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Single-Particle Properties of Isospin Asymmetric Nuclear Matter *

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The single-particle potentials in isospin asymmetric nuclear matter is investigated in the framework of the Brueckner theory by adopting the realistic Bonn B two-body interaction in combination with a consistent microscopic three-body force. The rearrangement contribution induced by the ground state correlations to single-nucleon potentials is calculated in terms of the hole-line expansion of the mass operator. With the modification of this rearrangement term the symmetry potential is discussed as a function of momentum for several isospin asymmetries.

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The investigation of isospin degree of freedom is of fundamental importance for heavy-ion collision (HIC) as well as nuclear astrophysics. Over the last few decades, both experimental and theoretical research on isospin physics have made considerable progress. The experimental observables from HIC at the intermediate and high energies requires a profound understanding of the isospin dependence of the in-medium nuclear effective interaction. Closely associated with the effective interaction is the single-nucleon potential, which reveals significant information on the momentum dependence of the mean field, effective mass, optical potential and so on. Microscopically, the single particle (s.p.) potential in nuclear matter has been studied by many authors based on microscopic theoretical approaches,[1−3] one of which is the nonrelativistic Brueckner theory. Recently, the Brueckner approach has been improved by constructing the consistent three-body force (TBF) when the realistic Bonn B potential[4] is adopted as the bare nucleon-nucleon interaction, where the entirely same microscopical meson-exchange parameters are chosen in both two-body and three-body forces.[5] It was shown that the inclusion of the new consistent TBF shifts the saturation point from ($0.34\,\mathrm{fm}^{-3}$, $-22\,\mathrm{MeV}$) to a nearly perfect value ($0.17\,\mathrm{fm}^{-3}$, $-15.9\,\mathrm{MeV}$).

According to the Landau definition of quasiparticle energy in the mass operator (nuclear self-energy), as Brown[6] pointed out, the mean field derived from the lowest-order Brueckner–Hartree–Fock (BHF) approximation is not adequate to describe the potential felt by a nucleon in the medium, and the higher-order contributions due to ground state correlation are essential to be included into the calculation of the s.p. potential. In Refs. [7,8], the influence of the ground state correlations on the s. p. potential has been explored and it proves that it is very necessary to provide a great improvement to the fulfillment of the Hugenholtz-Van Hove (HVH) theorem which is strongly violated at the lowest BHF level approximation. Several years ago, the importance of the rearrangement term in the hole-line expansion of the mass operator has also been verified in the work of Ref. [9] for s.p. properties of the hot nuclear matter in connection with the nucleon effective mass.

In this Letter, we extend our previous work within Brueckner theory by employing the Bonn B potential with the new supplemented consistent TBF, and investigate the isospin dependence of the first and second s.p. potentials for isospin asymmetric nuclear matter with the comparison with the results obtained from Argonne V_{18} (AV18) interaction.[10] The symmetry potential including the rearrangement contribution as a function of momentum is displayed. We begin with a short review of the theoretical framework.

The microscopic Brueckner–Bethe–Goldstone (BBG) description of nuclear matter is based on a linked cluster expansion of the energy per nucleon of nuclear matter.[11] The starting point of the BBG scheme is the Brueckner reaction G-matrix, which satisfies the following Bethe–Goldstone equation,

$$G[\omega;\rho] = v + \sum_{k_a,k_b} v \frac{|\, k_a k_b\rangle Q(k_a,k_b,\rho)\langle k_a k_b\,|}{\omega - e(k_a) - e(k_b) + i\epsilon} G[\omega;\rho], \tag{1}$$

where $v = v_2 + v_3$ is the nucleon-nucleon interaction composed of two-nucleon potential v_2 and averaged TBF v_3 from Eq. (4), ρ is the nucleon number den-

