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A THEORETICAL STUDY STRUCTURE FACTOR FOR THE S-WAVE AND D-WAVE PAIRINGS IN IMBLANCED D-WAVE SUPER FLUIDS IN BCS-BEC CROSSOVER REGIME AT FINITE TEMPERATURE

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Abstract: Using the theoretical formalism of **J. Tempere etal.(Phys. Rev.B72, 2008),** we have studied the imbalanced d-wave super fluids in the BCS-BEC cross over regime at finite temperature. We have theoretically evaluated excitation energy of gas of interacting fermions and the structure factor S (**q**, ω) for s-wave and d-wave scattering keeping scattering potential parameter k_0 and $k_1$fixed. Our theoretically evaluated results are in good agreement with the experimental data and also with other theoretical workers.

Keywords: Imbalanced d-wave super fluids, BCS-BEC crossover regime, Flude-Ferrel-Larkin-Ovchinnikov state, hyperfine spin state, Grassmann variables, Action functional. Polarized excitations, BCS super fluidity, strongly bound molecules, Unitarity limit, negative scattering length.

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INTRODUCTION

The subject of super fluidity in ultra cold trapped fermionic gases is an exciting field[1-5]of condensed matter physics including high-temperature superconductors. There are two important aspects which are particularly notable about these systems. They can be tuned to various ways which are not available to nature made superconductors. One can study the entire regime from BCS (Bardeen-Cooper-Schrieffer) to BEC (Bose-Einstein condensation), simply by the application of magnetic field in context with Feshbach resonance. Moreover, one can vary the concentrations of the two-spin species arbitrarily[6-9] in a fashion, this simulates the application of magnetic Zeeman fields. The latter tenability has important implications in other branches of physics such as dense QCD and nuclear matter[10-12]. The important fact is that there is a rich collection of experimental data from two different atomic groups[13-15] on ^{6}Li gases near unitarity. One can compare various theoretical results from this.

Eagles[16] and Leggett[17] observed that BCS-like wave function has much greater generality than was originally recognized at the time of its proposal. It is capable of describing both BCS and BEC like systems, providing the pairing attraction is tunable from arbitrarily weak (BCS) to arbitrarily strong (BEC). Generally, BCS is a weak state of bound Cooper pairs and BEC is a state of tightly bound molecules. From this, one has to solve self-consistently the fermionic chemical potential. This mean-field like ground state wave function can be generalized to include population balance. There are at least three well studied phases[18-20] .These have been proposed to accommodate difference in the population of the two spin species.

Generally in a mixture of two hyperfine spin states of a fermionic elements ,the amount of each hyperfine spin component can be controlled experimentally. This allows one to study the effect of population imbalance between spin components on pairing[21,22].

Clogston[23] performed the first theoretical study of Cooper pairing in an imbalanced Fermi mixture in the context of BCS superconductivity. He showed that a population imbalance destroys the superconductivity. This takes when the imbalance in chemical potentials is of the same order as the balanced order parameter. Experiments confirm that imbalance frustrates the pairing and reveal that the excess spin component is expelled out from the super fulid. A new pairing scenario has been proposed in the name of 'Fulde-Farrel-Larkin-Ovchinmikov scenerio[24]. In this scenario, the Fermi spheres of the two components spontaneously deform, leading to Cooper pairs with nonzero center-of-mass momentum. When the temperature is raised and excitations are populated, the superconductivity may be restored by creating a balanced pair condensate with an imbalanced gas of excitations. This may lead to reentrant

superconductivity proposed by Sarma[19]. In the Sarma state, the excess spin component is expelled from super fluid, not in position space, but in energy space. In Sarma state, the imbalanced Fermi gas with d-wave order parameter is very interesting. Since d-wave scattering length can be tuned through the Feshbach mechanism[25], one can investigate the d-wave super fluidity both in BEC and BCS regimes. The case of the d-wave pairing in the BEC/BCS crossover is interesting in view of high- temperature superconductivity[26] where the order parameter is found to exhibit d-wave symmetry[27].

