CORRELATION FUNCTIONS IN BCS-BEC TRANSITION REGION OF NUCLEAR MATTER

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The density, spin and isospin correlation functions in nuclear matter with a neutron-proton (*np*) condensate are calculated to study the possible signatures of the BEC-BCS crossover in the low-density region. It is shown that the criterion of the crossover (Phys. Rev. Lett. 2005, v. 95, 090402), consisting in the change of the sign of the density correlation function at low momentum transfer, fails to describe correctly the density-driven BEC-BCS transition at finite isospin asymmetry or finite temperature. As an unambiguous signature of the BEC-BCS transition, there can be used the presence (BCS regime) or absence (BEC regime) of the singularity in the momentum distribution of the quasiparticle density of states.

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1. INTRODUCTION

The transition from BCS superconductivity to Bose-Einstein condensation (BEC) occurs in a Fermi system, if either density is decreased or the attractive interaction between fermions is increased sufficiently. This transition was studied, first, in excitonic semiconductors [1]. Later it was realized that an analogous phase transition takes place in symmetric nuclear matter, when *np* Cooper pairs at higher densities go over to Bose-Einstein condensate of deuterons at lower densities [2, 3]. During this transition the chemical potential changes its sign at certain critical density (Mott transition), approaching half of the deuteron binding energy at ultra low densities. In Ref. [3] crossover from *np* superfluidity to BEC of deuterons was investigated in the T-matrix approach, where the pole in the T-matrix determines the critical temperature of BEC of bound states in the case of negative chemical potential and the critical temperature of the appearance of *np* Cooper pairs in the case of positive chemical potential. The influence of isospin asymmetry on the BEC-BCS crossover in nuclear matter was studied in Ref. [4] within the BCS formalism. It has been shown that Bose-Einstein condensate is weakly affected by an additional gas of free neutrons even at very large asymmetries. The same conclusion was also confirmed in Ref. [5] on the base of the variational approach for the thermodynamic potential. The recent upsurge of interest to the BEC-BCS crossover is caused by finding the BCS pairing in ultracold trapped quantum atom gases [6]. In this study we examine the possible signatures of the BEC-BCS crossover in low-density nuclear matter. It may have interesting consequences, for example, in the far tails of the density profiles of exotic nuclei, where a deuteron condensate can exist in spite of the fact that the density there can be quite asymmetric. Besides, similar physical effects can play an important role in expanding nuclear matter, formed in heavy ion collisions, or in nuclear matter in the crust of a neutron star. The main emphasis is laid on the behavior of the density, spin and isospin correlation functions across the BEC-BCS transition region. The study is motivated by the results of Ref. [7], where the authors state that the density correlation function of a two-component ultracold fermionic gas of atoms changes sign at low momentum transfer and this represents an unambiguous signature of the BEC-BCS crossover. This statement is checked for nuclear matter taking into account additional factors: finite isospin asymmetry or finite temperature. In both cases, this criterion fails to provide a correct description of the density-driven BEC-BCS crossover and cannot serve as the universal feature of transition between two states of the system.

2. BASIC EQUATIONS

Superfluid states of nuclear matter are described by the normal f and anomalous g distribution functions of nucleons

$$f_{\kappa_1\kappa_2} = \mathrm{Tr}\,\rho a^+_{\kappa_2} a_{\kappa_1}, \qquad g_{\kappa_1\kappa_2} = \mathrm{Tr}\,\rho a_{\kappa_2} a_{\kappa_1}, \tag{1}$$

where $\kappa \equiv (\mathbf{k}, \sigma, \tau)$, $\mathbf{k}$ is momentum, $\sigma\,(\tau)$ is the projection of spin (isospin) on the third axis, ρ is the density matrix of the system. We shall study *np* pairing correlations in the pairing channel with total spin S and isospin T of a pair $S = 1,\ T = 0$ and the projections $S_z = T_z = 0$. In this case the distribution functions for isospin asymmetric nuclear matter have the structure

$$f(\mathbf{k}) = f_{00}(\mathbf{k})\sigma_0\tau_0 + f_{03}(\mathbf{k})\sigma_0\tau_3 \tag{2}$$