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sity, ω means the starting energy, the Pauli operator $Q(k_a, k_b, \rho) = [1 - n(k_a)][1 - n(k_b)]$ denotes that the propagation of intermediate nucleon pairs is constrained above the Fermi momentum k_F, and the nucleon single-particle energy is

$$e(k) = e(k;\rho) = \frac{k^2}{2m} + U(k;\rho). \quad (2)$$

The BHF approximation for the single-particle potential $U(k;\rho)$ using the continuous choice prescription is expressed as

$$U(k;\rho) = Re \sum_{k' \le k_F} \langle kk'|G[e(k) + e(k');\rho]|kk'\rangle_A, \quad (3)$$

where the subscript A indicates anti-symmetrization of the matrix elements. It has been demonstrated that the nuclear equation of state can be calculated with good accuracy in the BHF two hole-line approximation with the continuous choice for the single-particle potential.[12,13] For the sake of avoiding the difficulty of solving the relevant Faddeev equations in the use of BHF calculation, the TBF is reduced to an effective, density-dependent, two-body force by averaging over the third nucleon in the medium,

$$v_3 = \overline{v}_{12}(\boldsymbol{r}) = \rho \int d^3 r_3 \sum_{\sigma_3,\tau_3} g(r_{13})^2 g(r_{23})^2 v_{123}, \quad (4)$$

where g is called the defect function, which takes account of the nucleon-nucleon in-medium correlations.[14–16]

In the BHF approximation with the TBF correction, Eqs. (1)–(4) constitute a coupled system that needs to be solved self-consistently. One first evaluates G-matrix and the defect function along with only the two-body force, and then constructs the effective interaction $\overline{v}_{12}(\boldsymbol{r})$ which is in turn added to the bare two-body force, and again calculates the defect function. This procedure is repeated until convergence is reached.

In the same spirit of the BBG theory, the mass operator can be expanded into the perturbation series in terms of the number of hole lines,[11,17]

$$M(k;\omega) = M_1(k;\omega) + M_2(k;\omega) + \cdots, \quad (5)$$

and the various terms of this expansion can be schematically illustrated in Fig. 1 by means of Goldstone diagrams. The mass operator in Eq. (5) is a complex quantity, whose real part $V(k) \equiv V(k, e(k))$ is identified with the potential energy felt by a proton or neutron in the nuclear medium when evaluated on the energy shell. To the lowest order approximation, the quasi-particle energy $e(k) = k^2/2\,m + \mathrm{Re}M(k, e(k))$ coincides with the BHF single particle energy, and the potential felt by a nucleon is denoted as $V_1(k)$. $M_2(k;\omega)$ is the so-called two-hole line contribution of mass operator, i.e. the rearrangement term, which describes the medium dependence of the effective G-matrix interaction via the ground state Pauli blocking effect. Its expression is written as

$$M_2(k_a;\omega) = \frac{1}{2} \sum_{k_b,k'_a,k'_b} [1 - n(k_b)]n(k'_a)n(k'_b) \times \frac{|< k_a k_b \mid G \mid k'_a k'_b >_A|^2}{\omega + e(k_b) - e(k'_a) - e(k'_b) - i\epsilon}. \quad (6)$$

In the same way, the real part of the on-shell rearrangement contribution $M_2(k)$ is indicated by $V_2(k)$. In terms of the G-matrix derived from Eq. (1), the first- and second-order contributions in the hole-line expansion of the mass operator can be evaluated.

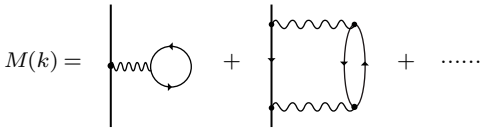


Fig. 1. Hole-line expansion of the mass operator.

