DI-NEUTRON CORRELATIONS IN LOW-DENSITY NUCLEAR MATTER

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Based on the relativistic Hartree-Bogoliubov theory, the influence of the effective interactions in the particle-hole channel on the di-neutron correlations is studied in the nuclear matter. In addition, the evolution of several characteristic quantities of di-neutron correlations, namely, the normal and anomalous density distribution functions as well as the probability density of the neutron Cooper pairs, with the neutron Fermi momentum is discussed.

Keywords: Di-neutron correlation; Nuclear matter; BCS-BEC crossover.

Pairing correlations play a crucial role in the fermion systems. For the neutron-neutron pairing, the correlation is expected to be significant in low-density nuclear matter. It is well known that the bare neutron-neutron interaction in the $^1S_0$ channel leads to a virtual state around zero energy characterized by a large negative scattering length $a \approx -18.5 \pm 0.4$ fm,[1] implying a very strong attraction between two neutrons in the spin singlet state. Furthermore, theoretical predictions suggest that around 1/10 of the normal nuclear density ρ_0, the $^1S_0$ pairing gap may take a considerably larger value than that around ρ_0.[2] In the weakly bound neutron-rich nuclei, the di-neutron correlations are enhanced due to the couplings with the continuum and play an important role for unstable nucleus and the formation of the halo.[3] Recently, di-neutron emission in ^{16}Be was observed for the first time with a small emission angle between the two neutrons, indicating the structure of di-neutron clusters inside neutron-rich nuclei.[4]

The progress in both theoretical and experimental investigations on di-neutron correlations in weakly bound nuclei has stimulated lots of interests in searching for possible BCS-BEC crossover of neutron pairing.[5–7] It has been found that the di-neutron correlations get stronger as density decreases, and the BCS-BEC crossover of the neutron pairing could occur at low densities. The spatial structure of neutron Cooper pair wave function evolves from BCS-type to BEC-type as density decreases. In finite nuclei, the coexistence of BCS- and BEC-like spatial structures of neutron pairs has also been revealed in the halo nucleus ^{11}Li.[8] From the two-particle wave function, a strong di-neutron correlation between the valence neutrons appears on the surface of the nucleus.

As the relativistic mean-field (RMF) theory and its extension the relativistic Hartree-Bogoliubov (RHB) theory had achieved lots of success in the descriptions of both nuclear matter and finite nuclei near or far from the stability line,[3,9] the di-neutron correlations in the $^1S_0$ channel were studied within the RHB theory in nuclear matter in our recent works.[7,10] From the characteristic quantities, such as the effective chemical potential, the quasi-particle excitation spectrum and the density correlation function, there is no evidence for a true BEC state of neutron pairs at any density. From the coherence length and the probability distribution of neutron Cooper pairs as well as the ratio between the neutron pairing gap and the kinetic energy at the Fermi surface, some features of the BCS-BEC crossover are seen in the density regions with the neutron Fermi momentum, $0.05\ \text{fm}^{-1} < k_{\text{Fn}} < 0.7\ (0.75)\ \text{fm}^{-1}$, for the symmetric nuclear (pure neutron) matter.

In this proceeding, following the previous investigations,[7,10] the influence of the RMF effective interactions in the particle-hole (ph) channel on the di-neutron correlations will be discussed in the RHB theory for the nuclear matter, and the evolution of several characteristic quantities, namely, the normal and anomalous density distribution functions as well as the probability density of the neutron Cooper pairs, with the neutron Fermi momentum will be studied further.

In the RHB theory, meson fields are treated dynamically beyond the mean-field theory to provide the pairing field via the anomalous Green's functions. In the case of infinite nuclear matter, the Dirac-Hartree-Fock-Bogoliubov equation reduces to the usual BCS equation. For the $^1S_0$ channel, the pairing gap function $\Delta(p)$ is,

$$\Delta(p) = -\frac{1}{4\pi^2}\int_0^\infty v_{pp}(k,p)\frac{\Delta(k)}{2E_k}k^2dk, \tag{1}$$

where $v_{pp}(k,p)$ is the matrix elements of nucleon-nucleon interaction in the momentum space for the $^1S_0$ pairing channel, and E_k is the quasi-particle energy. The corresponding normal and anomalous density distribution functions have the form,

$$\rho_k = \frac{1}{2}\left[1 - \frac{\varepsilon_k - \mu}{E_k}\right], \quad \kappa_k = \frac{\Delta(k)}{2E_k}, \tag{2}$$

with the single-particle energy ε_k, and the chemical potential μ.

For nuclear matter with given baryonic density ρ_b and isospin asymmetry $\zeta = (\rho_n - \rho_p)/\rho_b$, the gap function can be solved by a self-consistent iteration method with no-sea approximation. In the following studies, Bonn-B potential[11] will be adopted for $v_{pp}(k,p)$.

