Three-Body Force Effect on the Properties of Nuclear Matter

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Abstract

We give a review of our research work on the equation of state and single particle properties of nuclear matter within the framework of the extended Brueckner–Hartree–Fock approach. We discuss especially the three-body force (TBF) effect. The TBF effect has been shown to be necessary for describing the saturation properties of nuclear matter in nonrelativistic microscopic framework. As for asymmetric nuclear matter, the TBF turns out to result in a strong stiffening of the density dependence of symmetry energy at supra-saturation densities. Within the framework of the Brueckner theory, the TBF may lead to a rearrangement contribution to the single-particle (s.p.) potentials, which enhances significantly the repulsion and momentum-dependence of the s.p. potentials at high densities and high momenta.

Keywords: *Nuclear matter; equation of state; symmetry energy; Brueckner–Hartree–Fock approach; three-body force*

1 Introduction

One of the most important issues in nuclear physics is to constrain experimentally and theoretically the equation of state (EOS) and single-particle (s.p.) properties of nuclear matter [1–3], especially the density dependence of symmetry energy, which not only plays an essential role in predicting the properties of heavy nuclei and neutron-rich nuclei [4–7], but is also crucial for understanding many phenomena in nuclear astrophysics [8–11]. For instance, it has been shown by theoretical investigations [5, 6] that the neutron-skin thickness of heavy nuclei is correlated strongly with the density dependence of symmetry energy around the saturation density. In Ref. [7], the effect of symmetry energy on the α-decay energies of superheavy nuclei has been explored and the symmetry energy turns out to play a decisive role in explaining the experimentally observed enhancement of the stability against α-decay with increasing the mass number along an isotope chain for the synthesized superheavy nuclei not around shell closures. Concerning nuclear astrophysics, the EOS of nuclear matter

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is the basic input for the Tolman–Oppenheimer–Volkov (TOV) equation, and plays an extremely important role in modeling structure of neutron stars [12, 13]. The high-density behavior of symmetry energy determines the proton fraction in β-stable (n, p, e, μ) neutron star matter [14], and thus is crucial for understanding the cooling mechanism via neutrino emission in the inner part of neutron stars [15].

In recent years, the properties of asymmetric nuclear matter have been investigated extensively within various many-body approaches, including both *ab initio* and phenomenological methods. In a phenomenological many-body framework such as the Skyrme–Hartree–Fock approach, the nucleon-nucleon (NN) correlations in nuclear medium have been incorporated implicitly in the parameters of the adopted effective interactions, and the predicted high-density behavior of symmetry energy using different parameter sets may differ essentially and even may appear opposite [5]. In the *ab initio* approaches based on realistic NN interactions which are determined by experimental NN phase shifts, the nuclear correlations are taken into account using various approximation schemes for the exact nuclear many-body problem. Almost all *ab initio* approaches are able to reproduce more or less the empirical value of symmetry energy at the empirical saturation density and predict a monotonically increasing symmetry energy as a function of density, however, the stiffness of the density dependence of symmetry energy obtained by adopting different approaches and/or different NN interactions may become significantly different at high densities [16–18].

We have studied the the EOS and s.p. properties of asymmetric nuclear matter within the framework of the Brueckner–Hartree–Fock (BHF) approach extended to include a microscopic three-body force (TBF). In the present paper, we shall give a review of our research work concerning the properties of nuclear matter, and we shall discuss especially the TBF effect on the properties of asymmetric nuclear matter.

2 Theoretical approaches

The EOS and s.p. properties of nuclear matter can be predicted within the frameworks of various *ab initio* approaches. In our investigation, the BHF approach has been adopted, which is based on the Brueckner–Bethe–Goldstone (BBG) theory [19]. The extensions of the BBG scheme to the asymmetric nuclear matter and to include a microscopic TBF can be found in Refs. [14, 20] and Refs. [21, 22], respectively. Here we simply give a brief review for completeness. The key point of the BHF approach is the reaction G-matrix, which satisfies the following isospin-dependent Bethe–Goldstone (BG) equation,

$$G(\rho, \beta, \omega) = \upsilon + \upsilon \sum_{k_1 k_2} \frac{|k_1 k_2\rangle \, Q(k_1, k_2) \, \langle k_1 k_2|}{\omega - \epsilon(k_1) - \epsilon(k_2)} \, G(\rho, \beta, \omega), \tag{1}$$

