Effect of tensor correlations on the depletion of nuclear Fermi sea within the extended BHF approach*

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Abstract: We have investigated the effect of tensor correlations on the depletion of the nuclear Fermi sea in symmetric nuclear matter within the framework of the extended Brueckner-Hartree-Fock approach by adopting the $AV18$ two-body interaction and a microscopic three-body force. The contributions from various partial wave channels including the isospin-singlet $T=0$ channel, the isospin-triplet $T=1$ channel and the $T=0$ tensor $^3SD_1$ channel have been calculated. The $T=0$ neutron-proton correlations play a dominant role in causing the depletion of nuclear Fermi sea. The $T=0$ correlation-induced depletion turns out to stem almost completely from the $^3SD_1$ tensor channel. The isospin-singlet $T=0$ $^3SD_1$ tensor correlations are shown to be responsible for most of the depletion, which amounts to more than 70 percent of the total depletion in the density region considered. The three-body force turns out to lead to an enhancement of the depletion at high densities well above the empirical saturation density and its effect increases as a function of density.

Keywords: Ab initio methods, nuclear matter, three-nucleon forces, forces in hadronic systems and effective interactions

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1 Introduction

Tensor correlations and short-range correlations, which may lead to the depletion of hole states and the partial population of particle states, play a crucial role in understanding many properties of nuclear many-body systems. In Refs. [1, 2] the tensor component of nucleon-nucleon (NN) interactions has been shown to be responsible for the shell evolution of exotic nuclei. The investigation of Ref. [3] indicates that the contribution of the neutron-proton (np) tensor channel is decisive for determining the density dependence of nuclear symmetry energy. In dense neutron star matter, the short-range tensor correlations are expected to be especially important for understanding the cooling mechanism, the nucleon pairing and the transport phenomena of neutron stars [4]. Due to the NN correlations induced by NN interactions, a nuclear many-body system behaves in a much more complicated way and manifests more properties than a non-interacting Fermi system. For example, the NN correlations, especially the tensor correlations, may lead to a partial depletion of the nucleon momentum distribution below the Fermi momentum and a partial population above the Fermi momentum in nuclear matter [5]. The depletion of the Fermi sea measures the strength of the dynamical NN correlations induced by the NN interaction in a nuclear many-body system [6–8], and it plays an important role in testing the validity of the physical picture of independent particle motion in the standard shell model and/or a nuclear mean field model. Since the depletion of the lowest hole states in nuclear matter can be identified approximately as the depletion of the deeply bound states inside heavy finite nuclei, investigation of the nucleon momentum distribution in nuclear matter may provide desirable information on the structure of finite nuclei.

Experimentally, the (e,e′p) and (e,e′NN) reactions as well as proton-induced knockout reactions have been applied to investigate the effects of the short-range correlation [9–12]. Up to now, the related measurements have been repeatedly performed at various laboratories [13–23], and the existence of the short-range NN correlations has been confirmed by these experiments. The (e,e′p) experiments on ^{208}Pb at NIKHEF have in-

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dicated that the deeply bound proton states are depleted by 15%−20% in order to explain the measured coincidence cross sections [16]. The observed significant enhancement of the np short-range pairs over the proton-proton (pp) pairs at JLab [23] has shown that the tensor correlations play the dominant role in short-range correlations [24]. Theoretically, the nucleon momentum distribution and the short-range correlations in nuclear matter have been widely studied by adopting various microscopic approaches, such as the self-consistent Green's function theory [25–29], the extended Brueckner-Hartree-Fock (BHF) framework [30–36], the in-medium T-matrix approach [37, 38], the variational Monte Carlo method [24], and the correlated basis function approach [39, 40]. The depletions of the Fermi sea are predicted to be slightly larger than 15% based on various theoretical approaches [31, 34, 39, 40], which is in agreement with the experimental observations.

The occupation probabilities and hole state strengths in nuclear matter have been studied in Ref. [40] and it has been pointed out that the particle-hole excitations can also play a decisive role close to the Fermi surface. In the present paper, we shall concentrate on investigating the effect of the short range and tensor correlations. In the effective G-matrix, the ladder diagrams are summed up to infinite order and only the particle-particle channels are included. In calculating the single particle properties (i.e. off-shell mass operator, single particle potential, etc.), the effects of the particle-hole excitations can be taken into account by adopting the continuous choice for the single particle potential and by including the higher-order terms in the expansion of mass operator (i.e., M_2 and M_3), as has been discussed in Ref. [5]. In Ref. [34], the nucleon momentum distribution has been studied within the framework of the Brueckner-Bethe-Goldstone theory with high-order contributions included in the hole-line expansion of the mass operator. In our previous paper [41], the effect of a microscopic three-body force (TBF) on the nucleon momentum distribution was discussed and it was shown that inclusion of the TBF may lead to an enhancement of the depletion of nuclear Fermi sea in nuclear matter at high densities well above the saturation density. In this paper, we shall investigate the effect of tensor correlations on the depletion of nuclear Fermi sea within the framework of the extended Brueckner-Hartree-Fock (EBHF) approach.