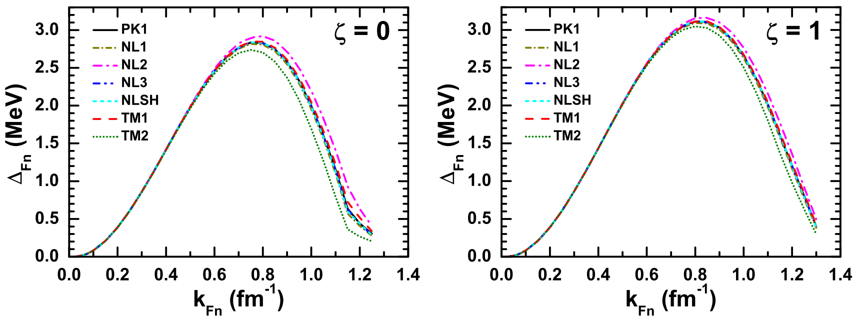

Fig. 1. Neutron pairing gap at the Fermi surface Δ_{Fn} as a function of the neutron Fermi momentum k_{Fn} for different RMF effective interactions in symmetric nuclear matter ($\zeta = 0$, left panel) and pure neutron matter ($\zeta = 1$, right panel).

One of most important properties of the pairing gap is its value at the Fermi surface. In Fig. 1, the neutron pairing gap at the Fermi surface, i.e., $\Delta_{\mathrm{Fn}} \equiv \Delta(k_{\mathrm{Fn}})$, is shown as a function of the neutron Fermi momentum k_{Fn} in symmetric nuclear matter ($\zeta = 0$) and pure neutron matter ($\zeta = 1$). Different nonlinear self-coupling effective interactions of the RMF theory are used in the *ph* channel.

It is found that the pairing gap Δ_{Fn} is strongly dependent on the nuclear matter density, or equivalently, the Fermi momentum. The pairing gap Δ_{Fn} increases with Fermi momentum (or density), reaches a maximum at a Fermi momentum of $k_{\mathrm{Fn}} \approx 0.8$ fm^{-1}, and then rapidly drops to zero. A systematical enhancement of Δ_{Fn} by about 0.3 MeV around $k_{\mathrm{Fn}} = 0.8$ fm^{-1} is revealed in pure neutron matter compared with those in symmetric nuclear matter.

In addition, it is seen in Fig. 1 that the influence of the selection of the RMF effective interaction on Δ_{Fn} is relatively small except two special versions NL2 and TM2 fitted for light nuclei. The divergence of Δ_{Fn} around

$k_{\rm Fn} = 0.8$ fm^{-1} due to the mean-field effects is about 0.2 MeV for symmetric nuclear matter and 0.1 MeV for pure neutron matter, and diminishes with decreasing Fermi momentum. As illustrated in a recent work,[10] the pairing strength required for appearance of a di-neutron BEC state in the low-density limit must be stronger than 1.1 times of Bonn-B potential, and the corresponding pairing gap $\Delta_{\rm Fn}$ is 4.12 MeV around $k_{\rm Fn} = 0.8$ fm^{-1}. Therefore, the conclusion that a true di-neutron BEC bound state does not occur at any density in nuclear matter[7] is still preserved although a various of RMF effective interactions are used in the *ph* channel. In the following, the discussion will be only related to the calculations using the effective interaction PK1, since the results do not depend sensitively on various other RMF effective interactions.

The normal and anomalous density distribution functions, ρ_k and κ_k, provide us valuable information on the mean field and the pairing field. In Fig. 2, neutron normal and anomalous density distribution functions are plotted as a function of $k/k_{\rm Fn}$ at several neutron Fermi momenta $k_{\rm Fn}$ in symmetric nuclear matter. When $k_{\rm Fn} = 1.2$ fm^{-1}, the normal density distribution function ρ_k is represented as a step function at $k/k_{\rm Fn} = 1.0$, and the neutron Cooper pair is interpreted as a BCS-like pair. As the Fermi momentum $k_{\rm Fn}$ decreases, the momentum distribution of ρ_k evolves smoothly and deviates from the step function gradually. After reaching a maximum deviation from the step function at $k_{\rm Fn} = 0.2$ fm^{-1}, the momentum distribution of ρ_k approaches to the step function again at dilute density. Thus, the evolution of ρ_k with Fermi momentum support the prediction again that the

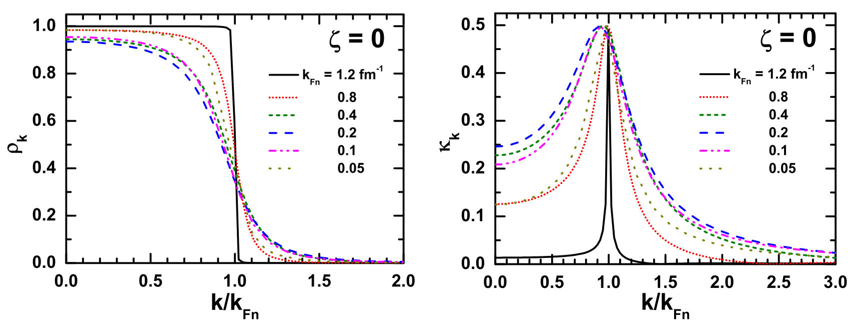

Fig. 2. Neutron normal and anomalous density distribution functions, ρ_k and κ_k, as a function of the ratio of the neutron momentum to the Fermi momentum $k/k_{\rm Fn}$ at several neutron Fermi momenta $k_{\rm Fn}$ in symmetric nuclear matter. The effective interaction PK1 is used for the mean-field calculation in the particle-hole (*ph*) channel.