$$g(\mathbf{k}) = g_{30}(\mathbf{k})\sigma_3\sigma_2\tau_2,$$

where σ_i and τ_k are the Pauli matrices in spin and isospin spaces, respectively. Using the minimum principle of the thermodynamic potential and procedure of block diagonalization [5], one can obtain expressions for the distribution functions

$$f_{00}(\mathbf{k}) = \frac{1}{2} - \frac{\xi_k}{4E_k}\left(\tanh\frac{E^+_k}{2T} + \tanh\frac{E^-_k}{2T}\right), \tag{3}$$

$$f_{03}(\mathbf{k}) = \frac{1}{4}\left(\tanh\frac{E^+_k}{2T} - \tanh\frac{E^-_k}{2T}\right), \tag{4}$$

$$g_{30}(\mathbf{k}) = -\frac{\Delta(\mathbf{k})}{4E_k}\left(\tanh\frac{E_k^+}{2T} + \tanh\frac{E_k^-}{2T}\right). \quad (5)$$

Here

$$E_k^{\pm} = E_k \pm \delta\mu = \sqrt{\xi_k^2 + \Delta^2(\mathbf{k})} \pm \delta\mu\,,\ \xi_k = \frac{k^2}{2m} - \mu\,, \quad (6)$$

Δ being the energy gap in the quasiparticle excitation spectrum, m being the effective nucleon mass, μ and $\delta\mu$ being half of a sum and half of a difference of neutron and proton chemical potentials, respectively.

Equations, governing *np* pairing correlations in the $S = 1,\ T = 0$ pairing channel, can be obtained on the base of Green's function formalism and have the form [5]

$$\Delta(\mathbf{k}) = -\frac{1}{V}\sum_{\mathbf{k'}} V(\mathbf{k},\mathbf{k'})\frac{\Delta(\mathbf{k'})}{2E_{k'}}\left(1 - f(E_{k'}^+) - f(E_{k'}^-)\right), \quad (7)$$

$$\rho = \frac{2}{V}\sum_{\mathbf{k}}\left(1 - \frac{\xi_k}{E_k}\left[1 - f(E_k^+) - f(E_k^-)\right]\right) \equiv \frac{2}{V}\sum_{\mathbf{k}} n_k\,, \quad (8)$$

$$\alpha\rho = \frac{2}{V}\sum_{\mathbf{k}}\left(f(E_k^-) - f(E_k^+)\right), \quad (9)$$

where $f(E)$ is Fermi distribution function. Eq. (7) is equation for the energy gap Δ and Eqs. (8), (9) are equations for the total density $\rho = \rho_n + \rho_p$ and neutron excess $\delta\rho = \rho_n - \rho_p \equiv \alpha\rho$ (α being the asymmetry parameter). Introducing the anomalous density

$$\psi(\mathbf{k}) = \left\langle a_{n,k}^+ a_{p,-k}^+ \right\rangle = \frac{\Delta(\mathbf{k})}{2E_k}\left(1 - f(E_k^+) - f(E_k^-)\right)$$

and using Eq. (8), one can represent Eq. (7) for the energy gap in the form

$$\frac{k^2}{m}\psi(\mathbf{k}) + (1 - n_k)\sum_{\mathbf{k'}} V(\mathbf{k},\mathbf{k'})\psi(\mathbf{k'}) = 2\mu\psi(\mathbf{k})\,. \quad (10)$$

In the limit of vanishing density, $n_k \to 0$, Eq. (10) goes over into the Schroedinger equation for the deuteron bound state [2,4]. Corresponding energy eigenvalue is equal to 2μ. The change in the sign of the mean chemical potential μ of neutrons and protons under decreasing density of nuclear matter signals the transition from the regime of large overlapping *np* Cooper pairs to the regime of non-overlapping bound states (deuterons).