In this paper, taking the theoretical formalism of J. Tempere etal[28], we have studied the imbalanced d-wave super fluids in the BCS-BEC crossover regime at finite temperature. We have evaluated excitation energy of gas of fermions and structure factor S(**q**,ω) for s-wave and d-wave scattering. We have kept different values of inverse d-wave scatteing length $1/a_d$ at $T=T_C$and potential parameters k_0 and k_1 =10 fixed with cosθ =1/2 in this calculation. We have also evaluated structure factor S(**q**,ω) for s-wave scattering keeping $1/a_s$=1.0 and T_C=9,218T_F, and for d-wave scattering keeping $1/a_d$ =0.1 and T_C=0.207T_F respectively. Our theoretically evaluated results are in good agreement with the experimental data[29] and also with other theoretical workers[30-32].

MATERIALS AND METHODS

One starts by writing down the Partition function of the interacting Fermi gas as a path integral over Grassman variables

$$Z \propto \int D\overline{\psi_{k,n,\sigma}} D\psi_{k,n,\sigma} Exp(-S) \qquad (1)$$

Here $\overline{\psi_{k,n,\sigma}}, \psi_{k,n,\sigma}$ are Grassman fields that depend on the wave number **K** and the fermionic Matsubara frequency ω_n =nπ/β with n an odd integer and β=$(K_\beta)^{-1}$. Two different hyperfine states are trapped so that one includes a spin quantum number б in the description. One denotes the two states as spin up $\sigma = \uparrow and spin down \sigma = \downarrow$. The action function S= S_0+S_I. S_0 is the non-interacting part and S_I is the interaction part. S_0 is defined as

$$S_0 = \Sigma_{k,n}\Sigma_\sigma(-i\omega_n + k^2 - \mu_\sigma)\overline{\psi_{k,n,\sigma}}\psi_{k,n,\sigma} \qquad (2)$$

where μ_6 is the chemical potential which fixes the amount of atoms of species б. The summation runs over all possible indices of the Grassman variables. One uses units such that

$\hbar = k_F = 2m_f = 1$. Here m_f is the mass of fermionic atom and k_F is the Fermi wave vector of the non-interacting balanced Fermi gas with same total particle density. Here one uses average chemical potential $\mu = (\mu\uparrow + \mu\downarrow)/2$ along with differences in chemical potentials and $\zeta = (\mu\uparrow - \mu\downarrow)/2$ is the chemical potential of the individual species. The interaction terms of the action functional are written in a form that emphasizes the pairs of colliding fermions.

$$S_I = \sum_{q,m} \sum_{k,n} \sum_{k',n'} V_{pp}(k,k') \overline{\psi_{\frac{q}{2}+k,\frac{m}{2}+n\uparrow}} \overline{\psi_{\frac{q}{2}-k,\frac{m}{2}-n\downarrow}} \psi_{\frac{q}{2}-k',\frac{m}{2}-n'\downarrow} \psi_{\frac{q}{2}+k',\frac{m}{2}+n'\uparrow} \quad (3)$$

where V_{pp} is the interaction potential. The wave numbers in the collision terms are written as sum of a center-of mass wave number **q** and the relative wave numbers **k, k'** before and after collisions. The Matsubara frequencies are decomposed in a center-of mass bosonic frequency $\Omega_m = \frac{2\pi m}{\beta}$ and relative fermion frequency $\omega_n, \omega_{n'}$. Here one considers only interactions that couple fermions from different hyperfine spin states. Now, one assumes that the interatomic potential can be factorized as

$$V_{pp}(k,K') = g\Gamma(k)\Gamma(k') \quad (4)$$

For s-wave pairing

$$g = g_s = \Gamma_s(k) = 1 \quad (5)$$

For d-wave pairing

$$g = g_d = \Gamma_d(k) = \frac{(\frac{k}{k_1})^2}{(1+\frac{k}{k_0})^{\frac{5}{2}}} \sqrt{\frac{28\pi}{15}} Y_{2,0}(\theta,\phi) \quad (6)$$

