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SPECIFIC HEAT OF ANTIFERROMAGNETIC SPIN FLUCTUATIONS IN CUPRATE SUPERCONDUCTORS

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It has been shown that the temperature dependence of the specific heat of the antiferromagnetic spin fluctuations in cuprate superconductors has the form $C = \alpha T^2$. The present thermodynamical calculations are the additional test confirming d-pairing in the cuprate superconductors.

1. Introduction

During last three years many experiments confirming d-pairing in cuprate superconductors has been carried out. For instance, NMR experiment [1,2], ARPES experiment [3], Josephson interferometry experiments [4,5] and others. At the same time the theory of d-wave superconductivity explaining these experiments was successfully developed [6]. Alternative interpretation is based on the mixed pairing state, $s + d$ [7]. At the present time the model of antiferromagnetic spin fluctuations suggested by Pines [1,2] is actively developed.

In conventional superconductors with the pairing of BCS type (s-wave) the temperature dependence of the heat capacity is exponentional, namely, $\sim \exp^{-\Delta/k_B T}$. It was pointed out in [8] that for the anisotropic gap the specific heat has the following temperature dependence: $C \sim T^n$. In Ref. [9] the temperature dependence of the specific heat was observed to have the form: $C \sim T^2$ and in magnetic field: $C \sim (H)^{1/2}T^3$. In the present paper we'll calculate the specific heat of antiferromagnetic spin fluctuations introduced by Pines.

2. Specific heat

The antiferromagnetic spin fluctuations which result in d-pairing in cuprate superconduction are described by the Lagrangian in lattice representation [10-13]:

$$L = \sum_{\vec{n}} \psi_\alpha^+(\vec{n})(\frac{\partial}{\partial \tau} - \mu)\psi_\alpha(\vec{n}) - t \sum_{\vec{n},\vec{p}} \psi_\alpha^+(\vec{n})\psi_\alpha(\vec{n}+\vec{p})$$
$$+ g \sum_{\vec{n}} \psi_\alpha^+(\vec{n}) \left(\frac{\sigma^i}{2}\right)_{\alpha,\beta} \psi_\beta(\vec{n}) S_i(\vec{n}) \qquad (1)$$
$$+ \frac{1}{2} \sum_{\vec{n}\vec{m}} S_i(\vec{n}) \chi_{ij}^{-1}(\vec{n},\vec{m}) S_j(\vec{m}),$$

where the summation is over all knots of infinite lattice, $\vec{p}$ ia a unit vecor, which connects the neighboring knots, μ is a chemical potential, $\sigma_{\alpha,\beta}$ is the Pauli matrix, $S_i(\vec{n})$ is the operator of spin fluctuations in lattice representation, $\psi_\alpha^+(\vec{n})$ is the operator of an electron creation on n-th site, and $\psi_\alpha(n)$ is the operator of a hole creation on n-th site, α is a spin projection, t is a band halfwidth, $\chi_{ij}(\vec{n},\vec{m})$ is the spin correlation function, which is modulated by

$$\chi(q,\omega) = \frac{\chi_Q}{1 + \xi^2(q-Q)^2 - i\omega/\omega_{SF}}, \qquad (2)$$
$$q_x > 0, \quad q_y > 0,$$

where χ_Q is the static spin susceptibility at wave vector $Q = (\pi/a, \pi/a)$, ξ is the temperature-dependent antiferromagnetic correlation length, ω_{SF} is the paramagnon energy. All these parameters are taken from NMR experiments [1,2].

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It is convinient to use the formalism of continual integration for Fermi systems. The big statistical sum can be written in the form of functional integral [10,11]:

$$e^{-\beta\Omega} = N \int \prod_{\vec{m}} dS_i(\vec{n}) d\psi_\alpha^+(\vec{n},\tau) d\psi_\alpha(\vec{n},\tau) \times \quad (3)$$

$$\exp\left\{ - \int_0^\beta d\tau L(\tau) \right\},$$

where $\beta = 1/kT$, N ia a normalization multiplier.

Detailed calculations of the big statistical sum are givem in [11]. In the weak coupling approximation (lowest order in g^2) we have calculated the thermodynamic potential. The analytical expression for the thermodynamical potential is given in [12,13]. The specific heat capacity was calculated using the formula:

$$C = -T \frac{\partial^2 \Omega}{\partial T^2}. \quad (4)$$

We have done the computer calculations for $YBa_2Cu_3O_{6.63}$. For the calculation we take the following parameters: $\omega_{SF}(T_C) \approx 7.7\ mev$, $\chi_S(Q) = 44\ ev$, $\xi/a \approx 2.5$, $t = 2\ ev$, $\mu = 0.25$, $T_c = 95$ K . We chose the value of constant g which satisfy the relation $2\Delta/kT_c = 3.4$, as was derived in [1,2]. The results of the numerical calculation are shown in Fig. 1. (curve 1). The calculations show the linear behaviour of the ratio of the specific heat to temperature, C/T, in the range from zero to critical temperature. The curve 2 in Fig. 1. show the temperature dependence which corresponds to the BCS model (s pairing).

3. Conclusion

It follows from the numerical calculations that the temperature dependence of the specific heat is described by the expression $C = \alpha T^2$ which corresponds to d-pairing. This kind of temperature dependence was observed in Refs. [9,14]. In future we plan to calculate the temperature dependence of the specific heat of antiferromagnetic fluctuations in magnetic field.

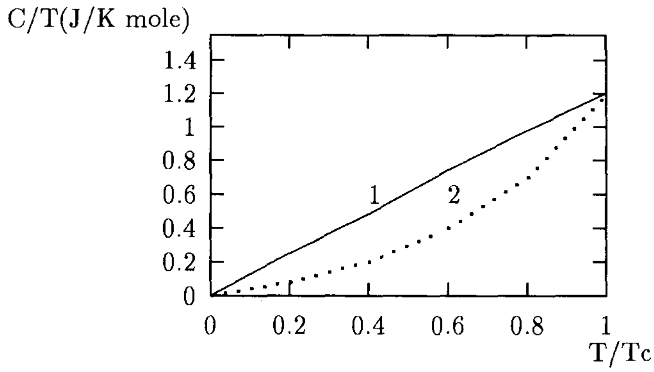

Figure 1. Temperature dependence of the electronic specific heat which corresponds to: 1 - d-wave pairing, 2 - s-wave pairing.

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