2 Theoretical approach

The present calculations are performed within the framework of the EBHF approach [5]. The extension of the Brueckner approach to include microscopic TBFs is given in Refs. [42, 43]. The BHF approach starts with the reaction G-matrix, which is the solution of the Bethe-Goldstone (BG) equation [44],

$$G(\rho;\omega)=V+V\sum_{k_1k_2}\frac{|k_1k_2\rangle Q(k_1,k_2)\langle k_1k_2|}{\omega-\epsilon(k_1)-\epsilon(k_2)}G(\rho;\omega), \quad (1)$$

where $k_i\equiv(\vec{k}_i,\sigma_1,\tau_i)$ denotes the momentum, the z-component of spin and isospin of a nucleon, respectively. V, ω and $Q(k_1,k_2)$ are the realistic NN interaction, the starting energy and the Pauli operator, respectively. Here by $\epsilon(k)$ we denote the single-particle (s.p.) energy, which is given by $\epsilon(k)=\hbar^2k^2/(2m)+U_{\rm BHF}(k)$. The continuous choice for the auxiliary potential $U_{\rm BHF}(k)$ is adopted in the present calculation. Under this choice, the s.p. potential is calculated as follows:

$$U_{\rm BHF}(k)={\rm Re}\sum_{k'\leqslant k_F}\langle kk'|G[\rho,\epsilon(k)+\epsilon(k')]|kk'\rangle_A, \quad (2)$$

and describes physically at the lowest BHF level the nuclear mean field felt by a nucleon in the nuclear medium.

In this paper, we adopt the Argonne V_{18} ($AV18$) two-body interaction [45] supplemented with a microscopic TBF [43] for the realistic NN interaction. The TBF adopted here is constructed by use of the meson-exchange current approach [42]. The coupling constants and the form factors of the TBF have been self-consistently determined to reproduce the $AV18$ two-body force using the one-boson-exchange potential model. More details can be found in Ref. [43]. For use in BHF calculations, the TBF is reduced to an equivalently effective, density-dependent two-body interaction according to the standard scheme described in Ref. [42]. In our calculation, a larger number of partial waves are included in the expansion of the G-matrix with the maximum total angular momentum $J_{\rm max}=6$.

To calculate the nucleon momentum distribution in nuclear matter within the framework of the EBHF approach, we adopt the method given in Refs. [5, 34]. Based on the Brueckner-Bethe-Goldstone theory, the mass operator $M(k,\omega)$ can be expanded in a perturbation series according to the number of hole lines,

$$M(k,\omega)=M_1(k,\omega)+M_2(k,\omega)+M_3(k,\omega)+\cdots . \quad (3)$$

The terms of this expansion can be represented by means of Goldstone diagrams. The mass operator $M(k,\omega)$ is a complex quantity whose real part under the on-shell condition can be identified with the potential energy felt by a nucleon with momentum k and energy ω in nuclear matter. In the expansion of the mass operator, $M_1(k,\omega)$ is the first-order contribution, which corresponds to the standard BHF s.p. potential, and the real part of its on-shell value coincides with the auxiliary potential under the continuous choice given by Eq. (2). The higher-order terms are included to take the density dependence of the effective G-matrix into account, which is important for describing realistically and reliably the s.p. properties within the Brueckner theory [5]. The second-order term M_2 is called the Pauli rearrangement term and describes the effect of ground state correlations [33, 46], which is essential to reach a satisfactory agreement between the predicted depth of the microscopic BHF s.p. potential and the empirical value [5] as well as to restore the Hugenholtz-Van Hove theorem [47]. Ground state correlations also have a crucial effect on generating the self-energy of a nucleon to describe reliably the s.p. strength distribution in finite nuclei and nuclear matter below the Fermi energies [11]. The Pauli rearrangement contribution can be calculated according to Ref. [5]. The third-order term M_3 is called the renormalization term and it is given by [5, 33, 47]:

