Single particle properties in asymmetric nuclear matter and TBF rearrangement effect *

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Abstract We have developed the formula and the numerical code for calculating the rearrangement contribution to the single particle (s.p.) properties in asymmetric nuclear matter induced by three-body forces within the framework of the Brueckner theory extended to include a microscopic three-body force (TBF). We have investigated systematically the TBF-induced rearrangement effect on the s.p. properties and their isospin-behavior in neutron-rich nuclear medium. It is shown that the TBF induces a repulsive rearrangement contribution to the s.p. potential in nuclear medium. The repulsion of the TBF rearrangement contribution increases rapidly as a function of density and nucleon momentum. It reduces largely the attraction of the BHF s.p. potential and enhances strongly the momentum dependence of the s.p. potential at large densities and high-momenta. The TBF rearrangement effect on symmetry potential is to enhances its repulsion (attraction) on neutrons (protons) in dense asymmetric nuclear matter.

Key words asymmetric nuclear matter, single particle properties, Brueckner theory, three-body force rearrangement effect

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1 Introduction

One of the main aims of heavy ion collisions (HIC) induced by radioactive beams is to extract reliable information about the equation of state (EOS) of asymmetric nuclear matter which is of great interest in nuclear physics, heavy ion physics and astrophysics[1—4]. Since the nuclear EOS can not be measured directly in the experiments of HIC, one has to compare the experimental observables and the theoretical simulations by using transport models. The single particle (s.p.) potentials felt by protons and neutrons in isospin asymmetric nuclear medium are basic ingredients of the transport models (such as BUU and QMD) for HIC and control together with nucleon-nucleon cross sections the collision dynamics. Nucleon effective mass stems from the non-local nature of the s.p. potential felt by a nucleon propagating in nuclear medium and describes the momentum dependence of the s.p. potential. The effective mass is of great interest[5] since it is closely related with many nuclear and astrophysical phenomena such as the dynamics of HIC at intermediate and high energies, the damping of nuclear excitations and the giant resonances, the adiabatic temperature of collapsing stellar matter[6]. Recently, the determination of the momentum-dependent symmetry potential and the neutron-proton effective mass splitting in neutron-rich nuclear matter is receiving more and more attention[7—13]. The reliable information on the

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density- and momentum-dependence of symmetry potential and the effective mass splitting in neutron-rich matter is expected to be crucial for constraining uniquely the asymmetric nuclear matter EOS.

Microscopically the s.p. properties in symmetric and asymmetric nuclear matter have been studied extensively by adopting the Brueckner-Hartree-Fock (BHF) and the extended BHF (EBHF) approaches[14—22], the Green function method[23—26] and the relativistic Dirac-BHF (DBHF) theory[10—12]. In Refs. [18, 19], the proton and neutron s.p. potentials and effective masses in neutron-rich nuclear matter have been investigated systematically within the framework of the BHF and EBHF approaches. In Refs. [20, 21], the calculations have been extended to include three-body forces and to the case of finite temperature asymmetric nuclear matter. However, the three-body force (TBF) effect was included only at the BHF level via its modification of the G-matrix in the calculation of the s.p. properties and the TBF rearrangement effect on the s.p. properties was completely ignored in our previous investigations[20, 21]. It has been pointed out in Ref. [27] that the BHF s.p. potential at high densities predicted without considering three-body forces is too attractive and its momentum dependence turns out to be too weak for describing the experimental elliptic flow data. As well known, within the non-relativistic BHF framework the repulsive contribution of three-body forces is crucial for reproducing the empirical saturation properties of cold nuclear matter[20, 28]. In the framework of the Brueckner theory, the TBF is included by reducing it to an equivalent density-dependent two-body force and as a consequence its effect on the s.p. properties is twofold. First, it affects the s.p. properties at the BHF level and the EBHF level via direct influence on the G-matrix[20]. Second, it may induce an extra rearrangement contribution to the s.p. potential[29]. The TBF-induced rearrangement contribution is expected to be repulsive and strongly momentum-dependent at high densities and momenta.

