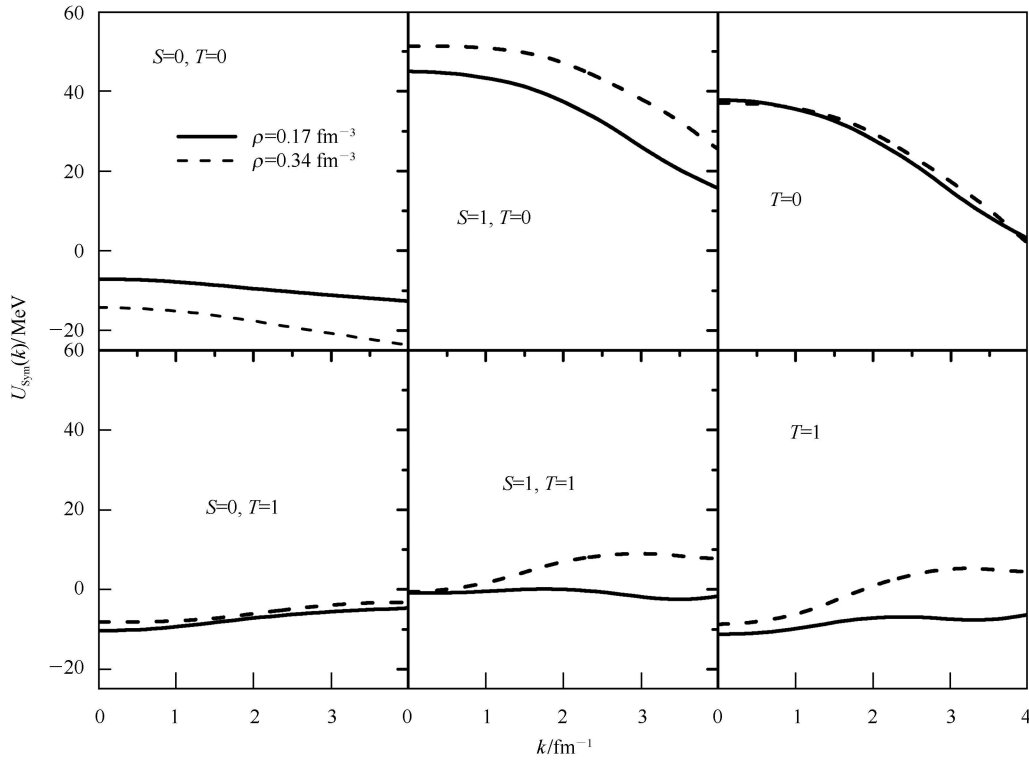


Fig. 3. Decomposition of nuclear symmetry potential into various spin-isospin channels for two values of density  $\rho = 0.17$  and  $0.34 \text{ fm}^{-3}$ , respectively.

of density, while the symmetry potential in the  $T = 1$  channel becomes slightly larger at a higher density. In the  $T = 0$  channel, the symmetry potential is a decreasing function of momentum and the decreasing rate is almost completely determined by the contribution from the even channel  $ST = 10$ .

In symmetric nuclear matter, the present investigation shows that the contribution from the isospin-singlet  $T = 0$  channel is almost the same as the contribution from the isospin-triplet  $T = 1$  channel, indicating that both the interactions between the like nucleons (i.e., neutron-neutron and proton-proton) and between the unlike nucleons (neutron-proton) play a decisive role in determining the isoscalar properties of nuclear matter. In asymmetric nuclear matter, it is found that the isovector part of the s.p. potential stems mainly from the  $T = 0$  channel, implying that the isospin-dependence of the s.p. potential in asymmetric nuclear matter is governed by the interaction between proton and neutron. We also checked that the contribution of the  $T = 0$  channel stems almost completely from the contribution of the  $T = 0$  tensor  $SD$  coupled channel, while the contributions of the other isospin-singlet  $T = 0$  channels cancel al-

most completely. On the one hand, the above result reveals a microscopic mechanism of the symmetry potential. In asymmetric nuclear matter (for example,  $\beta = 0.6$ ), the neutron number is greater than the proton number. As a result, a neutron may feel less interaction from surrounding protons and a proton may feel stronger interaction from surrounding neutrons in asymmetric nuclear matter as compared with the case of symmetric nuclear matter. Consequently, the effect of the symmetry potential (i.e., the isovector part of the s.p. potential) is repulsive on neutrons and attractive on protons due to the attraction of the tensor  $SD$  coupled channel. On the other hand, the present result on the s.p. potential is consistent with our previous conclusion for the EOS of nuclear matter [32]. Therefore, we may conclude that both the isospin-dependence of the s.p. potential and the EOS of asymmetric nuclear matter are determined mainly by the contribution of the  $T = 0$  channel, implying a direct correspondence between the symmetry potential and symmetry energy. In the transport models for heavy ion collisions, the direct input is the symmetry potential rather than the symmetry energy. The present result confirms that one can use the transport

model simulation to extract the information of symmetry energy by comparing the isospin observables from experiments.