$$M_3(k,\omega)=-\sum_h \kappa_2(h)\langle kh|G(\omega+\epsilon(h))|kh\rangle_A \ , \quad (4)$$

where h denotes the hole state below the Fermi momentum, and $\kappa_2(h)=-[\partial M_1(h,\omega)/\partial\omega]_{\omega=\epsilon(h)}$ describes the depletion of the Fermi sea at the lowest-order approximation [5, 47]. This term takes into account the effect of the depletion of the Fermi sea. For simplicity, we adopt an approximation given in Ref. [34] to replace the depletion coefficient $\kappa_2(h)$ in Eq. (4) by its value at the average momentum inside the Fermi sea, i.e., $\kappa=\kappa_2(h=0.75k_F)$. By including the $M_3(k,\omega)$ term, the *renormalized* BHF approximation is obtained for the mass operator [5], i.e.,

$$\widetilde{M}_1(k,\omega)\equiv M_1(k,\omega)+M_3(k,\omega)\approx(1-\kappa)M_1(k,\omega) \ . \quad (5)$$

Similarly, one may obtain the *renormalized* $\widetilde{M}_2$ [5]: $\widetilde{M}_2(k,\omega)=(1-\kappa)M_2(k,\omega)$. In terms of the off-shell mass operator, it is convenient to calculate the nucleon momentum distribtution below and above the Fermi momentum [5, 34] as follows:

$$n(k)=1+\left[\partial\widetilde{U}_1(k,\omega)/\partial\omega\right]_{\omega=\epsilon(k)}, \qquad \text{for } k<k_F \quad (6)$$

$$n(k)=-\left[\partial\widetilde{U}_2(k,\omega)/\partial\omega\right]_{\omega=\epsilon(k)}, \qquad \text{for } k>k_F \quad (7)$$

where $\widetilde{U}_1$ and $\widetilde{U}_2$ are the real parts of $\widetilde{M}_1$ and $\widetilde{M}_2$, respectively.

3 Results and discussion

In Fig. 1 we show the contributions from different partial wave channels to the nucleon momentum distribution in symmetric nuclear matter at three typical densities, ρ=0.17, 0.34 and 0.51 fm^{-3}. In the figure, the solid lines correspond to the total distributions; the dashed lines denotes the contribution from the isospin $T=0$ np channels; the dotted lines are the contribution from the isospin-triplet $T=1$ channels; and the dot-dashed lines indicate the contribution from the $T=0$ $^3SD_1$ tensor channel. The results of Fig. 1 are obtained by adopting purely the $AV18$ two-body interaction, and the TBF is not included. It is seen that the NN correlations may lead to a depletion of the nucleon hole states below the Fermi surface and a partial occupation of the particle states above the Fermi surface in the correlated ground state of nuclear matter. We notice that the depletion of the Fermi sea is mostly induced by the isospin $T=0$ np correlations. In Table 1, we report the predicted contributions from different channels to the depletion [i.e., $1-n(k=0)$] of the lowest momentum state in nuclear matter. From Table 1, at the lowest momentum (k=0), the T=0 channels contribute depletions of 11.5%, 10.8% and 10.2%, which amount to almost 81%, 73% and 67% respectively of the total depletions of 14.2%, 14.8% and 15.3% at ρ=0.17, 0.34 and 0.51 fm^{-3}, respectively. However, the contribution from the $T=1$ channels amounts to only about 19%, 27% and 33% of the total depletion for densities $\rho=0.17$, 0.34 and 0.51 fm^{-3}, respectively. It is worth noticing from Fig. 1 that the dashed (red) curves almost overlap with the corresponding dot-dashed (blue) curves, except for momenta around the Fermi momentum, indicating that the contribution of the $T=0$ np channel almost completely stems from the SD tensor correlations. Therefore, we may conclude that the depletion of the Fermi sea in symmetric nuclear matter is essentially dominated by the SD np tensor correlations.