Let us consider the two-body density correlation function

$$\mathcal{D}(\mathbf{x},\mathbf{x'}) = \mathrm{Tr}\ \rho\Delta\hat{n}(\mathbf{x})\Delta\hat{n}(\mathbf{x'})\,,\ \Delta\hat{n}(\mathbf{x}) = \hat{n}(\mathbf{x}) - \hat{n}\,, \quad (11)$$

$$\hat{n}(\mathbf{x}) = \sum_{\sigma\tau}\psi_{\sigma\tau}^+(\mathbf{x})\psi_{\sigma\tau}(\mathbf{x})\,,$$

$\hat{n}$ being the spatial average of $\hat{n}(\mathbf{x})$. Its general structure in the spatially uniform and isotropic case reads [7]

$$\mathcal{D}(\mathbf{x},\mathbf{x'}) = \rho\delta(\mathbf{r}) + \rho D(r)\,,\quad \mathbf{r} = \mathbf{x} - \mathbf{x'}\,. \quad (12)$$

The function $D(r)$ is called the density correlation function as well. We will be just interested in the behavior of the function $D(r)$. After calculating the traces in Eq. (11), for its Fourier transform one can get

$$D(q) = I_g^{30}(q) - I_f^{00}(q) - I_f^{03}(q)\,, \quad (13)$$

where

$$I_f^{00}(q) = \frac{4}{\pi^3\rho}\int_0^\infty drr^2 j_0(rq)\left[\int_0^\infty dkk^2 f_{00}(k) j_0(rk)\right]^2,$$

$$I_f^{03}(q) = \frac{4}{\pi^3\rho}\int_0^\infty drr^2 j_0(rq)\left[\int_0^\infty dkk^2 f_{03}(k) j_0(rk)\right]^2,$$

$$I_g^{30}(q) = \frac{4}{\pi^3\rho}\int_0^\infty drr^2 j_0(rq)\left[\int_0^\infty dkk^2 g_{30}(k) j_0(rk)\right]^2.$$

Here j_0 is the spherical Bessel function of the first kind and zeroth order. The functions I_f^{00}, I_f^{03} and I_g^{30} represent the normal and anomalous contributions to the density correlation function. Analogously, we can consider the two-body spin $\mathcal{S}$ and isospin $\mathcal{T}$ correlation functions

$$\mathcal{S}_{\mu\nu}(\mathbf{x},\mathbf{x'}) = \mathrm{Tr}\ \rho\Delta\hat{s}_\mu(\mathbf{x})\Delta\hat{s}_\nu(\mathbf{x'})\,,\ \Delta\hat{s}_\mu(\mathbf{x}) = \hat{s}_\mu(\mathbf{x}) - \hat{s}_\mu\,,$$

$$\hat{s}_\mu(\mathbf{x}) = \frac{1}{2}\sum_{\sigma\sigma'\tau}\psi_{\sigma\tau}^+(\mathbf{x})(\sigma_\mu)_{\sigma\sigma'}\psi_{\sigma'\tau}(\mathbf{x})\,, \quad (14)$$

$$\mathcal{T}_{\mu\nu}(\mathbf{x},\mathbf{x'}) = \mathrm{Tr}\ \rho\Delta\hat{t}_\mu(\mathbf{x})\Delta\hat{t}_\nu(\mathbf{x'})\,,\ \Delta\hat{t}_\mu(\mathbf{x}) = \hat{t}_\mu(\mathbf{x}) - \hat{t}_\mu\,,$$

$$\hat{t}_\mu(\mathbf{x}) = \frac{1}{2}\sum_{\sigma\tau\tau'}\psi_{\sigma\tau}^+(\mathbf{x})(\tau_\mu)_{\tau\tau'}\psi_{\sigma\tau'}(\mathbf{x})\,, \quad (15)$$

