FLUCTUATION EFFECTS IN HIGH-TEMPERATURE SUPERCONDUCTOR OXIDES

P.P.Popovich

Institute of Solid State Physics and Chemistry, Uzhhorod National University,
54 Voloshin Str., Uzhhorod, 88000, Ukraine
e-mail: popovich@iss.univ.uzhgorod.ua

Theories modelling the excessive electrical conductivity caused by superconductive fluctuation above T_c are reviewed. The zero magnetic field case for single crystals and bulk polycrystalline materials is studied. The present work is a review of the theoretical results obtained in conductivity fluctuation theories.

Introduction

In modern physics one of the most interesting discoveries is the high-temperature superconductivity. A new wave of interest was initiated after its discovery by Bednorz and Müller [1]. The simplest method to study the fluctuation effects in high- temperature superconductors (HTSC) is the observation of the temperature dependence of the electrical resistivity. Amplitude fluctuations of the complex order parameter (a macroscopic wave function of the Cooper pair condensate) dominate above critical temperature (T_c) and lead to paraconductivity, where T_c is the Ginzburg-Landau transition temperature. Phase fluctuations of the order parameter are predominant below T_c. Fluctuation theories give explanations for the rounding of the resistivity vs. temperature (RT) curves near T_c and for the origin of paraconductivity. These fluctuation models of electrical conductivity were initially developed for low-T_c superconductors (LTSC). In this case the superconducting coherence length is large and the volume of fluctuation is small. For this reason paraconductivity in metallic LTSC is experimentally accessible only in case of restricted dimensionality (film, filament). The first experimental observation of paraconductivity in amorphous Bi film was published by Glover in 1967 [2].

Superconducting coherence length in HTSC is much shorter (about 100 times) than in LTSC. The temperature range, where the rounding of a RT curve, which is caused by thermodynamical fluctuation, appears near T_c, is much wider, and it is in the range of 1÷100 K.

Paraconductivity is a contribution to the electrical conductivity in the normal state just above T_c. It can be described as a difference between the expected (background) and measured values of conductivity:

$$\Delta\sigma = \sigma_{measured} - \sigma_{background} \qquad (1)$$

The temperature dependence of the background resistivity is usually approximated by $\rho(T)=AT+B$ for polycrystalline materials, and by $\rho(T)=A/T+BT$ in case of single crystals or c-axis oriented films [3].

A more sophisticated approximation of the conductivity of ceramic samples is described as a collection of randomly oriented grains, joined by intergrain coupling [4]. Generally the electric current flows through CuO_2 planes and one obtains $\rho(T)=(1/p)\rho_g(T)+\rho_c(T)$, where p is a sample-dependent but temperature-independent parameter, which accounts for the cross-section reduction caused by randomly placed grains $(0\leq p\leq 1)$; ρ_g is the average resistivity and sample-dependent; ρ_c is the intragranular resistivity of grains $(0\leq \rho_c\leq p)$ and approximately equal to the single crystal ab resistivity.

Aslamazov-Larkin theory

The first attempt to explain the origin of paraconductivity was made by Aslamazov and Larkin (AL) [5]. The direct acceleration of the fluctuation-induced superconducting pairs leads to the AL contribution. Without such fluctuations the resistivity above T_c is

$$\sigma_n = \frac{ne^2}{m}\tau_{tr}, \qquad (2)$$

where n is the volume density of the normal electrons, and τ_{tr} is their mean scattering time. The addition term in conductivity, which caused by fluctuations, depends on the dimensionality of sample:

$$\Delta\sigma_{2D}^{AL} = \frac{1}{16}\times\frac{e^2}{\hbar d}\times\in^{-1} \qquad (3)$$

$$\Delta\sigma_{3D}^{AL} = \frac{1}{32}\times\frac{e^2}{\hbar\xi(0)}\times\in^{-0.5} \qquad ,(4)$$

where $\in=(T-T_c)/T_c$ is the reduced temperature, $\xi(0)$ is the coherence length at $T = 0$, d is the interspacing distance between layers.