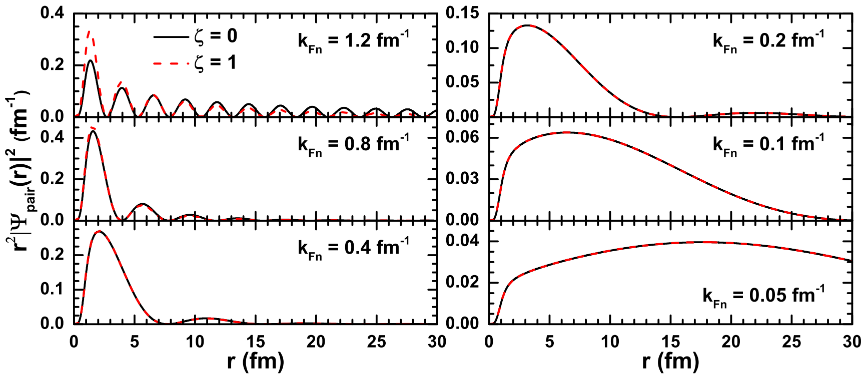

Fig. 3. Probability density $r^2|\Psi_{\rm pair}(r)|^2$ of the neutron Cooper pairs as a function of the relative distance r between the pair partners at several neutron Fermi momenta $k_{\rm Fn}$ in symmetric nuclear matter ($\zeta = 0$, black solid lines) and pure neutron matter ($\zeta = 1$, red dashed lines). The effective interaction PK1 is used for the mean-field calculation in the particle-hole (ph) channel.

most BEC-like state could appear at $k_{\rm Fn} \sim 0.2$ fm^{-1} by examining the density correlation function.[7] For the anomalous density distribution function κ_k, the evolved feature with $k_{\rm Fn}$ exhibits a BCS-BEC crossover as well,[12] namely, the pairing exists only on the Fermi surface at $k_{\rm Fn} = 1.2$ fm^{-1}, expand the momentum distribution to both lower and higher regions than the Fermi momentum as the density decreases until $k_{\rm Fn} = 0.2$ fm^{-1}, and then narrow again at dilute area.

To investigate the spatial structure of neutron Cooper pairs, it is useful to look into its wave function represented as a function of the relative distance $r = |\boldsymbol{r}_1 - \boldsymbol{r}_2|$ between the pair partners. The Cooper pair wave function in momentum space $\Psi_{\rm pair}(k)$ is just the anomalous density distribution function κ_k, and its coordinate representation is deduced from the Fourier transform,

$$\Psi_{\rm pair}(r) = \frac{C}{(2\pi)^3} \int \kappa_k e^{i\boldsymbol{k}\cdot\boldsymbol{r}} d\boldsymbol{k}, \tag{3}$$

where C is the constant determined from the normalization condition.

In Fig. 3, the probability density of the neutron Cooper pairs $r^2|\Psi_{\rm pair}(r)|^2$ multiplied by the volume element r^2 is shown as a function of the relative distance r between the pair partners at different neutron Fermi momenta $k_{\rm Fn}$. Nearly identical results are given for the symmetric nuclear matter ($\zeta = 0$) and pure neutron matter ($\zeta = 1$), except for $k_{\rm Fn} = 1.2$ fm^{-1}, where a larger amplitude of the first peak is obtained in pure neutron matter.

The radial shape of $r^2|\Psi_{\rm pair}(r)|^2$ changes as density decreases. When $k_{\rm Fn} = 1.2$ fm^{-1} and 0.8 fm^{-1}, the profile shows an oscillatory behavior convoluted by a decreasing exponent, which is a typical behavior of BCS state. A significant amplitude outside the first node is observed. As density goes down to $k_{\rm Fn} = 0.4$ fm^{-1} and 0.2 fm^{-1}, the wave function becomes compact in shape and the oscillation almost disappears, resembling the strong coupling BEC-like bound state. This indicates that a possible BCS-BEC crossover may occur in uniform matter at such low densities. At very dilute density of $k_{\rm Fn} = 0.1$ fm^{-1} and 0.05 fm^{-1}, the wave function becomes more extended again and approaches to zero slowly.

In summary, the influence of the RMF effective interactions in the *ph* channel on the di-neutron correlations is discussed in the nuclear matter in this proceeding. The conclusion that a true di-neutron BEC bound state does not occur at any density in nuclear matter[7] is still preserved for various RMF effective interactions. The evolution of several characteristic quantities of di-neutron correlations with the neutron Fermi momentum is studied further, which supports the prediction that the most BEC-like state could appear at $k_{\rm Fn} \sim 0.2$ fm^{-1} from the density correlation function.[7]

Acknowledgments

This work was partly supported by the Fundamental Research Funds for the Central Universities (Grant Nos. lzujbky-2012-k07 and lzujbky-2012-7).

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