where $k_i \equiv (\vec{k}_i, \sigma_i, \tau_i)$ denotes the momentum and the z-components of spin and isospin of a nucleon, respectively; υ is a realistic NN interaction; ω is the starting energy; $Q(k_1, k_2)$ is the Pauli operator. The isospin asymmetry parameter is defined as $\beta = (\rho_n - \rho_p)/\rho$, where ρ, ρ_n, and ρ_p denote the total, the neutron and the proton densities, respectively. For the interaction υ in our calculation, we adopt some realistic two-body interaction (i. e., the Argonne V_{18} interaction [23] or the Bonn potential [24]) plus the corresponding microscopic TBF [22, 25] constructed in a consistent way with the adopted two-body interaction by using the meson-exchange current approach [21].

The s.p. energy is given by $\epsilon(k) = \hbar^2k^2/(2m)+U_{BHF}(k)$. In solving the BG equation, the continuous choice [26] is adopted for the auxiliary potential $U_{\rm BHF}$ since it has been shown to provide a much faster convergence of the hole-line expansion than the gap choice [27]. Under the continuous choice, the s.p. potential describes physically at the lowest BHF level the nuclear mean field felt by a nucleon in nuclear medium, and it can be obtained from the real part of the on-shell G-matrix,

$$U_{\rm BHF}(k) = \sum_{k'} n(k')\,{\rm Re}\langle kk'|G\big(\epsilon(k)+\epsilon(k')\big)|kk'\rangle_A. \tag{2}$$

In the BHF approximation, the EOS of asymmetric nuclear matter (i. e., the energy per nucleon of asymmetric nuclear matter as a function of density ρ and isospin asymmetry β) is given by

$$\begin{aligned} E_A(\rho,\beta) = \frac{3}{5}\frac{\hbar^2}{2m}\left[\Big(\frac{1-\beta}{2}\Big)^{5/3} + \Big(\frac{1+\beta}{2}\Big)^{5/3}\right]\big(3\pi^2\rho\big)^{2/3} \\ + \frac{1}{2\rho}{\rm Re}\sum_{\tau,\tau'}\sum_{k\le k_F^\tau,k'\le k_F^{\tau'}} \langle kk'|G\big(\rho,\beta;\epsilon(k)+\epsilon(k')\big)|kk'\rangle_A, \end{aligned} \tag{3}$$

where the first term is the contribution of the kinetic part and the second term is the potential part.

As is well known, a nonrelativistic *ab initio* model of rigid nucleons interacting via realistic two-body forces fitting in-vacuum NN scattering data is not able to reproduce the empirical saturation properties of nuclear matter. Within the framework of the BHF approach, the saturation points predicted by various NN interactions are shown to locate in a narrow band (Coester band) which is far away from the empirical point [17, 28]. There are two different ways to introduce the medium effects and to solve the above problem. One is to adopt a relativistic theory, such as the Dirac-BHF method [24], suggesting that nucleons propagate in nuclear medium as *dressed* Dirac spinors which may incorporate a special class of TBF (i. e., the TBF involving the virtual excitations of nucleon-antinucleon pairs) and respond for the main relativistic contribution to the nuclear matter EOS [22, 29, 30]. The other is to introduce TBFs in nonrelativistic approaches. Up to now, several different kinds of TBF models have been applied in the BHF calculations. One is the semi-phenomenological TBF model, such as the Urbana TBF [31], in which few adjustable parameters are usually determined by fitting the observed triton binding energies and/or the empirical saturation properties of symmetric nuclear matter. Another kind of TBF models adopted in the BHF calculations is the microscopic one [21, 22, 25] based on the meson exchange theory for NN interactions. In the microscopic TBF model, there is no adjustable parameter in the sense that the meson parameters are essentially determined self-consistently by the corresponding two-body force. The classical parts of the microscopic TBF model associated with the π and ρ meson exchanges have been developed during a long period by several authors [32–34]. The extension to include the σ and ω exchanges as well as the associated virtual nucleon-antinucleon pair excitations have been done by Grangé *et al.* [21]. Further improvement and development of the model have been achieved in Refs. [22, 25]. In recent years, nuclear TBF has also been developed systematically within the framework of the chiral effective field theory [35].

