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THE HEBEL-SLICHTER ENHANCEMENT IN NARROW BAND SYSTEMS

H. B. Brom[1] and D. van der Marel[2]

[1] Kamerlingh Onnes Laboratory, Leiden University, P.O. Box 9506, 2300 RA Leiden, the Netherlands.
[2] Faculty of Applied Physics, Delft University of Technology, 2628 CJ Delft, the Netherlands.

In a non-interacting gas of fermions the chemical potential (μ) becomes negative above a characteristic temperature of the order the Fermi temperature T_F. It is shown numerically for a narrow band system with a negative μ that the Hebel-Slichter enhancement (HSE) due to the formation of a superconducting condensate is suppressed. Only in the extreme case of $T_c \gg T_F$ the HSE disappears completely.

1. INTRODUCTION

Cooling through the superconducting transition in the high-T_c superconductors does not enhance the nuclear-relaxation rate[1]. This "Hebel-Slichter" enhancement (HSE) or coherence peak is expected and indeed observed in various normal BCS-superconductors. For the suppression of the enhancement in the high-T_c's (for the same reason to occur at microwave frequencies) a number of explanations has been proposed based on strong pair breaking, gap anisotropy or two-fluid phenomenology[2-6]. For narrow band conductors with a low band filling there is another factor, which influences the rate-enhancement. A dilute electron gas is no longer degenerate at high temperatures. As a function of temperature a gradual cross-over takes place from Fermi statistics to Boltzmann statistics. Assuming an energy independent density of states (such as in a two-dimensional (2D) system) the chemical potential μ becomes negative at a characteristic temperature $T_F/\ln 2$. This means that the lower band edge will lie above the chemical potential and effectively a gap has opened in the single particle excitation spectrum. If in this extreme case the electrons form a superconducting fluid due to an attractive interaction, the already existing gap will suppress the singularity in the density of quasi-particle states just above the gap and the HSE is suppressed.

In this paper we illustrate this mechanism for various parameter sets using the negative U Hubbard model[7] in the Hartree approximation. This is defined by the Hamiltonian

$$H = \sum_{k,\sigma}(\xi_k - \mu)c^\dagger_{k\sigma}c_{k\sigma} - U\sum_R c^\dagger_{R\uparrow}c_{R\uparrow}c^\dagger_{R\downarrow}c_{R\downarrow} \qquad (1)$$

Although the simplifications implicit in this model are very strong, the essential physical picture is not affected. The conditions required to suppress the HSE seem not to be fulfilled in the high T_c cuprates.

2. DETAILS OF THE CALCULATION AND THE PARAMETER SET

The opening of the superconducting gap will influence the temperature dependence of the chemical potential, μ. Because the total number of electrons ($2N$) is conserved the T-dependence of μ is found from the coupled BCS-equations at non-zero temperature

$$2\Delta = \sum_q U\frac{1-2f(\beta E_q)}{E_q}\Delta$$
$$N = \sum_k\left(\frac{E_k-\epsilon_k}{E_k} + 2\frac{\epsilon_k}{E_k}f(\beta E_k)\right) \qquad (2)$$

The energy of a quasi-particles is denoted by $E_k = (\epsilon_k^2 + \Delta^2)^{1/2}$, Δ is the gap parameter, and $\epsilon_k = \xi_k - \mu$ is the single electron energy relative to the chemical potential. For simplicity we will work with an energy independent density of states per site and spin, $\rho = 1/W$, where W is the bandwidth. This corresponds to a single 2D band. The gap equation then becomes

$$2W/U = \int_{-\mu}^{W-\mu} d\epsilon \frac{1-2f(\beta\sqrt{\epsilon^2+\Delta^2})}{\sqrt{\epsilon^2+\Delta^2}} \qquad (3)$$