## 4 Summary

In the present paper, we have extended our previous work of Ref. [32] and investigated the proton and neutron s.p. potentials in isospin asymmetric nuclear matter by decomposing the potentials into various spin-isospin  $ST$  channels within the framework of the BHF approach extended to include a microscopic three-body force. In symmetric nuclear matter, the s.p. potentials in both isospin-singlet  $T = 0$  and isospin-triplet  $T = 1$  channels are attractive and they are comparable in magnitude. In asymmetric nuclear matter, the isospin-dependence of the s.p. potentials

in the  $T = 1$  channel turn out to be quite weak as compared with the s.p. potentials in the  $T = 0$  channel. As a consequence, the isovector part of the proton and neutron s.p. potentials is shown to be essentially determined by the contribution from the  $T = 0$  channel in consistence with the conclusion obtained for the EOS of nuclear matter [32]. The symmetry potential has also been decomposed into various spin-isospin channels. It is shown that the symmetry potential in the  $T = 0$  channel is much larger than that in the  $T = 1$  channel at not too high momenta, and the momentum dependence of the symmetry potential is governed by the contribution from the  $T = 0$  channel.

The present results are expected to provide some microscopic information for constraining the isospin dependence of effective nucleon-nucleon interactions in asymmetric nuclear medium.

## References

- 1 LI B A, CHEN L W, Ko C M. Phys. Rep., 2008, **464**: 113
- 2 Vautherin D, Brink D M. Phys. Rev. C, 1972, **5**: 626
- 3 Friedrich J, Reinhard P G. Phys. Rev. C, 1986, **33**: 335
- 4 Dobaczewski J, Nazarewicz W et al. Phys. Rev. C, 1996, **53**: 2809
- 5 Goriely S, Samyn M, Heenen P H, Pearson J M, Tondeur F. Phys. Rev. C, 2002, **66**: 024326
- 6 Goriely S, Samyn M, Bender M, Pearson J M. Phys. Rev. C, 2003, **68**: 054325
- 7 Lesinski T, Bender M et al. Phys. Rev. C, 2007, **76**: 014312
- 8 Brito L, Chomaz P et al. Phys. Rev. C, 2007, **76**: 044316
- 9 Onsi M, Pearson J M. Phys. Rev. C, 2002, **65**: 047302
- 10 Stone J R, Miller J C et al. Phys. Rev. C, 2003, **68**: 034324
- 11 Stone J R, Reinhard P G. Progr. Part. Nucl. Phys., 2006, **58**: 587
- 12 Meissner U G, Rakhimov A M et al. Eur. Phys. J. A, 2007, **32**: 299
- 13 Denisov V Y, Norenberg W. Eur. Phys. J. A, 2002, **15**: 375
- 14 WANG N, WU X Z, LI Z X, LIU M, Scheid W. Phys. Rev. C, 2006, **74**: 044604
- 15 Goriely S, Samyn M et al. Phys. Rev. C, 2007, **75**: 064312
- 16 Brown B A. Phys. Rev. Lett., 2000, **85**: 5296
- 17 CHEN L W, Ko C M, LI B A. Phys. Rev. C, 2005, **72**: 064309
- 18 Lesinski T, Bennaceur K et al. Phys. Rev. C, 2006, **74**: 044315
- 19 Chabanat E, Bonche P, Haensel P, Meyer J, Schaeffer R. Nucl. Phys. A, 1997, **627**: 710; Nucl. Phys. A, 1998, **635**: 231; Nucl. Phys. A, 1998, **643**: 441
- 20 Pudlifer B S, Pandharipande V R, Carlson J, Pieper S C, Wiringa R B. Phys. Rev. C, 1997, **56**: 1720
- 21 CAO L G, Lombardo U et al. Phys. Rev. C, 2006, **73**: 014313
- 22 ZUO W, Lejeune A, Lombardo U, Mathiot J F. Nucl. Phys. A, 2002, **706**: 418; Eur. Phys. J. A, 2002, **14**: 469
- 23 ZUO W, CAO L G, LI B A, Lombardo U, SHEN C W. Phys. Rev. C, 2005, **72**: 014005
- 24 Day B D. Rev. Mod. Phys., 1967, **39**: 719
- 25 ZUO W, Bombaci I, Lombardo U. Phys. Rev. C, 1999, **60**: 024605
- 26 Jeukenne J P, Lejeune A, Mahaux C. Phys. Rep., 1976, **25**: 83
- 27 SONG H Q, Baldo M, Giansiracusa G, Lombardo U. Phys. Rev. Lett., 1998, **81**: 1584; Baldo M, Fiasconaro A, SONG H Q, Giansiracusa G, Lombardo U. Phys. Rev. C, 2002, **65**: 017303
- 28 Lejeune A, Mahaux C. Nucl. Phys. A, 1978, **295**: 189
- 29 Baldo M. Nuclear Methods and the Nuclear Equation of State. Ed. Baldo M. Singapore: World Scientific, 1999. 1
- 30 Wiringa R B, Stoks V G J, Qchiavilla R. Phys. Rev. C, 1995, **51**: 38
- 31 Grangé P, Lejeune E, Martzolff M, Mathiot J F. Phys. Rev. C, 1989, **40**: 1040
- 32 ZUO W, ZHOU S G, LI J Q, ZHAO E G, Scheid W. Chin. Phys. C (HEP & NP), 2009, **33**: 547