In order to include the TBF contribution into the two-body BG equation and to avoid the in-medium three-body Faddeev problem, we have reduced the TBF to an effectively equivalent two-body interaction according to a standard and extensively adopted scheme [21]. In the r-space, the equivalent two-body force $V_3^{\rm eff}$ reads:

$$\langle \vec{r}_1'\vec{r}_2'|V_3^{\rm eff}|\vec{r}_1\vec{r}_2\rangle = \frac{1}{4}{\rm Tr}\sum_n \int {\rm d}\vec{r}_3\,{\rm d}\vec{r}_3'\,\phi_n^*(\vec{r}_3')\big(1-\eta(r_{13}')\big)\big(1-\eta(r_{23}')\big) \times W_3(\vec{r}_1'\vec{r}_2'\vec{r}_3'|\vec{r}_1\vec{r}_2\vec{r}_3)\,\phi_n(\vec{r}_3)\big(1-\eta(r_{13})\big)\big(1-\eta(r_{23})\big). \quad (4)$$

The justification of the above approximation can be found in Refs. [21, 33]. In this averaging scheme, the direct and most important single-exchange TBF contributions are taken into account.

As well known, at the lowest mean field approximation, the BHF approach has two problems in predicting nuclear s.p. properties. First, the predicted optical potential at the saturation density is shown to be too deep as compared to its empirical value [26], and the Hugenholtz–Van Hove (HVH) theorem is destroyed seriously. The solution of this problem is to go beyond the lowest order approximation by taking into account the effect of ground state (g.s.) correlations [26, 36]. The contribution of the g.s. correlations can be obtained according to the hole-line expansion of the mass operator,

$$M(k,\omega) = M_1(k,\omega) + M_2(k,\omega) + M_3(k,\omega) + \ldots, \quad (5)$$

where $M_1(k,\omega)$ corresponds to the lowest-order BHF contribution and its on-shell value describes the nuclear mean field $U_{\rm BHF}$ at the lowest-order BHF approximation. The second-order contribution M_2 is called Pauli rearrangement term and it gives the dominant contribution of the g.s. correlations.

Second, at the lowest-order BHF approximation, the predicted potential at high densities and high momenta is too attractive and its momentum dependence turns out to be too weak for describing the experimental elliptic flow data [37]. In order to solve these two problems, we have improved the Brueckner calculation of the s.p. properties in two aspects. The first is to extend the calculation of the effect of g.s. correlations to asymmetric nuclear matter [20]. The second is to take into account the TBF-induced rearrangement contribution in calculating the s.p. properties as shown in Ref. [38] where the TBF rearrangement term has been derived,

$$U_{\rm TBF}(k) \approx \frac{1}{2}\sum_{k_1k_2} n_{k_1}n_{k_2}\left\langle k_1k_2\left|\frac{\delta V_3^{\rm eff}}{\delta n_k}\right|k_1k_2\right\rangle_A. \quad (6)$$

3 EOS of symmetric nuclear matter

We display in Fig. 1 the EOS of symmetric nuclear matter predicted within different *ab initio* theoretical frameworks including the BHF approach [22, 25], the many-body variational method [39], and the relativistic Dirac–Brueckner–Hartree–Fock (DBHF) theory [24]. In the figure, the box indicates the location of the empirical saturation point; other symbols indicate the predicted saturation points. It is clear that without TBF, the saturation points obtained within the two nonrelativistic frameworks (i. e., the BHF and variational approaches) are far away from the empirical one. At low densities well below the saturation density, the TBF effect is reasonably small. At