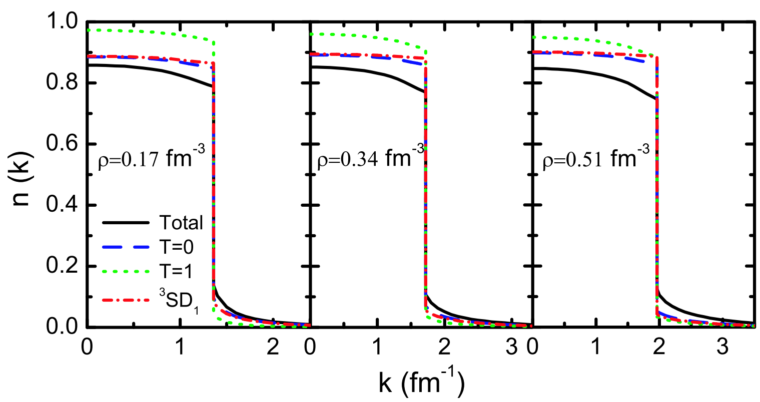

Fig. 1. (color online) Contributions from different partial wave channels to nucleon momentum distribution in symmetric nuclear matter at three typical densities.

Table 1. The calculated contributions from different channels to the depletion [i.e., $1-n(k=0)$] of the lowest hole state in nuclear matter. The results in this table have been obtained without including the TBF.

ρ/fm^{-3}	T=1	T=0	$^3SD_1$	total
0.17	0.027	0.115	0.113	0.142
0.34	0.040	0.108	0.105	0.148
0.51	0.051	0.102	0.099	0.153

To see the TBF effect, we show in Fig. 2 the same results as in Fig. 1 but obtained by adopting the $AV18$ two-body interaction plus the microscopic TBF. As already shown in Ref. [41], the TBF effect on the nucleon momentum distribution at relatively low densities around the empirical saturation density is negligibly small. However, the TBF effect becomes noticeable at high densities well above the saturation density and it has been shown to enhance the depletion of the nuclear Fermi sea [41]. The TBF-induced enhancement of the depletion turns out to be more pronounced at higher densities since the TBF is expected to induce stronger short-range correlations at higher densities. Table 2 gives the contributions from different channels to the depletion of the lowest momentum state predicted by including the TBF. By comparing Tables 1 and 2, inclusion of the TBF increases the depletion of the lowest hole state from 14.2%, 14.8% and 15.3% to 14.7%, 18.1% and 20.2% for $\rho=0.17$,0.34 and 0.51 fm^{-3}, respectively. Inclusion of the TBF does not alter the main conclusions obtained in the case without including the TBF, i.e., the depletion of the nuclear Fermi sea is dominated by the $T=0$ SD tensor correlations between neutron and proton. For the lowest momentum state, the $T=0$ channels contribute a 11.9%, 13.5% and 14.2% depletion, which amounts to almost 81%, 75% and 70% of the total depletion of 14.7%, 18.1% and 20.2% at $\rho=0.17$, 0.34 and 0.51 fm^{-3}, respectively. The isospin-singlet $T=0$ channels contain purely the np correlations since the nn and pp interactions vanish in the $T=0$ channels. However, the isospin-triplet $T=1$ channels consist of three T_z components, i.e., $T_z=-1$, 0 and 1, and consequently contain both np and nn (pp) correlations. If we neglect the small charge-breaking effect in the $AV18$ interaction, we may expect the nn, np, pn and pp correlations[1)] in the $T=1$ channels are approximately of the same strength. Accordingly, the nn, np, pn and pp correlations contribute equally to the depletion in the $T=1$ channels and each accounts for 25%. Finally, we conclude that about 90.5% (87.3%, 85.1%) of the total depletion of the lowest hole state stems from the np correlations, whereas only about 4.8% (6.3%, 7.5%) is induced by the nn or pp correlations for $\rho=0.17$ fm^{-3} (0.34, 0.51 fm^{-3}). In Ref. [23], the definite experimental evidence for the strong enhancement of the np short-range correlations over the pp and nn correlations observed at JLab has been reported. It is shown in Ref. [23] that 80% of the nucleons in the ^{12}C nucleus acted independently or as described within the shell model, whereas among the 20% of correlated pairs, 90±10% are in the form of pn short-range correlated (SRC) pairs; only 5±1.5% are in the form of pp SRC pairs and 5±1.5% in the nn SRC pairs. Our above results provide microscopic support for the experimental observation at Jlab.