$\hat{s}_\mu, \hat{t}_\mu$ being spatial averages of $\hat{s}_\mu(\mathbf{x}), \hat{t}_\mu(\mathbf{x})$, respectively. Their general structure for isospin asymmetric nuclear matter without spin polarization is

$$\mathcal{S}_{\mu\nu}(\mathbf{x},\mathbf{x'}) = \frac{\rho}{4}\delta_{\mu\nu}\delta(\mathbf{r}) + \rho S_{\mu\nu}(r)\,, \quad (16)$$

$$\mathcal{T}_{\mu\nu}(\mathbf{x},\mathbf{x'}) = \frac{\rho}{4}\delta_{\mu\nu}\delta(\mathbf{r}) + \frac{\alpha\rho}{4} i\varepsilon_{\mu\nu 3}\delta(\mathbf{r}) + \rho T_{\mu\nu}(r) \quad (17)$$

Then, calculating traces in Eqs. (14), (15), for the Fourier transforms of the spin and isospin correlation functions one can get

$$S_{\mu\nu}(q) = -\frac{1}{4}\{\delta_{\mu\nu}(I_f^{00}(q) + I_f^{03}(q)) + (\delta_{\mu\nu} - 2\delta_{3\mu}\delta_{3\nu})I_g^{30}(q)\}\,, \quad (18)$$

$$T_{\mu\nu}(q) = -\frac{1}{4}\{\delta_{\mu\nu}(I_f^{00}(q) + I_g^{30}(q)) - (\delta_{\mu\nu} - 2\delta_{3\mu}\delta_{3\nu})I_f^{03}(q)\}\,. \quad (19)$$

Note that if to put $\mu = \nu = 3$ in Eqs. (18), (19), one gets the longitudinal spin S^l and isospin T^l correlation functions, while setting $\mu,\nu = 1,2$ gives the transverse spin and isospin correlation functions

$$S_{\mu\nu}^t(q) = -\frac{\delta_{\mu\nu}}{4}(I_f^{00}(q) + I_f^{03}(q) + I_g^{30}(q)) \equiv \delta_{\mu\nu}S^t(q),$$
$$\mu,\nu = 1,2, \quad (20)$$

$$T^t_{\mu\nu}(q) = -\frac{\delta_{\mu\nu}}{4}(I^{00}_f(q) - I^{03}_f(q) + I^{30}_g(q)) \equiv \delta_{\mu\nu} T^t(q).$$

The following relationships between the correlation functions hold true

$$S^l(q) = \frac{D(q)}{4}, \qquad S^t(q) = T^l(q). \tag{21}$$

At zero temperature and zero momentum transfer, the correlation functions satisfy the sum rule

$$S^t(q=0) = T^l(q=0)$$
$$= -\frac{1}{2\pi^2\rho}\int dk k^2 (f^2_{00}(k) + f^2_{03}(k) + g^2_{30}(k)) = -\frac{1}{4}, \tag{22}$$

where the r.h.s. is independent of density and isospin asymmetry. Besides, the transverse isospin correlation function satisfies the relationship

$$T^t(q=0) = -\frac{1}{2\pi^2\rho}\int dk k^2 (f^2_{00}(k) - f^2_{03}(k) + g^2_{30}(k))$$
$$= -\frac{1-\alpha}{4}, \tag{23}$$

where the r.h.s. is independent of density.

3. CORRELATION FUNCTIONS IN NUCEAR MATTER WITH A *NP* CONDENSATE

Further for numerical calculations we shall use the effective zero range force [5], developed to reproduce the pairing gap in $S=1, T=0$ pairing channel with Paris NN potential:

$$V(\mathbf{r}_1, \mathbf{r}_2) = v_0 \left\{1 - \eta \left(\frac{\rho(\frac{\mathbf{r}_1+\mathbf{r}_2}{2})}{\rho_0}\right)^\gamma\right\} \delta(\mathbf{r}_1 - \mathbf{r}_2), \tag{24}$$

where $\rho_0 = 0.16\,\text{fm}^{-3}$ is the nuclear saturation density, $v_0 = -530\,\text{MeV}\cdot\text{fm}^3$, $\eta = 0$, $m = m_G$, m_G being the the effective mass, corresponding to the Gogny force D1S. Besides, in the gap equation (7), Eq. (24) must be supplemented with a cut-off parameter, $\varepsilon_c = 60\,\text{MeV}$.