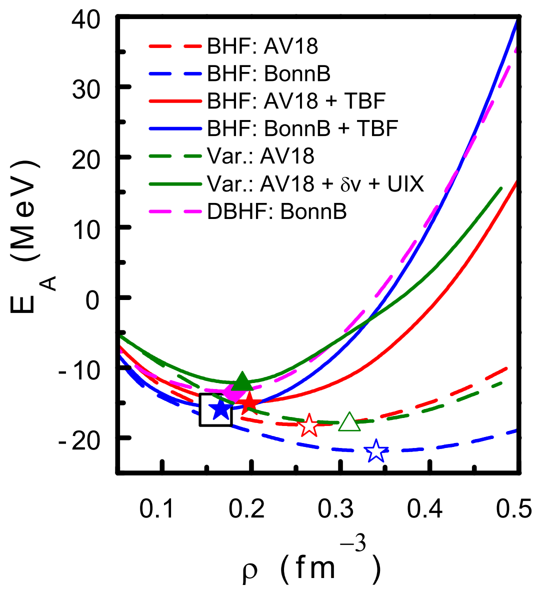

Figure 1: EOS of symmetric nuclear matter predicted by different microscopic approaches. The results of the BHF approach are taken from Refs. [22] and [25]. The DBHF prediction is taken from Ref. [24]. The results of the variational approach are from Ref. [39]. The dashed curves are obtained by purely two-body interactions; the solid ones are the results by the two-body interactions plus various TBFs.

supra-saturation densities, the TBF provides a repulsive contribution to the nuclear EOS, and its repulsion increases monotonically as a function of density. It is worth stressing that inclusion of the TBF contribution improves remarkably the saturation points predicted by the two nonrelativistic *ab initio* approaches, indicating that the TBF is necessary for reproducing the empirical saturation properties of nuclear matter in a non-relativistic microscopic framework.

Within the BHF framework, by including the TBFs, the calculated saturation density may be improved significantly from 0.265fm^{-3} and 0.33fm^{-3} to 0.167fm^{-3} and 0.19fm^{-3}, respectively when the AV18 and BonnB interactions are adopted as the two-body interaction. The latter two values are compatible with the empirical value and the DBHF prediction of roughly 0.18fm^{-3}. Concerning the relativistic effect in the DBHF approach, it has been shown quantitatively in Refs. [22, 25] that the main relativistic correction to the EOS of nuclear matter can be reproduced by the TBF component involving the virtual excitations of nucleon-antinucleon pairs due to the 2σ-meson exchange.

4 EOS of asymmetric nuclear matter

The isovector part of the EOS of nuclear matter (i. e., the difference between the energy per nucleon of asymmetric nuclear matter and that of symmetric nuclear matter) as a function of β^2 at four typical densities, $\rho = 0.085$, 0.17, 0.34 and 0.45 fm^{-3}, is reported in Fig. 2. It is clearly seen that the isovector part of the EOS fulfills satisfactorily a linear dependence on β^2 in the whole asymmetry range of $0 \leq \beta \leq 1$, i. e.,

$$E_A(\rho, \beta) - E_A(\rho, 0) = E_{sym}(\rho)\beta^2. \tag{7}$$

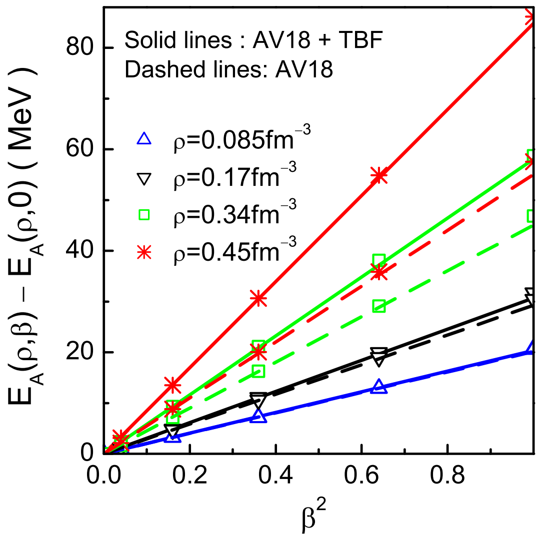

Figure 2: Isovector part of EOS of asymmetric nuclear matter. Different symbols show predictions by the BHF approach for four different densities, and the lines are the corresponding linear fits. Taken from Ref. [22].