In the present paper, we shall present systematically our research work of the TBF-induced rearrangement effect on the s.p. properties and their isospin dependence in neutron-rich nuclear matter, including the proton and neutron s.p. potentials and effective masses, the nuclear symmetry potential, and the isospin splitting of neutron-proton effective mass.

2 Theoretical approaches

Our investigation is based on the Brueckner-Bethe-Goldstone (BBG) theory for asymmetric nuclear matter[18, 19]. The extension of the BBG scheme to include three-body forces can be found in Refs. [20, 28]. The starting point of the BBG scheme is the Brueckner reaction G matrix, which satisfies the Bethe-Goldstone (BG) equation. In solving the BG equation for the G-matrix, we adopt the continuous choice for the s.p. potential since it provides a much faster convergency of the hole-line expansion than the gap choice[30]. Under the continuous choice, the s.p. potential describes physically at the BHF level the nuclear mean field felt by a nucleon in nuclear medium[31].

The realistic nucleon-nucleon (NN) interaction $\upsilon_{\rm NN}$ in the present calculation contains two parts, i.e., the Argonne V_{18} (AV_{18}) two-body interaction[32] plus the contribution of the microscopic TBF based on the meson-exchange current approach[28]. We have investigated the TBF effect on the EOS of nuclear matter in Ref. [20]. The microscopic TBF turns out to provide a repulsive contribution to the EOS of nuclear matter and improves remarkably the predicted saturation properties. We have also shown that the main relativistic correction to the nuclear EOS in the DBHF approach can be reproduced quantitatively by the 2σ-N$\bar{\rm N}$ component (i.e., the Z-diagram contribution) of the microscopic TBF. However, the TBF components from the other elementary processes becomes important at high densities and can not be completely neglected even at the saturation density. As for the isospin dependence of the nuclear EOS, we find that the TBF leads to a strong stiffening of the density dependence of symmetry energy at high densities[20]. In our BHF calculation, the TBF contribution has been included by reducing the TBF to an equivalently effective two-body interaction $V_3^{\rm eff}$ according to the standard scheme as described in Ref. [28]. It is worth stressing that the effective force $V_3^{\rm eff}$ depends strongly on density. It is the density dependence of the $V_3^{\rm eff}$ that induces the TBF rearrangement contribution to the s.p. properties in nuclear medium within the BHF framework.

The s.p. potential in nuclear medium can be derived from the functional variation of the energy density with respect to the occupation probability of s.p. states[29], i.e.,

$$U(k) = \frac{\delta E}{\delta n_k} = \sum_{k_1} n_{k_1} \langle kk_1|G|kk_1\rangle_A + \frac{1}{2}\sum_{k_1k_2} n_{k_1}n_{k_2}\langle k_1k_2|\frac{\delta G}{\delta n_k}|k_1k_2\rangle_{\rm A}, \quad (1)$$

where the first term in the right hand side corresponds to the standard BHF s.p. potential. In the case without including the TBF, the above equation becomes identical with the hole-line expansion of the mass operator[14]. By the aid of the BG equation, after some operator derivations, the second term can be worked out as follows:

$$\frac{\delta G}{\delta n_k} = \frac{\delta V_3^{\rm eff}}{\delta n_k} + G\frac{Q}{e_{12}}\frac{\delta V_3^{\rm eff}}{\delta n_k} + \frac{\delta V_3^{\rm eff}}{\delta n_k}\frac{Q}{e}G + G\frac{Q}{e_{12}}\frac{\delta V_3^{\rm eff}}{\delta n_k}\frac{Q}{e}G + G\frac{\delta(Q/e_{12})}{\delta n_k}G\ . \quad (2)$$