To find the correlation functions one should first solve the gap equation (7) self-consistently with Eqs. (8), (9). Then the correlation functions can be determined directly from Eqs. (13), (18) and (19). The results of numerical determination of the energy gap as a function of density for different asymmetries at zero temperature are shown in Fig. 1.

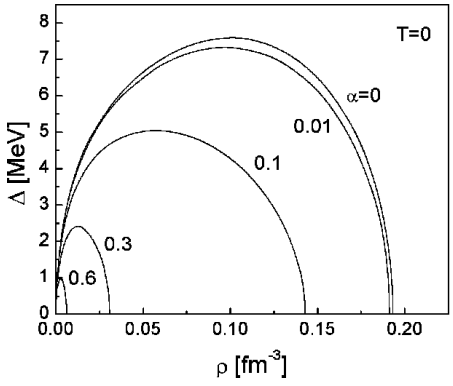

Fig. 1. *Energy gap as a function of density at zero temperature and different asymmetries*

As one can see, with increasing asymmetry the magnitude of the energy gap is decreased and the density interval, where a *np* condensate exists, shrinks to lower density. In reality solutions exist for any $\alpha < 1$ (the phase curves for larger values of α are not shown in Fig. 1) and correspond to the formation of BEC of deuterons at very low densities of nuclear matter.

Now we consider the correlation functions $D(q)$ and $S^t(q)$ for symmetric nuclear matter at zero temperature, depicted in Fig. 2 (at $\alpha = 0$, $T^t(q) = S^t(q)$)).

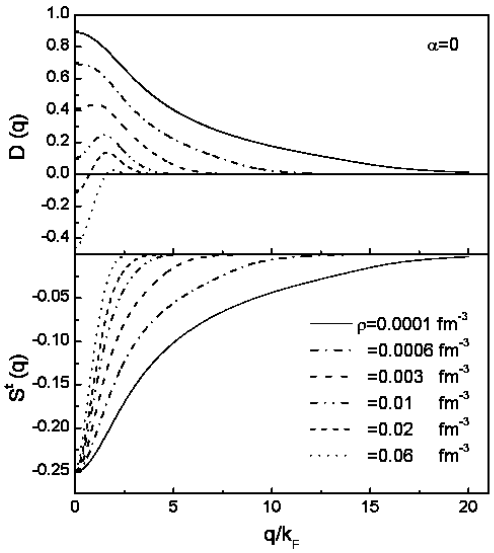

Fig. 2. *Density and transverse spin correlation functions as functions of momentum at zero temperature and different densities for symmetric nuclear matter*

The density correlation function changes sign at low momentum transfer when the system smoothly evolves from the BEC regime to the BCS one. These two regimes are distinguished by negative and positive values of the chemical potential μ, respectively. In view of Eq. (21), the longitudinal spin correlation function $S^l(q)$ changes sign through the BEC-BCS crossover as well. The transverse spin correlation function, and, according to Eq. (21), the longitudinal and transverse isospin correlation functions change fluently between BEC and BCS limits. The behavior of the density correlation function in isospin symmetric case at zero temperature qualitatively agrees with the behavior of the density correlation function in an ultracold fermionic atom gas with singlet pairing of fermions [7]. In Ref. [7] the change in the sign of the density correlation function at low momentum transfer was considered as a signature of the BEC-BCS crossover. We would like to extend their calculations taking into account the finite isospin asymmetry and finite temperature.

Fig. 3 shows the dependence of the density correlation function $D(q=0)$ at zero momentum transfer as a function of density for a set of various isospin asymmetry parameters and zero temperature. It is seen that with increasing the asymmetry parameter the density correlation function decreases. For strong enough asymmetry,

the function $D(q=0)$ is always negative. In accordance with the above criterion, the density region, where the function $D(q=0)$ has positive or negative values, would correspond to the BEC or BCS regime, respectively.