Maki-Thompson contribution

The experiments have showed discrepancy between AL theory prediction and experimental data in case of cleaner films. This motivated Maki and Thompson (MT) to complete the original AL equations with an additional term, which takes into consideration the indirect acceleration of the decayed pairs [6]. The MT theory deals with the regular and anomalous contributions. Since these contributions are opposite in sign, it is important to determine which one will dominate. In case of the in-plane resistivity the anomalous term is additive and dominates. Because the regular contribution is too small, it can be neglected. The origin of this additional conductivity is the acceleration of those electrons, which were Cooper pairs before scattering. In order to simplify the solution, the low-momentum $k_c=\xi^{-1}(0)\delta^{0.5}$ was eliminated, where $\delta=(T_{c0}-T_c)/T_c$ is the reduced shift of T_c due to "pair-breaking" interactions (paramagnetic impurities, external magnetic field, etc). The magnetic field change the critical temperature of the superconducting sample, so

$$\delta = \delta_0 + \frac{1}{2}\left(\frac{eH_{\parallel}\xi(0)d}{\hbar c}\right)^2, \qquad (5)$$

where δ_0 is the contribution due to other pair-breaking processes. The decayed pairs are accelerated and look like superconducting fluctuation. Their results for different dimensionality of fluctuations are the following:

$$\Delta\sigma_{2D}^{MT} = \frac{1}{16}\times\frac{e^2}{\hbar d}\times\in^{-1} + \frac{1}{8}\times\frac{e^2}{\hbar d}\times\frac{1}{\in-\delta}\ln\left(\frac{\in}{\delta}\right) \quad ,(6)$$

$$\Delta\sigma_{3D}^{MT} = (1+4)*\frac{1}{32}*\frac{e^2}{\hbar\xi(0)}*\in^{-0.5} \qquad (7)$$

The total paraconductivity is given by the sum of the AL and the MT terms. It is evident that the ratio between 2D Maki-Thompson and Aslamazov-Larkin models is

$$\frac{\Delta\sigma_{2D}^{MT}}{\Delta\sigma_{2D}^{AL}} = \frac{2\in}{\in-\delta}\ln\left(\frac{\in}{\delta}\right). \qquad (8)$$

This ratio goes to zero at T_c ($\in=0$), it equals to 2 at T_{c0} ($\in=\delta$), and diverges logarithmically for $T>>T_{c0}(\in>>\delta)$.

Lawrence-Doniach model

Lawrence and Doniach worked out a model which covers the region between 2D and 3D AL fluctuations for anisotropic HTSC [7]. They considered that the fluctuation have 2D character within *ab* layers, which are coupled together by the Josephson relations. The result is in the form of

$$\Delta\sigma_{LD} = \frac{e^2}{16\hbar s\in}\times\left[1+\left[\frac{2\xi_c(0)}{s}\right]^2\times\frac{1}{\in}\right]^{-\frac{1}{2}} \quad ,(9)$$

where s is the distance between the CuO_2 bilayers. This equation contains the crossover from 2D to 3D fluctuation near T_c which is caused by increasing of the coherence length, so, the coupling strength increases between the layers with decreasing temperature. This crossover temperature is described as

$$T_0 = T_c * \left[1+\left[\frac{2\xi_c(0)}{s}\right]^2\right]. \qquad (10)$$

Conductivity changes caused by density of states fluctuations

Thermodynamic fluctuations above T_c cause a creation of nonequilibrium Cooper-pairs. These pairs produce a reduction in the quasi-particle density of states, which give a negative term in full zero-field conductivity [8]. One can obtain that

$$\Delta\sigma_{DOS} = \frac{e^2 k}{2s}\left[\ln\frac{2}{\epsilon^{\frac{1}{2}} + (\epsilon + r)^{\frac{1}{2}}}\right], \qquad (11)$$

where $r(T)=7\zeta(3)\pi^2 J^2/8T^2 k_B^2$ is the parameter which characterizes the dimensional cross-over in fluctuation behaviour, J is a hopping integral describing the Josephson interaction between layers, $\zeta(x)$ is the Riemann zeta function.