In the right hand side of Eq. (2), the last term stems from the density dependence of the effective interaction G-matrix and it gives the second- and higher-order hole-line corrections to the s.p. potential[14]. The lowest contribution of the last term corresponds to the core polarization (also called Pauli rearrangement) which affects mainly the s.p. potential below the Fermi surface and weakens the momentum dependence of the optical potential[19]. The first four terms arise from the effective force $V_3^{\rm eff}$ which is an equivalent effective two-body interaction of the TBF and depends strongly on density. In the four terms of the TBF rearrangement contribution, the first term is predominated over the other three terms. All the other three terms contain the interaction matrix elements between two particle states (unoccupied) and two hole states (occupied), and are negligible as compared to the first term. Accordingly, the TBF-induced rearrangement contribution to the s.p. potential can be calculated as follows,

$$U_{\rm tbf}(k) \approx \frac{1}{2}\sum_{k_1k_2} n_{k_1}n_{k_2}\left\langle k_1k_2\left|\frac{\delta V_3^{\rm eff}}{\delta n_k}\right|k_1k_2\right\rangle_{\rm A}\ . \quad (3)$$

As soon as we obtained the G-matrix from the BHF approach, we can calculate the TBF rearrangement contribution to the s.p. potential according to Eq. (3).

3 Results and discussions

Within the Brueckner framework extended to include the microscopic TBF, the full s.p. potential may be separated into three parts:

$$U(k) = U_{\rm bhf}(k) + U_{\rm cor}(k) + U_{\rm tbf}(k). \quad (4)$$

In the right hand side of the above equation, the first contribution corresponds to the lowest-order BHF s.p. potential and is determined by the on-shell G-matrix, i.e., $U_{\rm bhf}(k) = \sum_{k'} n(k'){\rm Re}\langle kk'|G(\epsilon(k)+\epsilon(k'))|kk'\rangle_{\rm A}$. The second term stems from the ground state correlations and it gives the second- and higher-order hole-line corrections to the s.p. potential according to the hole-line expansion of mass operator[14]. The leading-order contribution of the second term corresponds to the core polarization (also called Pauli rearrangement). The Pauli rearrangement of G-matrix gives the higher-order corrections in the hole-line expansion of mass operator and describes the influence of the ground state two-hole correlations on the s.p. potential[14—16]. The effect of the ground state correlations has been investigated extensively in literature[14—17, 19, 23—26]. The third term is the rearrangement contribution induced by the TBF, i.e., Eq. (3).

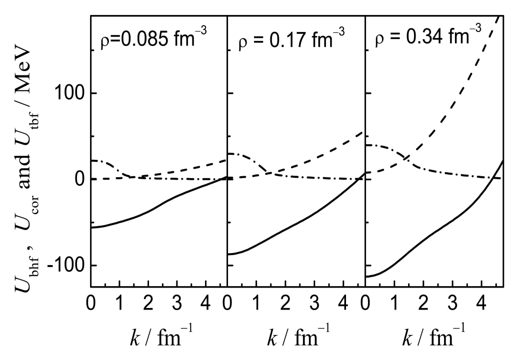

Fig. 1. Various contributions to nucleon s.p. potential vs. momentum in symmetric nuclear matter at three typical values of density. Solid curves: $U_{\rm bhf}(k)$; Dashed curves: $U_{\rm tbf}(k)$; Dot-dashed curves: $U_{\rm cor}(k)$.

In Fig. 1 we show separately the three different contributions to the s.p. potential in symmetric nuclear matter. It is seen that the BHF part (solid curves) is strongly attractive at low momenta and its attraction increases as a function of density. The ground state correlations (the Pauli rearrangement effect) lead to a repulsive contribution to the s.p. potential. It is clear from Fig. 1 that the Pauli rearrangement contribution (dot-dashed curves) affects the s.p. potential mainly at low momenta below and around the Fermi surface and is expected to weaken the momentum dependence of the optical potential. The contribution of the ground state correlations is not only important for satisfactorily reproducing the depth of the empirical nuclear optical potential[14], but also crucial for restoring the Hugenholtz-Van Hove theorem[15, 19] and necessary for generating a nucleon self-energy to describes realistically the s.p. strength distribution in nuclear matter and finite nuclei below the Fermi energy[23]. However, it can not provide any appreciate improvement of the high-momentum 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 for describing the experimental elliptic flow data of high energy HIC[27]. The rearrangement contribution induced by the TBF (dashed curves) turns out to be completely different from the Pauli rearrangement effect. Its repulsion increases monotonically and rapidly as a function of momentum and density. Its effect is more pronounced at higher momenta and it enhances remarkably the momentum dependence of the s.p. potential at high momenta.