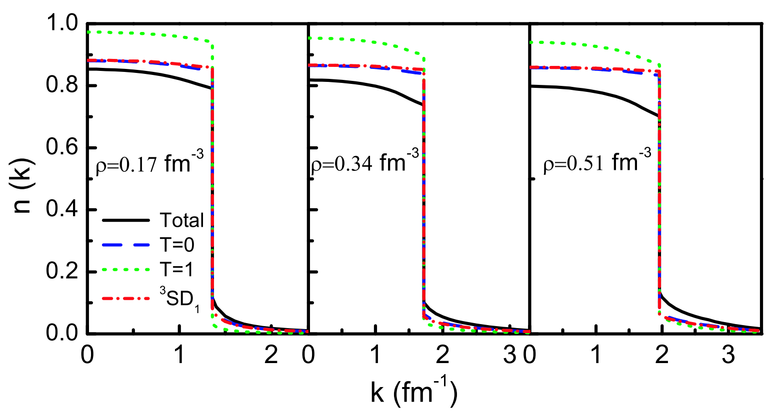

Fig. 2. (color online) Contributions from different partial wave channels to nucleon momentum distribution in symmetric nuclear matter at three typical densities, including the TBF.

1) We distinguish explicitly the notation np and pn only in this sentence and the following sentence simply for convenience of our discussion.

Table 2. The calculated contributions from different channels to the depletion [i.e., $1-n(k=0)$] of the lowest hole state in nuclear matter. The results have been obtained including the TBF.

ρ/fm^{-3}	T=1	T=0	$^3SD_1$	total
0.17	0.028	0.119	0.118	0.147
0.34	0.046	0.135	0.133	0.181
0.51	0.060	0.142	0.140	0.202

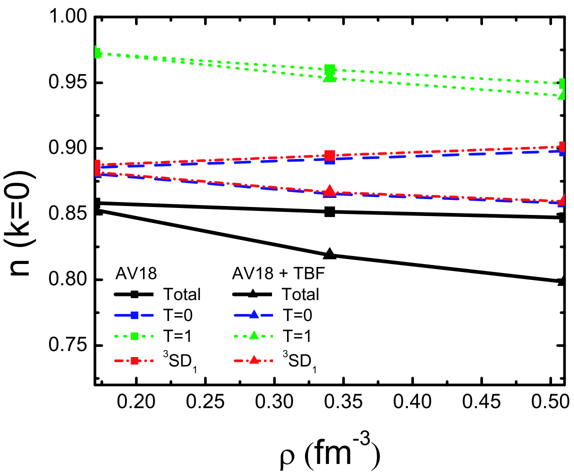

Fig. 3. (color online) The density dependence of the occupation probabilities of the lowest hole state predicted by considering the $T=0$, $T=1$, $^3SD_1$ channel correlations and the total correlations. The square symbols are obtained without the TBF; the triangles are calculated by including the TBF.

In Fig. 3, we display the predicted density dependence of the occupation probabilities of the lowest hole state in nuclear matter. It can be seen that without the TBF, the total depletion is almost independent of density in the region from 0.17 fm^{-3} to 0.51 fm^{-3}, in good agreement with the previous BHF result [34] and the prediction of Ref. [29], which used the Green Function theory. Without the TBF, the depletion due to the $T=1$ correlations increases and that caused by the $T=0$ correlations decreases slowly as the density increases. The TBF effect on the $T=1$ channel depletion is seen to be quite weak and it leads to a slight enhancement at high densities. Inclusion of the TBF considerably enhances the depletion induced by the $T=0$ correlations at high densities well above the saturation density. The TBF-induced enhancement of the total depletion and the $T=0$ channel depletion increases monotonically as a function of density. Again it is worth noticing that the $T=0$ np correlations play a predominant role in generating the depletion over the $T=1$ correlations in the whole density range considered here. The $T=0$ channel depletion turns out to be determined almost completely by the $^3SD_1$ tensor correlations.

4 Summary

In summary, we have investigated the effect of tensor correlations on the depletion of the nuclear Fermi sea in nuclear matter within the framework of the extended BHF approach by adopting the $AV18$ two-body interaction supplemented with a microscopic TBF. The contributions from various partial wave channels including the isospin-singlet $T=0$ channels, the isospin-triplet $T=1$ channels and the $T=0$ tensor $^3SD_1$ channel have been calculated and discussed. The main conclusions can be summarized as follows: (1) the $T=0$ neutron-proton correlations play a predominant role in generating the depletion of nuclear Fermi sea in symmetric nuclear matter over the $T=1$ correlations, which provides robust and microscopic support for the recent experimental observation at Jlab [23]; (2) the $T=0$ correlation-induced depletion stems almost completely from the $^3SD_1$ tensor channel; and (3) the TBF effect on the depletion is shown to increase monotonically as a function of density and it enhances sizably the total depletion and the depletion caused by the $T=0$ np correlations at high densities well above the saturation density.

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