Here $Y_{2,0}(\theta,\phi)$ is Spherical harmonics. K_1, $k_2$parameters fixing the range of the potential. The constant g<0 (g>0) corresponds to attraction (repulsion). These constants are related to the s-wave and d-wave scattering length. Now, for given temperature T, density n and density imbalance δn, one solves the gap and number equations numerically and determine Δ, μ and ξ.

The critical temperature can be found as the temperature where Δ vanishes. The gap equation is determined by S_{sp} alone through

$$\frac{\delta S_{sp}}{\delta \Delta} = 0 \qquad (7)$$

Where S_{sp} is the saddle point action

$$S_{sp} = -\Sigma_{k,n} \ln[(i\omega_n - \xi - E_k)(-i\omega_n + \xi - E_k)] - \frac{\beta V}{g}\Delta^{\square}\Delta \qquad (8)$$

Where $\Delta_{q,m}$ and $\Delta_{q,m}$ auxiliary fields of bosons and characterized by the center-of –mass pair wave number. The gap equation is written in an unified form for the s-wave and d-wave pairings.

$$\int \frac{dk}{(2\pi)^3}|\Gamma(k)|^2 [\frac{\sinh \beta E_k}{2E_k(\cosh \beta E_k + \cosh \beta \xi)} - \frac{1}{2k^2}] + \lambda(a) = 0 \qquad (9)$$

Where $$E_k = \sqrt{(k^2 - \mu^2)^2 + |\Gamma(k)\Delta|^2} \qquad (10)$$

E_K is Bogoliubov energy. λ(a) is the parameter which describes the coupling strength for s-wave and d-wave pairings.

$$\Lambda_s(a_s) = 1/8\pi a_s \quad , \quad \lambda_d(a_d) = 2/\pi\lambda_d^5 \qquad (11)$$

The number equations are determined from the thermodynamic potential through the following equations

$$(\frac{\partial F}{\partial \mu})_{T,V,\Delta} = -n \qquad 12(a)$$

$$(\frac{\partial F}{\partial \xi})_{T,V,\Delta} = -\delta n \qquad 12(b)$$

Where n= $n\uparrow + n\downarrow$ is the total local density and $\delta n = n\uparrow - n\downarrow$ is the local population imbalance. For a finite temperature below T_C the chemical potential μ, ξ and the gap equation Δ

are determined self-consistently as the solutions of gap equation (9) coupled with the number equations 12(a) and 12 (b). In principle, one can write the exact thermodynamic potential

$$F=F_{sp}+F_{fl}+F_{other} \qquad (13)$$

Where F_{sp}, F_{fl} are given by

$$\frac{F_{sp}}{V}=-\int\frac{dk}{(2\pi)^3}[\frac{1}{\beta}\ln(2\cosh\beta\xi+2\cosh\beta E_k)-\xi_k]-\frac{1}{g}|\Delta|^2 \qquad (14)$$

And

$$\frac{F_{fl}}{\beta V}=\frac{1}{2}\int\frac{dq}{(2\pi)^3}\Sigma_m[|M_{1,1}(q,i\Omega_m)|^2-|M_{1,2}(q,i\Omega_m|^2] \qquad (15)$$