Both the TBF effect and the thermal effect do not destroy the linear dependence of $E_A(\rho,\beta)$ on β^2 [22, 40]. The symmetry energy $E_{sym}(\rho)$ is defined generally as

$$E_{sym}(\rho) = \frac{1}{2}\left[\partial^2 E_A/\partial\beta^2\right]_{\beta=0}. \tag{8}$$

The linear β^2 dependence of $E_A(\rho,\beta)$ predicted within the framework of different *ab initio* many-body approaches and by using various NN interactions provides a microscopic support for the empirical β^2 law extracted from the nuclear mass table, and extends its validity up to the highest asymmetry and to high densities well above the saturation density. The above simple β^2 law of $E_A(\rho,\beta)$ may lead to several important consequences. First, it implies that the isovector part of the EOS of asymmetric nuclear matter at a given density is determined essentially by the symmetry energy. Second, the symmetry energy can be calculated directly as the difference between the EOS of pure neutron matter and that of symmetric nuclear matter, i. e., $E_{sym}(\rho) = E_A(\rho,1) - E_A(\rho,0)$. Third, due to the linear β^2 dependence of $E_A(\rho,\beta)$, the difference of the neutron and proton chemical potentials in neutron star matter can be explicitly related to the symmetry energy: $\mu_n - \mu_p = 4\beta E_{sym}$.

5 High-density behavior of symmetry energy

We show in Fig. 3 the density dependence of symmetry energy predicted within three different *ab initio* theoretical frameworks, including the BHF approach [22, 25], the variational method [39], and the DBHF theory [41]. It is worthy of notice that the predicted symmetry energy increases monotonically as a function of density regardless of the adopted *ab initio* approach and/or the realistic NN interaction. At subsaturation densities, the difference between different predictions has been shown to be quite small [3], and the TBF effect is seen to be reasonably weak; whereas the high-density behaviors of symmetry energy predicted by three different *ab initio* approaches may become significantly different. In the BHF calculations, the inclusion of the TBF

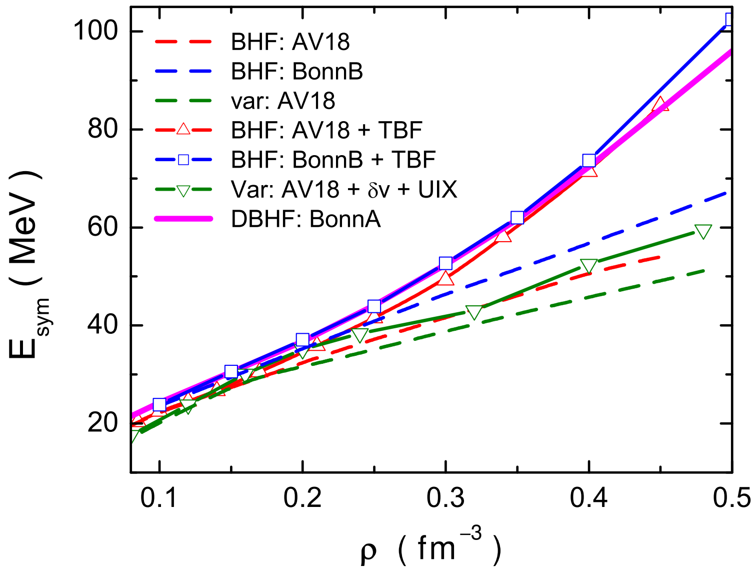

Figure 3: Symmetry energy vs density predicted within three different *ab initio* theoretical frameworks: the BHF [22, 25], the variational approach [39], and the DBHF [41].

results in that the predicted symmetry energy almost completely coincides with the DBHF prediction up to $\rho = 0.5\text{fm}^{-3}$. Within the two nonrelativistic *ab initio* frameworks, the TBF effect on the symmetry energy is repulsive, and the inclusion of the TBFs leads to a stiffening of the density dependence of symmetry energy at suprasaturation densities. It is worth noting that the TBF symmetry energy repulsion at high densities within the BHF framework is much stronger than that within the variational framework. At high densities well above the saturation density, the TBF effect may even enlarge remarkably the discrepancy between the BHF and variational predictions. To clarify this problem, further investigation is necessary.