Within the framework of the Brueckner theory, the TBF is expected to affect the predicted s.p. potential in two different ways: first, it influences the s.p. potential at the BHF and the EBHF levels directly via its modification of the G-matrix; second, it may induce a strong rearrangement contribution to the s.p. potential. In order to discuss clearly the TBF effects, we compare in Fig. 2 the s.p. potentials in symmetric nuclear matter obtained in four different cases. It is seen that the s.p. potential at the BHF level without including any TBF is most attractive. At low densities below and around the normal nuclear matter density, the TBF effects are reasonably small. The TBF effects turn out to become significant rapidly as the density increases. The TBF effect via its modification of the G-matrix at the BHF level provides an moderate repulsion at high densities which is more pronounced at lower momenta and weakens the momentum dependence of the s.p. potential. It affects the s.p. properties in a wide range of nucleon momentum, but its repulsion is shown to be much weaker as compared to the TBF-induced rearrangement effect. The TBF-induced rearrangement effect provides an additional repulsive and strongly momentum-dependent contribution at high densities and high momenta. The repulsion of the rearrangement contribution induced by the TBF reduces largely the attraction and enhances strongly the momentum-dependence of the s.p. potential at large densities and high momenta. By comparing the solid curves and the dot-dashed curves, we see that inclusion of the ground state correlation effect makes the s.p. potential less attractive at low momenta around and below the Fermi momentum. Whereas, above the Fermi momentum, the effect of the ground state correlations vanishes rapidly.

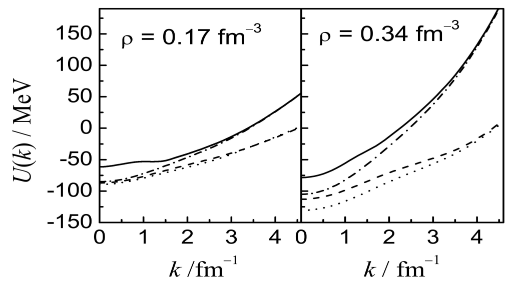

Fig. 2. The s.p. potentials in symmetric nuclear matter at two typical densities. Dotted curves: s.p. potential at the BHF level predicted by adopting the AV_{18} two-body force; Dashed curves: BHF s.p. potential including the TBF effect at the BHF level via the G-matrix; Dot-dashed curves: including the TBF effect via both the G-matrix and the TBF-induced rearrangement contribution; Solid curves: Full s.p. potential including all the three terms of Eq. (4).

In isospin asymmetric nuclear medium, the s.p. potential felt by protons is generally different from the neutron s.p. potential. It has been shown[18, 19] that within the BHF and EBHF frameworks the proton s.p. potential in neutron-rich nuclear matter becomes more attractive and the neutron one becomes more repulsive as the neutron excess increases. The iso-vector parts of the neutron and proton s.p. potentials in neutron-rich matter may be described by the symmetry potential defined as:

$$U_{\rm sym} = (U_{\rm n} - U_{\rm p})/2\beta \ , \qquad (5)$$

where β is the isospin asymmetry parameter defined as $\beta = (\rho_{\rm n} - \rho_{\rm p})/\rho$, being ρ, $\rho_{\rm n}$ and $\rho_{\rm p}$ the total nucleon, neutron and proton number densities respectively. In Ref. [22] we have shown that the symmetry potential predicted in the BHF framework is almost independent on β, indicating a linear dependence of the neutron and proton s.p. potentials on β and providing an microscopic support for the Lane potential[33]. We have also found that the symmetry potentials obtained by the BHF approach and the DBHF approach of Refs. [10, 12] display an overall agreement. Whereas the phenomenological Skyrme-like and/or Gogny parametrizations of symmetry potential[7] adopted in the dynamical simulations of HIC show a remarkably different behavior as a function of density and momentum from our microscopic $U_{\rm sym}$, indicating that it is necessary to apply the microscopic symmetry potential in the dynamic simulation of HIC. In Fig. 3, we show the TBF rearrangement effect on symmetry potential. It is seen that the predicted symmetry potential depends strongly on both density and momentum. At low densities around and below the normal nuclear matter density $\rho_0 = 0.17\ \rm fm^{-3}$, the TBF rearrangement effect turns out to be almost negligible and the predicted symmetry potentials $U_{\rm sym}$ decrease rapidly above the Fermi surface as a function of momentum. In the momentum region relevant to the intermediate-energy HIC up to a beam energy about 300 MeV/A, the predicted $U_{\rm sym}$ is positive, implying that its effect is repulsive on neutrons and attractive on protons. As the density increases, the TBF rearrangement effect becomes pronounced. One can see by comparing the solid curves and the corresponding dashed curves that the TBF-induced rearrangement effect enhances considerably the symmetry potential $U_{\rm sym}$ at high densities, i.e., it enhances the repulsion (attraction) of the $U_{\rm sym}$ on neutrons (protons).

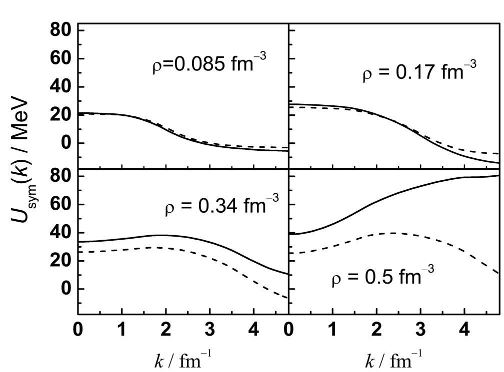

Fig. 3. Symmetry potential vs. momentum. Dashed curves: without the TBF rearrangement contribution; solid curves: including the TBF rearrangement contribution.

4 Summary

In summary, we have reported our investigation on the s.p. properties (including the neutron and proton s.p. potentials and symmetry potential) in asymmetric nuclear matter within the framework of the Brueckner-Bethe-Goldstone theory extended to include a microscopic TBF. We have discussed particularly the TBF-induced rearrangement effect on the s.p. properties and their isospin dependence in neutron-rich nuclear matter. We find that the TBF induces a repulsive rearrangement contribution to the s.p. potential. At low densities and low nucleon momenta, the TBF-induced rearrangement effects are shown to be reasonably small. Whereas, as the density and the nucleon momentum increase, the TBF rearrangement effects get enlarged rapidly. The TBF-induced rearrangement effect on the s.p. potential turns out to be completely different from the effect of the ground state correlations. The ground state correlations modify the s.p. potential mostly in the low momentum region around and below the Fermi surface. Whereas, the TBF induces a strongly repulsive and momentum-dependent rearrangement modification of both the neutron and proton s.p. potentials at high densities and large momenta, which is much more pronounced than the TBF effect via its modification of the G-matrix at the BHF level. Such a strongly repulsive and momentum-dependent rearrangement contribution in dense nuclear medium is crucial for reducing the disagreement of the large-density and high-momentum BHF s.p. potential with the parametrized potential for describing the elliptic flow data[27] and those predicted by the DBHF approach[10, 12]. Therefore, for practical applications to the dynamical simulations of HIC by transport models, it is necessary to take into account both the contributions of the ground-state correlations and the TBF rearrangement in calculating the microscopic s.p. potential. The predicted symmetry potential depends sensitively on density and momentum in both cases of including and not including the TBF rearrangement contribution. In the density region around and below the normal nuclear matter density, the TBF rearrangement effect is almost negligible for the symmetry potential. While at high densities, the TBF rearrangement leads to a considerable enhancement of the symmetry potential, indicating its isovector contribution is repulsive for neutrons and attractive for protons in neutron-rich matter.

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