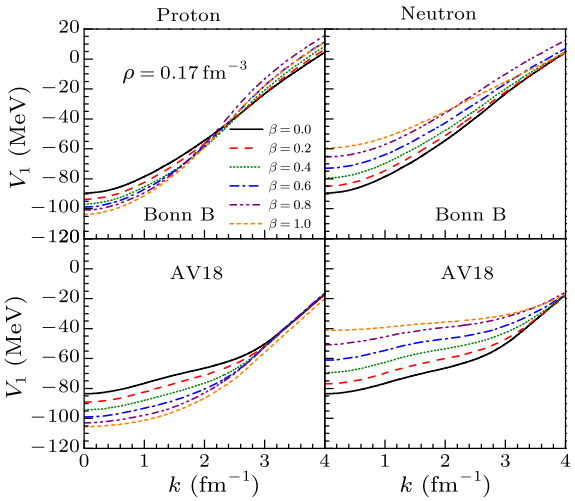


Fig. 2. The first-order single-particle potentials for proton (left panel) and neutron (right panel) as a function of momentum for several different asymmetry parameters at the density $\rho = 0.17\,\mathrm{fm}^{-3}$. The results in upper and lower panels are obtained by adopting the Bonn B and AV18 two-body nucleon-nucleon interactions with the complementarity of the microscopic three-body forces, respectively.

The first-order proton and neutron potential (i.e. mean field) is plotted in Fig. 2 as a function of momentum for several different asymmetry parameters $\beta = (\rho_n - \rho_p)/\rho$ at the normal density $\rho = 0.17\,\mathrm{fm}^{-3}$. In general, the proton mean field exhibits more attractive and the neutron mean field exhibits more repulsive with the asymmetry increasing regardless, of which the kind of two-body interaction is adopted. It can be noticed that a point of intersection occurs at a certain value of the momentum for proton or neutron mean field, where the isospin effect on neutron and

proton potential vs β is reversed. The signature of the reversal could be explained in virtue of the competition between the isospin $T = 0$ and $T = 1$ channels, as already pointed out in Refs. [18,19]. However, compared the predictions from Bonn B potential with the ones from AV18 interaction, the former provides deeper proton and neutron s.p. potentials for symmetric matter ($\beta = 0$).

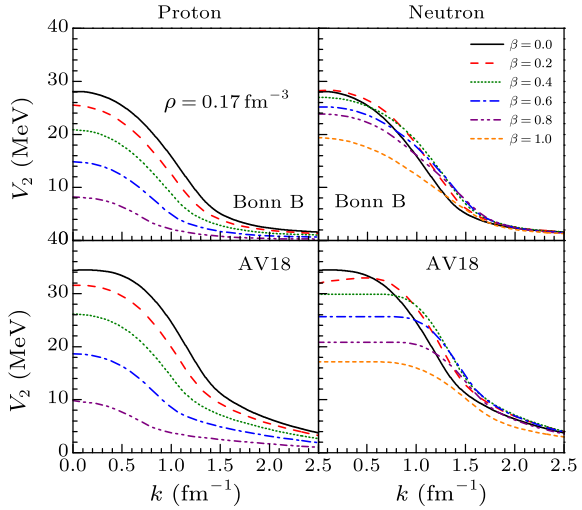


Fig. 3. The second-order single-particle potentials for proton (left panel) and neutron (right panel) as a function of momentum for several different asymmetry parameters at the density $\rho = 0.17\,\mathrm{fm}^{-3}$. The results in upper and lower panels are obtained by adopting the Bonn B and AV18 two-body nucleon-nucleon interactions with the complementarity of the microscopic three-body forces, respectively.

In Fig. 3 the real part of the second-order term of the on-shell mass operator is depicted. It is repulsive and plays a role complementary to the pure BHF mean field V_1 due to the ground state hole-hole correlation. As a result of the Pauli rearrangement effect, the second-order s.p. potential contribution mostly focuses on the region below Fermi momentum k_F and remarkably disappears above the Fermi surface. As the isospin asymmetry increases, the repulsion arising from the second-order s.p. potential of proton is gradually reduced not only for the Bonn B interaction but also for AV18 potential employed. However, the result from the Bonn B manifests the less magnitude of repulsion.

In order to concentrate on only the isospin dependence, we present in Fig. 4 the first- (upper panel) and second- (lower panel) s.p. potential with respect to the β at the momentum $k = 0\,\mathrm{fm}^{-1}$. It can be seen clearly that the first contributions of proton V_{1p} and neutron V_{1n} versus asymmetries both have the distinct linear behavior when the two different interactions are considered. Going from symmetric ($\beta = 0$) to neutron ($\beta = 1$) matter the proton second s.p. potential is significantly decreased and until disappears as a consequence of the reduced number of the protons. By reason of the influence of the changed proton phase-space, the real rearrangement term V_2 of neutrons correspondingly goes down with the weaker isospin effect for both interactions.