6 Single particle potential in nuclear matter

In our calculation of the s.p. potential, we take into account three different contributions, i. e., the leading-order contribution $U_{\rm BHF}$ corresponding to the lowest-order BHF s.p. potential, the Pauli rearrangement contribution U_2 due to the effect of g.s. correlations in nuclear medium, and the rearrangement contribution $U_{\rm TBF}$ induced by the TBF. The full s.p. potential is the sum of these contributions,

$$U(k) = U_{\rm BHF}(k) + U_2(k) + U_{\rm TBF}(k). \tag{9}$$

We show in Fig. 4 these three contributions to the symmetric nuclear matter at three typical densities of $\rho = 0.085$, 0.17, and 0.34 fm^{-3}. The lowest-order BHF s.p. potential $U_{\rm BHF}$ is seen to be strongly attractive at low momenta, and its attraction increases as a function of density. The g.s. correlations lead to a repulsive contribution U_2 which is much smaller in magnitude than the lowest-order BHF contribution $U_{\rm BHF}$. It is

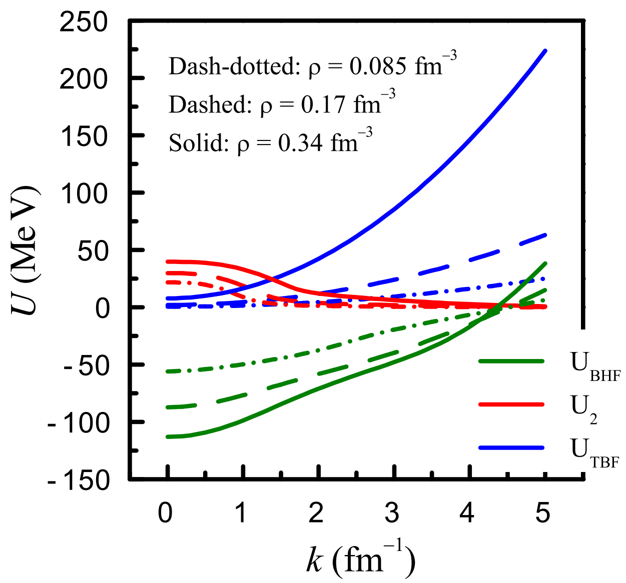

Figure 4: Three different contributions, $U_{\rm BHF}$, U_2 and $U_{\rm TBF}$, to symmetric nuclear matter at three densities. Taken from Ref. [42].

clearly seen that the contribution of g.s. correlations modifies the s.p. potential mainly at low momenta around and below the Fermi surface, and it decreases rapidly around the Fermi momentum and vanishes at high momenta well above the Fermi momentum. As discussed in Ref. [38], the inclusion of the effect of g.s. correlations cannot provide any appreciable improvement of the *high-momentum* behavior of the BHF s.p. potential at high densities. The TBF-induced rearrangement contribution $U_{\rm TBF}$ is repulsive, and it turns out to be completely different from the Pauli rearrangement contribution U_2. At low densities and/or low momenta well below the Fermi momentum, the TBF rearrangement potential $U_{\rm TBF}$ is fairly small. However, the $U_{\rm TBF}$ increases monotonically and rapidly as a function of density and momentum. At high densities and high momenta, it becomes strongly repulsive and momentum-dependent. Such a strongly repulsive and momentum-dependent rearrangement potential induced by the TBF is necessary for improving the *high-momentum* behavior of the lowest-order BHF s.p. potential which has been shown to be too attractive at high densities and whose momentum dependence turns out to be too weak to describe the experimental elliptic flow data in heavy-ion collisions at high energies [37].

Now let us discuss briefly the isospin dependence of the nucleon s.p. potentials in asymmetric nuclear matter. In asymmetric nuclear matter ($\beta > 0$), the neutron potential U^n becomes different from the proton one U^p. At relatively low momenta, the neutron s.p. potential $U^n_{\rm BHF}$ at the lowest-order BHF approximation becomes less attractive while the proton one becomes more attractive as the asymmetry β increases. The different β-dependence of the neutron and proton potentials stems essentially from the isospin $T = 0$ neutron-proton short-range correlations in the SD channel [14,20]. As discussed in Ref. [20], the contribution of the g.s. correlations may destroy the linear β-dependence fulfilled at the lowest-order BHF approximation by the neutron and proton potentials at a fixed momentum. The isospin dependence of the TBF rearrangement potentials has been shown to be relatively weak in magnitude as compared to the lowest-order BHF potentials [38].