The Fermi level relative to the bottom of the band at T=0 for the system without pairing interaction is denoted by k_BT_F. Integration of eq.(2) gives for the T-dependence of N/n

$$2k_BT_F = W + 2k_BT\ln\left(\frac{\cosh(\frac{1}{2}\beta\sqrt{\mu^2+\Delta^2})}{\cosh(\frac{1}{2}\beta\sqrt{(W-\mu)^2+\Delta^2})}\right) \qquad (4)$$

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The nuclear relaxation rate T_1^{-1} is given by the following expression [8], where we made a change of variables from the more commonly used dE to $d\epsilon$.

$$\frac{1}{T_1 T} \propto \int_{-\mu}^{W-\mu} d\epsilon f(E)(1-f(E))\frac{(E(E+\omega)+\Delta^2)}{E((E+\omega)^2-\Delta^2)^{1/2}} \quad (5)$$

Here $\mu(T)$ and $\Delta(T)$ have to be solved numerically from the coupled equations (3) and (4). If we take $\omega = 0$ the denominator has a singularity in the integration, which gives rise to a logarithmic divergence. Assuming a finite value of ω has the effect of smearing the singularity, so that a finite value of $1/T_1T$ is obtained just below T_c. We also observe that if $\mu < 0$, the singularity falls outside the range of integration. As a result the singular nature of the HSE disappears even with $\omega = 0$, although still an enhancement is possible. For $|\mu/W| \gg 1$ the enhancement is completely suppressed. The result taking $k_BT_F/W = 0.1$ is displayed in Fig. 1 for a number of values of the interaction strength parametrized by $\exp(-2W/U)$.

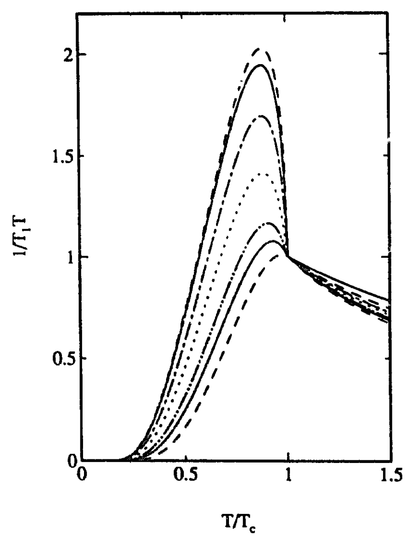

Fig.1. Temperature dependence of $1/T_1T$ taking k_BT_F/W = 0.1. From top to bottom: $\exp(-2W/U)$ = 0.1 ,0.05, 0.15, 0.2, 0.3, 0.4, 0.8. We took ω/W = 0.001 in all curves.

Clearly the HSE is indeed suppressed in the limit of strong interactions. We also notice that above the transition temperature $1/T_1T$ is not temperature independent as a result of the cross-over to Boltzmann statistics at high temperatures.

In order to check the physical conditions under which this mechanism for the suppression of the HSE applies we now make an estimate of the required bandwidth, Fermi temperature and U. As we can see in Fig. 1 an interaction strength of at least $\exp(-2W/U) = 0.4$ is needed. The self-consistent solution of Eq. (4) at $T = 0$ is[7,9]:

$$\Delta/W = \frac{\sqrt{(k_BT_F/W)(1-k_BT_F/W)}}{\sinh(W/U)} \quad (6)$$

Using this formula we obtain $\Delta/W = 0.63$. Assuming a T_c of 90 K Δ/k_B is about 160 K within the present BCS approach. Hence we need a bandwidth of about 22 meV. The Fermi temperature would then be only 25 K and U is 48 meV. Experimental estimates of T_F in high T_c cuprates are of the order of 1000 K. So it seems unlikely that the suppression of the HSE in the high T_c cuprates results from a negative value of μ.

3. CONCLUSIONS

We have evaluated numerically the suppression of the HSE as a function of the interaction strength for low band filling. If μ is slightly negative the coherence peak is partially suppressed. According to present knowledge of the electronic structure of high T_c cuprates it is not likely that this mechanism is responsible of the suppression of the HSE in this class of superconductors.

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