And F_{other} comes from the contributions of all higher order terms $O(F^3)$ in the exact action. $M_{1,1}(q,i\Omega_n)$ is the matrix element of the functional integral taken over Matsubara frequency and center-of mass wave numbers. The saddle point is not as the q=0 state but with a state having finite wave number. This wave number is equal to the difference of wave numbers of each component. The local density and local population imbalance can be written as sum of several contributions:

$$n=n_{sp}+n_{fl}+n_{other} \qquad 16(a)$$

$$\delta n=\delta n_{sp}+\delta n_{fl}+\delta n_{other} \qquad 16(b)$$

Where n_{sp} and δn_{sp} are the saddle-point results, n_{fl} and δ_{fl} are the fluctuation contributions and n_{other} and δ_{other} are higher orders fluctuation contributions to the density and population imbalance which are neglected in the present calculations. The saddle-pint contributions to the density and population imbalance are obtained using saddle-point term of the thermodynamic potential (15) and equation (12) by the following equations:

$$n_{sp}=\frac{1}{2\pi^2}\int_0^\infty k^2dk[1-\frac{\varepsilon_k}{E_k}\frac{\sinh(\beta E_k)}{\cosh(\beta\xi)+\cosh(\beta E_k)}] \qquad 17(a)$$

$$\delta n_{sp} = \frac{1}{2\pi^2}\int_0^\infty k^2 dk[\frac{\sinh(\beta\xi)}{\cosh(\beta\xi)+\cosh(\beta E_k)}] \qquad 17(b)$$

The fluctuation contribution to the number equation is determined on the basis of the fluctuation contribution to the thermodynamic potential and is given by

$$n_{fl} = -\int \frac{dq}{(2\pi)^3}[\frac{1}{\pi}\int_{-\infty}^{\infty} \mathrm{Im}\{\frac{J(q,\omega+i\gamma)}{e^{\beta(\omega+i\gamma)}-1}\}d\omega + \frac{1}{\beta}\sum_{n=-n_0}^{n_0} J(q,i\Omega_n) \qquad 18(a)$$

$$\delta n_{fl} = -\int \frac{dq}{(2\pi)^3}[\frac{1}{\pi}\int_{-\infty}^{\infty} \mathrm{Im}\{\frac{K(q,\omega+i\gamma)}{e^{\beta(\omega+i\gamma)}-1}\}d\omega + \frac{1}{\beta}\sum_{n=-n_0}^{n_0} K(q,i\Omega_n) \qquad 18(b)$$

Where the functions J (q,z) and K(q,z) for complex argument z are given by

$$J(q,z) = \frac{1}{\Gamma(q,z)}[M_{1,1}(q,-z)\frac{\partial M_{1,1}(q,z)}{\partial\mu} - M_{1,2}(q,-z)\frac{\partial M_{1,2}(q,z)}{\partial\mu}] \qquad 19(a)$$

$$K(q,z) = \frac{1}{\Gamma(q,z)}[M_{1,1}(q,-z)\frac{\partial M_{1,1}(q,z)}{\partial\xi} - M_{1,2}(q,-z)\frac{\partial M_{1,2}(q,z)}{\partial\xi}] \qquad 19(b)$$

Where

$$\Gamma(q,z) = M_{1,1}(q,z)M_{1,1}(q,-z) - M_{1,2}(q,z)M_{1,2}(q,-z) \qquad (20)$$

The functions $M_{1,1}(q,z)$ and $M_{1,2}(q,z)$ of the complex argument z are analytical in the complex z plane except for the branching line which lies at the real axis z=ω. In equation 19(a) and 19(b) the number n_0 is arbitrarily chosen and the parameter γ lies in the range of $\Omega_{n_0} < \gamma < \Omega_{n_{0+1}}$.

In particular, if one chooses n_0=0 then the above formulae leads to the expression for the fluctuation contribution to the fermion density similar to that derived in ref13.

$$n_{fl} = \frac{1}{\pi}\int \frac{dq}{(2\pi)^3 q^2}\int_{-\infty}^{\infty} d\omega S(q,\omega) \qquad (21)$$

Where S(**q,**ω**)** is the structure factor and is given by

$$S(q,\omega) = -\frac{q^2\,\mathrm{Im}[J(q,\omega+i\delta)]}{e^{\beta\omega}-1}, \delta \to 0^+ \qquad (22)$$