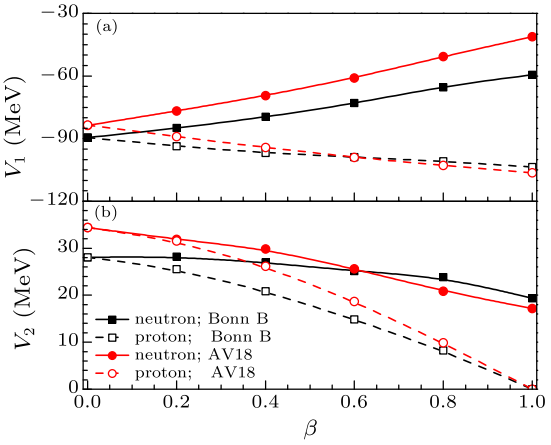


Fig. 4. The first-order (upper panel) and second-order (lower panel) single-particle potentials at density $\rho = 0.17\,\mathrm{fm}^{-3}$ and momentum $k = 0\,\mathrm{fm}^{-1}$ versus asymmetry parameters with the Bonn B and AV18 two-body interactions plus three-body forces are adopted.

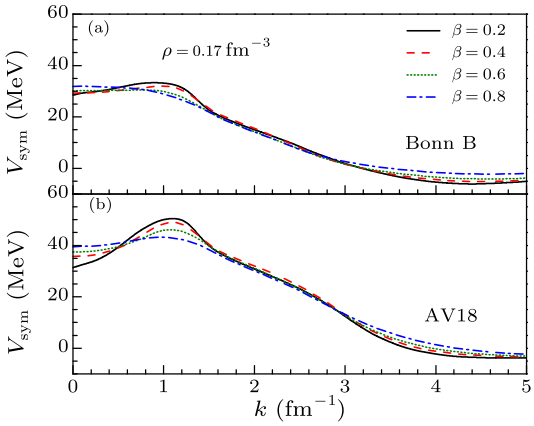


Fig. 5. Symmetry potential vs momentum k for different asymmetry parameters at the density $\rho = 0.17\,\mathrm{fm}^{-3}$, in which the Bonn B (upper panel) and AV18 (lower panel) two-body interactions plus three-body forces are adopted.

Usually, the symmetry potential is defined as $V_{sym} = (V_n - V_p)/2\beta$, where V_n and V_p denote the sum of the first- and second-order neutron and proton s.p. potentials, respectively. In Fig. 5, the symmetry potential with the rearrangement modification is displayed as a function of the momentum for different asymmetry parameters at the normal density. Around the Fermi momentum, its value is enhanced evidently, especially in the lower isospin asymmetries, which is mainly attributed to the contribution of the ground state correlations, i.e., the arrangement term V_2. It is also indicated that above the Fermi surface, the symmetry potential is seldom dependent on the isospin asymmetry. When the Bonn B potential plus the consistent TBF is taken into account (see the up-

per panel of Fig. 5), the curve of $\beta = 0.2$ is comparable with the result from the Dirac–Brueckner–Hartree–Fock (DBHF) approach.[20]

In conclusion, with the complementarity of the consistent TBF and the rearrangement contribution we investigate the momentum and isospin dependence of first and the second s.p. potential and the symmetry potential within the Brueckner theory. Our research shows that when the Bonn B potential is adopted, the proton and neutron mean field provides more attraction, whereas the rearrangement term indicates less repulsion for symmetric nuclear matter compared with the results from AV18 interaction. No matter which interaction is employed, the proton and neutron mean field exhibits distinct linear behavior. It turns out that the predicted symmetry potential is sensitively dependent on momentum, but hardly depends on the isospin asymmetry above the Fermi surface. It is also proved that our calculation of the symmetry potential with Bonn B interaction is comparable with the result from the Dirac-Brueckner-Hartree-Fock (DBHF) approach.

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