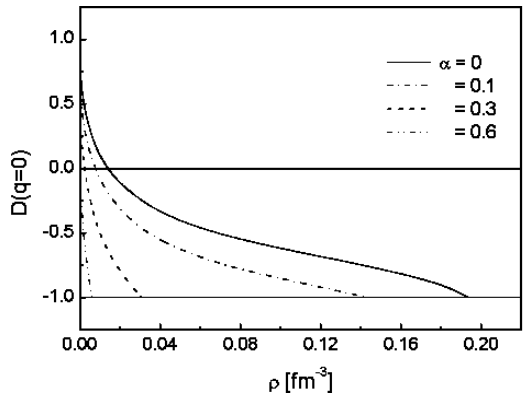

Fig. 3. *Density correlation function $D(q=0)$ as a function of density at zero temperature for different isospin asymmetry parameters*

Hence, as follows from Fig. 3, for strong isospin asymmetry we would have only the BCS state for all densities where a *np* condensate exists. Obviously, this conclusion contradicts with the behavior of the mean chemical potential μ being negative at very low densities for any $\alpha < 1$, and, hence, giving evidence to the formation of BEC of bound states [5]. Thus, at strong enough isospin asymmetry the criterion of the crossover, based on the change of the sign of the density correlation function, fails to predict the transition to the BEC of deuterons in low-density nuclear matter.

Now we consider symmetric nuclear matter at finite temperature. Fig. 4 shows the dependence of the density correlation function $D(q=0)$ at zero momentum transfer as a function of density for a set of various temperatures. It is seen that for not too high temperatures the density response function is nonmonotonic and twice changes sign in the region of low densities.

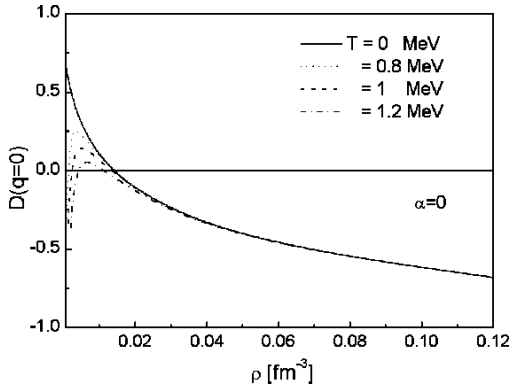

Fig. 4. *Density correlation function $D(q=0)$ as a function of density at different temperatures for symmetric nuclear matter*

Hence, in accordance with the above criterion, we would have the density interval $\rho_1 < \rho < \rho_2$ with the BEC state, surrounded by the density regions with the BCS state. However, this conclusion contradicts with the behavior of the mean chemical potential μ for these temperatures, being a monotone function of density and indicating the formation of a BEC state at low densities ($\mu < 0$) and a BCS state at larger densities ($\mu > 0$). Thus, at finite temperature the criterion of the crossover, formulated in Ref. [7], fails to provide the correct description of the transition between two regimes.

Qualitatively the boundary between BEC and BCS states corresponds to the point, where the chemical potential changes its sign. According to Eq. (6), at this point there is a qualitative change in the quasiparticle excitation spectrum: the momentum corresponding to the minimum in the excitation spectrum shifts from a finite value in the BCS state to the zero value in the BEC state. The appearance of the minimum in the quasiparticle excitation spectrum is clearly reflected in the quasiparticle density of states

$$\nu(k) = \frac{1}{\pi^2} \frac{k^2}{\left| \frac{dE_k}{dk} \right|}.$$

The density of states $\nu(k)$ is singular in the stationary points of the excitation spectrum ($\frac{dE_k}{dk} = 0$), except the point $k = 0$, where $\nu(k)$ vanishes, assuming that $\frac{dE_k}{dk}$ goes to zero no faster than k^2. Thus, the appearance of the singularity in the momentum distribution of the quasiparticle density of states represents the universal signature of the BEC-BCS transition (see also Ref. [8]).