The results obtained in the present section extend the path integral approach to the case of d-wave pairing and of an imblanced Fermi gas at arbitratry temperatures. The function Q(q,ώ) can also be written as

$$Q(q,\omega) = \lim \delta \to 0^+ \{\mathrm{Im}[J(q,\omega+i\delta)]\} \qquad (23)$$

Furthermore, Q(q,ώ) changes its sign as ώ passes through ώ=0. This is necessary to ensure that the relative contribution to the fluctuation density from excitation with given (**q**,ω) remain positive. This contribution is proportional to S(**q,**ω**)**.

Results and Discussion

In this paper, we have theoretically studied excitation energy of gas of interacting fermions and structure factor S(**q,**ω**)** for s-wave and d-wave pairings in imblanced d-wave super fluids in BCS-BEC crossover regime at finite temperature. The entire evaluation has been performed by taking theoretical formalism of J. Tempere etal[28]. In table T1, we have shown the evaluated results of excitation energy of gas of interacting fermions in (**q**,ω) space for d-wave scattering keeping $1/a_d$=-0.17 at T= T_C and potential parameters k_0 and k_1=10 fixed with cosθ=1/2. a_d is d-wave scattering length. We have evaluated ω and $\Omega_b(q)$ where $\Omega_b(q)$ is pole of the structure factor S(**q,**ω**).** Our theoretical results indicate that as q increases both ω and $\Omega_b(q)$ increases very sharply. In table T2, we repeated the calculation by taking the value of inverse scattering length $1/a_d$=-0.12 and keeping other values same as that of table T1. In this case also, we observed that as q increases both ω and $\Omega_b(q)$ increases but increase is not so fast as seen in tableT1. In table T3, we again repeated the calculation taking $1/a_d$=0 which is called unitarity limit keeping other parameters same as that of table T1. In this case , we observed that for lower value of q (q<5) the increase of both ω and $\Omega_b(q)$ is slower but for q (q>5) increase is faster. In table T4, we repeated the calculation for positive value of inverse scattering length $1/a_d$ =0.2 keeping other parameters same as that of table T1. This is the non-damped case ($1/a_d$>0). In this case also, the values of both ω and $\Omega_b(q)$ are larger than the values obtained in table T3 for each value of q.

From these calculations, it appears that the lower bound value of $\omega_0(q) = \frac{q^2}{2} - 2\mu$ for the continuum of free two-particle excitations coincides with $\Omega_b(q)$ at$1/a_d=0$. In the case of d-wave scattering the value of $1/a_d=0$ is the boundary between the regime of the BCS-pairing ($1/a_d<0$) and BEC-pairing ($1/a_d>0$). In table T5 and T6, we have shown the evaluated results of structure factor S(**q,**ω**)** for s-wave scattering keeping $1/a_s=1.0$ and $T_C=0.218T_F$ and for d-wave scattering keeping $1/a_d=0.1$ and $T_C=0.207T_F$. Structure factors were evaluated in strong coupling limit. Because the scattering potential for the d-wave scattering is angle-dependent and structure factor S(**q,**ω**)** depends on three variables. S(**q,**ω**) =**S(q,cosθ,ω). S(**q,**ω**)** is avareged over the directions

$$S(\mathbf{q},\omega) = \frac{1}{2}\int_0^{\pi} S(q,\omega)\sin\theta d\theta \qquad (24)$$

From evaluated theoretical results shown in table T5 and T6, it appears that in the strong coupling case (on the BEC side of the resonance) where there is non-damped isolated pole in the structure factor. Structure factor in the strong coupling regime contains δ-like peak which lies outside the continuum of free pair excitations. In order to visualize those δ-like peaks, one uses a finite damping parameter γ=0.01. In the strong coupling regime, the regular part of S(**q,**ω**)** is negligibly small with respect to the main contribution due to isolated pole which describes the BEC pairing. Here the critical temperature is given by Fermi temperature $T_F = \frac{\hbar^2 k^2{}_F}{2mK_\beta}$.