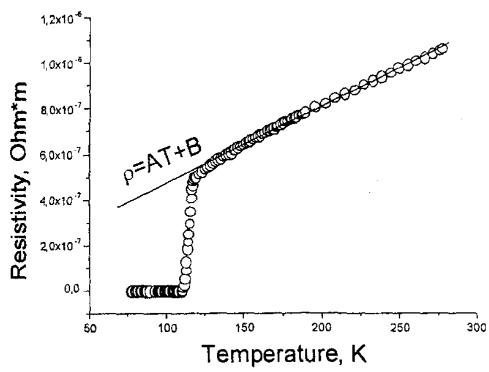

Fig.1. Temperature dependence of the electrical resistivity of $YBa_2Cu_3O_{7-\delta}$. The solid line shows the background conductivity.

Case of polycrystalline materials

These theories were performed for single crystals. The picture in case of polycrystalline structure is more difficult. These materials may be modelled by the collection of the randomly oriented grains. Since the polycrystalline samples are more isotropic by their nature than single crystals, in the latter the fluctuations are reduced. According to the above mentioned statements, the "standard" AL equations change to the following ones[9]:

$$\Delta\sigma_p^{2D} = \frac{1}{4}\left[\frac{e^2}{16\hbar d}\epsilon^{-1}\left\{1+\left(1+\frac{8\xi_c^4(0)}{d^2\xi_{ab}^2(0)}\epsilon^{-1}\right)^{0.5}\right\}\right] \qquad (12)$$

$$\Delta\sigma_{3D}^{AL} = \frac{1}{32} * \frac{e^2}{\hbar\xi_p(0)} * \epsilon^{-0.5} \qquad (13)$$

Because of $\xi_{ab} > \xi_c$ and $d > \xi_c$, the equation could be simplified and written in the following form:

$$\Delta\sigma_p^{2D} = a\epsilon^{-1} + b\epsilon^{-2}$$

$$a = \frac{e^2}{16\hbar d}, \qquad b = \frac{e^2\xi_c^4(0)}{16\hbar d^3\xi_{ab}^2(0)} \qquad (14)$$

$$\Delta\sigma_p^{3D} = \frac{e^2}{32\hbar\xi_p(0)}\epsilon^{-0.5}. \qquad (15)$$

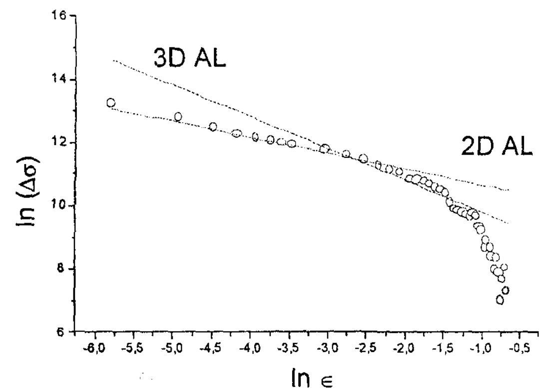

Fig.2. ln(Δσ) vs. ln∈ function for $YBa_2Cu_3O_{7-\delta}$ ceramic. Δσ is the excess conductivity, $\epsilon = (T-T_c^{mf})/T_c^{mf}$ is the reduced temperature.

Conclusions

Order parameter fluctuations dominating above T_c lead to paraconductivity. In the normal phase nonequilibrium Cooper pairs appear and decay, caused by the change of density of states. Order parameter phase fluctuations below T_c generate resistance in thin wires and breakdown of fluxoid quantization in small rings. Paraconductivity is caused by direct and indirect acceleration of Cooper pairs, and by changing of the density of states. The microscopic origin of the high temperature superconductivity is still an unsolved problem. Calculation of parameters like penetration depth and coherence length from fluctuation theories is extremely useful in uncovering some features of superconductors.

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ФЛУКТУАЦІЙНІ ЕФЕКТИ У ВИСОКОТЕМПЕРАТУРНИХ НАДПРОВІДНИКОВИХ ОКСИДАХ

П.П.Попович

Інститут фізики і хімії твердого тіла, Ужгородський національний університет,
вул. Волошина, 54, Ужгород, 88000
e-mail: popovich@iss.univ.uzhgorod.ua

Зроблено огляд теорій, що моделюють надлишкову електричну провідність, спричинену надпровідниковими флуктуаціями вище від T_c. Вивчається випадок з нульовим магнітним полем для монокристалів та об'ємних полікристалічних матеріалів. Робота є оглядом теоретичних результатів, отриманих у теоріях флуктуацій провідності.