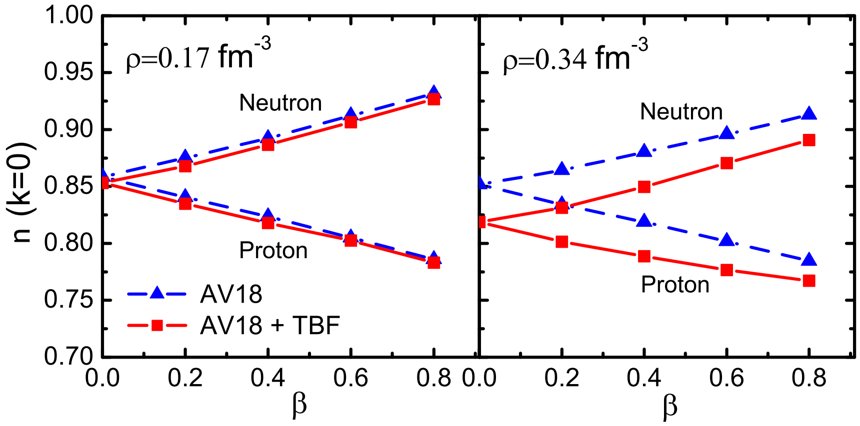

Figure 5: Neutron and proton momentum distributions at zero momentum in asymmetric nuclear matter vs isospin asymmetry β for two densities, 0.17 fm^{-3} (left panel) and 0.34 fm^{-3} (right panel). Taken from Ref. [43].

7 Nucleon momentum distribution

Nucleon momentum distribution measures the strength of the dynamical NN correlations in a nuclear many-body system. Its information not only plays a significant role in understanding the nature of NN interactions, but is also crucial for testing the validity of the physical picture of independent particle motion in the mean field theory or in the standard shell model. In order to discuss the isospin dependence and the TBF effect clearly, we report in Fig. 5 the predicted proton and neutron momentum distributions at zero momentum $k = 0$ as functions of asymmetry β in two cases with and without considering the TBF [43]. It is clearly seen that the neutron and proton momentum distributions become different in asymmetric nuclear matter at $\beta > 0$. At a higher asymmetry, the neutron Fermi sea tends to be more occupied while the proton Fermi sea becomes less occupied. One may notice that the neutron (proton) occupation probability at zero momentum increases (decreases) almost linearly as a function of asymmetry β, which indicates that the short-range tensor correlations between neutrons and protons become stronger (weaker) for proton (neutron) at a higher asymmetry. At low densities around and below the saturation densities, the TBF effect is negligibly small. However, at high densities well above the saturation density, the TBF may lead to an overall enhancement of the depletion of the neutron and proton hole states, which is expected since the TBF induces extra short-range correlations in dense nuclear medium.

8 Summary

In summary, we have reviewed part of our research work on the EOS and the s.p. properties of nuclear matter within the framework of the Brueckner approach extended to include a microscopic TBF. We have discussed especially the TBF effects and compared our results with the predictions of different *ab initio* approaches. TBF provides a repulsive contribution to the EOS of nuclear matter, and is shown to be necessary for reproducing the empirical saturation properties of nuclear matter within the framework of a nonrelativistic *ab initio* approach. The EOS of asymmetric nuclear matter turns out to fulfill satisfactorily a linear dependence on β^2 in the whole asymmetry range of $0 \leq \beta \leq 1$. Both the TBF and the thermal effect do not destroy the β^2 law fulfilled by the EOS of asymmetric nuclear matter. The symmetry energy predicted by three different *ab initio* approaches and/or different realistic NN interactions is shown to increase monotonically as a function of density. In the nonrelativistic approaches, the TBF may lead to a strong enhancement of the stiffness of symmetry energy at high densities. The TBF symmetry energy repulsion at high densities is found to be much stronger within the BHF than that within the variational framework.

In predicting the s.p. properties, we have improved the Brueckner calculation in two aspects. The first one is to extend the calculation of the g.s. correlation effect to the asymmetric nuclear matter. Second, we include the TBF-induced rearrangement contribution in our calculations. Both improvements are shown to be necessary for predicting reliably the s.p. properties of nuclear matter within the Brueckner approach. Especially, the TBF rearrangement potential turns out to be strongly repulsive and momentum-dependent at high densities and momenta, which is necessary for improving the large-density and high-momentum behavior of the s.p. potentials. At high densities well above the saturation density, the TBF effect leads to an overall enhancement of the depletion of nuclear Fermi sea since the TBF may induce extra short-range correlations in dense nuclear medium.

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