CONCLUSION:

From the above results of investigations, we have come across the following conclusions;

(1) At the Unitarity limit the existing theories do not succeed to find the free energy of the system. Therefore to make a theory for unitarity is that one needs to take into account not only the fluctuations of the order parameter but also the normal state interaction correctly.

(2) Our investigations of the structure factor reveals that for d-wave scattering the damping of the pole for S(**q,**ω**)** is very small in the BCS regime in contrast to that for the s-wave scattering.

Table T1

An evaluated results of excitation energy of gas of interacting fermions in (q,ω) space for d-wave scattering. Here $1/a_d$=-0.17 at T= T_C for k_0=10 and k_1=10 and cosθ=1/2

q	ω	$\Omega_b(q)$
0	1.24	1.86
1	2.62	3.58
2	3.86	4.95
3	5.67	6.22
4	7.86	8.58
5	11.42	12.20
6	14.86	15.47
7	18.56	19.29
8	22.49	23.56
9	30.48	32.39
10	45.86	50.46

TableT2

An evaluated results of excitation energy of gas of interacting fermions in (q,ω) space for d-wave scattering. Here $1/a_d$=-0.12 at T= T_C for k_0=10 and k_1=10 and cosθ=1/2

q	ω	$\Omega_b(q)$
0	0.586	0.672
1	2.437	2.586
2	4.539	5.027
3	6.284	6.486
4	7.593	7.674
5	8.487	9.068
6	9.586	9.954
7	10.257	11.543
8	14.349	15.863
9	16.686	17.086
10	20.533	21.695

TableT3

An evaluated results of excitation energy of gas of interacting fermions in (q,ω) space for d-wave scattering. Here $1/a_d=0$ at $T= T_C$ for $k_0=10$ and $k_1=10$ and $\cos\theta=1/2$

q	Ω	$\Omega_b(q)$
0	0.058	0.047
1	1.287	0.998
2	3.286	2.432
3	4.685	3.254
4	6.543	4.483
5	9.336	8.358
6	12.689	10.465
7	14.168	13.269
8	16.453	14.286
9	19.253	18.686
10	24.589	22.164

Table T4

An evaluated results of excitation energy of gas of interacting fermions in (q,ω) space for d-wave scattering. Here $1/a_d=0.2$ at $T= T_C$ for $k_0=10$ and $k_1=10$ and $\cos\theta=1/2$

q	Ω	$\Omega_b(q)$
0	5.863	1.355
1	7.439	6.256
2	10.156	8.359
3	12.258	10.582
4	15.106	14.156
5	17.288	15.058
6	20.589	18.407
7	25.654	22.536
8	30.287	26.432
9	35.486	30.168
10	40.532	35.289

Table T5

An evaluated results of structure factor S(q,ω) for s-wave scattering $1/a_S$ =1.0, T_C=0.218T_F

q	ω	S(q, ω)
0.0	0.000	0.000
0.4	0.327	5.286
0.5	0.486	7.842
0.6	0.532	10.326
0.7	0.698	15.349
0.8	0.732	17.863
0.9	0.814	21.408
1.0	0.924	25.326
1.1	0.993	27.059
1.2	1.032	29.324
1.3	1.087	31.685
1.4	1.105	32.076

Table T6

An evaluated results of structure factor S(q,ω) for d-wave scattering $1/a_d$ =0.1 in the strong coupling region, $T_C=0.207T_F$

q	ω	S(q, ω)
0.0	0.000	0.000
0.1	0.432	2.246
0.2	0.586	3.354
0.3	0.635	4.864
0.4	0.686	5.325
0.5	0.735	6.436
0.6	0.789	8.323
0.7	0.807	10.254
0.8	0.812	12.866
0.9	0.847	14.586
1.0	0.893	16.108
1.2	1.047	20.432

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