4. DISCUSSION AND CONCLUSIONS

The transition from large overlapping Cooper pairs to tightly bound pairs of fermions can be described entirely within the mean-field approximation (BCS theory). An important question appears: to what extent can the BCS theory be trusted and what is the role of the beyond mean-field effects? In order to give a correct answer, it is necessary to compare calculations, based on the BCS theory, with the results of more exact schemes. The value of μ/ε_F for $\eta \equiv (a_s k_F)^{-1} = 0$ (a_s being the s-wave scattering length) is usually referred to as the "unitary limit". In this limit, when the density is held fixed, one expects that all sensitivity to the detailed features of the interaction is lost. As a result, this limit is particularly sensitive to many-body correlation effects, and the BCS calculations, based on the single-parameter potential, predict this value as being equal to 0.59 in the isospin symmetric case and at zero temperature [8]. Recent more accurate calculations based on the Green's function Monte Carlo approach [9] have lowered the upper limit on this ratio to 0.44 ± 0.01, which shows that beyond mean-field effects account for at least a 25% improvement in the binding energy over the mean-field result. Thus, the consideration based on the BCS theory, gives a qualitatively correct picture of the BEC-BCS transition, but further work is needed in or-

der to include many-body effects in a quantitative way and to study the changes in the features of the BEC-BCS crossover.

In summary, we have calculated the density, spin and isospin correlation functions in superfluid nuclear matter with *np* pairing correlations, intending to find the possible signatures of the BEC-BCS crossover. It is shown that the transverse spin, and longitudinal and transverse isospin correlation functions satisfy the sum rule at zero momentum transfer and zero temperature, and change smoothly between BEC and BCS regimes. In Ref. [7], it was learned that the density correlation function in a two-component ultracold fermionic atom gas with singlet pairing of fermions changes sign at low momentum transfer across the BEC-BCS transition, driven by a change in the scattering length of the interaction at zero temperature. We have shown that for spin triplet pairing the longitudinal spin correlation function plays an analogous role to the density correlation function and changes sign at low momentum transfer across the crossover in symmetric nuclear matter at zero temperature. However, while giving a satisfactory description of the density-driven BEC-BCS crossover in dilute nuclear matter at zero temperature for the isospin symmetric case, this criterion fails to provide the correct description of the crossover at finite isospin asymmetry or finite temperature. Hence, the criterion in Ref. [7] cannot be considered as the universal indication of the BEC-BCS transition. During the Mott transition, when the chemical potential changes sign, there is a qualitative change in the quasiparticle energy spectrum: the minimum shifts from a finite (BCS state) to zero-momentum value (BEC state). As such, the presence (BCS) or absence (BEC) of the singularity in the momentum distribution of the quasiparticle density of states represents the universal signature of the BEC-BCS transition.

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КОРРЕЛЯЦИОННЫЕ ФУНКЦИИ В ОБЛАСТИ БКШ-БЭК-ПЕРЕХОДА В ЯДЕРНОЙ МАТЕРИИ

А.А. Исаев

Получены корреляционные функции по плотности, спину и изоспину в ядерной материи с нейтрон-протонным конденсатом с целью изучения возможных признаков БКШ-БЭК-перехода в области малых плотностей. Показано, что критерий перехода (Phys. Rev. Lett. 2005, v. 95, 090402), состоящий в изменении знака корреляционной функции по плотности при малых переданных импульсах, является неадекватным для описания БКШ-БЭК-перехода при конечной асимметрии или температуре. Соответствующим однозначным критерием является наличие (БКШ) или отсутствие (БЭК) особенности в импульсном распределении плотности состояний квазичастиц.

КОРЕЛЯЦІЙНІ ФУНКЦІЇ В ОБЛАСТІ БКШ-БЕК-ПЕРЕХОДУ ЯДЕРНОЇ МАТЕРІЇ

О.О. Ісаєв

Знайдені кореляційні функції за щільністю, спіном та ізоспіном в ядерній матерії з нейтрон-протонним конденсатом з метою вивчення можливих ознак БКШ-БЕК-переходу в області низьких густин. Показано, що критерій переходу (Phys. Rev. Lett. 2005, v. 95, 090402), який полягає у зміні знака кореляційної функції за щільністю при малих переданих імпульсах, є неадекватним для опису БКШ-БЕК-переходу при скінченої асиметрії або температурі. Відповідним однозначним критерієм є наявність (БКШ) або відсутність (БЕК) особливості в імпульсному розподілі щільності станів квазічастинок.