ANALYSIS OF FLUCTUATION CONDUCTIVITY IN $Y_{0,6}Cd_{0,4}Ba_2Cu_3O_{7-\delta}$

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The mechanism of formation of excess conductivity in cuprate high-temperature superconductors (HTSC) $Y_{0,6}Cd_{0,4}Ba_2Cu_3O_{7-\delta}$ and $YBa_2Cu_3O_{7-\delta}$ was considered within the framework of the local pair model taking into account the Aslamazov-Larkin theory near T_c. The temperature T_0 of the transition from the 2D fluctuation region to the 3D region (the temperature of the 2D-3D crossover) is determined. The coherence lengths of the fluctuation Cooper pairs ξ_c (0) along the *c* axis are calculated. It was shown that a partial substitution of Y by Cd in the Y – Ba – Cu – O system leads to a decrease in ξ_c (0) by ~ 2 times (from 6.32 Å to 3.18 Å), as well as to the expansion as the region of existence pseudogaps and superconducting (SC) fluctuations near T_c. The temperature dependence of the pseudogap Δ * (T) and the values of Δ * (T_c) are determined, and temperatures Tm corresponding to the maximum temperature dependence of the pseudogap in these materials are estimated. The maximum values of the pseudogap in samples $Y_{0,6}Cd_{0,4}Ba_2Cu_3O_{7-\delta}$ and $YBa_2Cu_3O_{7-\delta}$ are 34.56 meV and 28.4 meV correspondingly.

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INTRODUCTION

In recent years, the group of works [1–5] devoted to the analysis of pseudogap effects in HTSC compounds has appeared. Pseudogap (PG) is a unique phenomenon characteristic of HTSC with an active CuO_2 plane (cuprates) in the doping region less than optimal. It manifests itself in studies of the phenomena of tunneling, photoemission, heat capacity [2, 4] and other properties of HTSC. It is assumed that at a certain temperature $T^*>>T_c$ (T_c is the critical temperature of the superconducting transition) the density of states on the Fermi surface is redistributed: on a part of this surface the density of states decreases. Below the temperature T*, the compound is in a pseudogap state. In these works, possible conduction mechanisms in the modes of the normal, superconducting, and pseudogap states in HTSC are also discussed.

Recently, the work [6], devoted to the study of the pseudogap state in $Pb_{0.55}Bi_{1.5}Sr_{1.6}La_{0.4}CuO_{6+\delta}$ (Pb-Bi2201) appeared. A series of Pb-Bi2201 single crystals was obtained, on which a wide range of investigations were conducted to identify the pseudogap state. The results of studies on three different experimental methods indicate that the appearance of a pseudogap at T≅132 K should be perceived only as a phase transition. Thus, the authors confirmed the assumption that at the temperature decreasing, the HESC material must undergo two phase transitions: first the appearance of a pseudogap, and then a transition to the superconducting state.

However, as noted by A. Abrikosov [7], the pseudogap state cannot really be considered as some kind of new phase state of matter, since the PG is not separated from the normal state by a phase transition. So the question of a possible phase transition at T=T* also remains open. At the same time, it can be said that a crossover occurs at T=T* [1]. Below this temperature, due to reasons not yet established to date, the density of quasiparticle states at the Fermi level begins to decrease. Actually for this reason, this phenomenon is called "pseudogap". For the first time, this result was obtained in experiments on the study of NMR in a weakly doped Y123 system, in which an anomalous decrease of the Knight shift [2] during cooling, which is directly related to the density of states at the Fermi level in the Landau theory, was observed.

In order to receive answers to the above questions in this work, we have analyzed the excess conductivity separated from resistive measurements on partially doped $Y_{0,6}Cd_{0,4}Ba_2Cu_3O_{7-\delta}$ with a SC transition at 85 K.

Thus, the aim of this work is to study the normal state of $YBa_2Cu_3O_{7-\delta}$ (Y1) and $Y_{0,6}Cd_{0,4}Ba_2Cu_3O_{7-\delta}$ (Y2) in the temperature range $T^*>T>T_c$, to determine their physical characteristics, as well as to study the possibility of the occurrence of the PG states in these compounds. The analysis was carried out on the basis of the study of excess conductivity above T_c in the framework of the local pair (LP) model [3, 4] taking into account the Aslamazov –Larkin fluctuation theory [8] near T_c.

EXPERIMENTAL RESULTS AND THEIR PROCESSING

The method for obtaining $Y_{0,6}Cd_{0,4}Ba_2Cu_3O_{7-\delta}$ is described in [9].

The temperature dependences of the specific resistivity ρ of the samples Y1 and Y2 are showed in fig.1. The critical temperatures of the SC transition T_c were determined from the maximum obtained by differentiating of the curve ρ(T). Critical temperatures of investigated samples are T_{c1} =92.63K (Y1) and T_{c2}= 89.23 (Y2) (fig.1). In this case, the resistivity of the sample $Y_{0,6}Cd_{0,4}Ba_2Cu_3O_{7-\delta}$ in the normal phase at 300 K increases almost 2 times in comparison with $YBa_2Cu_3O_{7-\delta}$.

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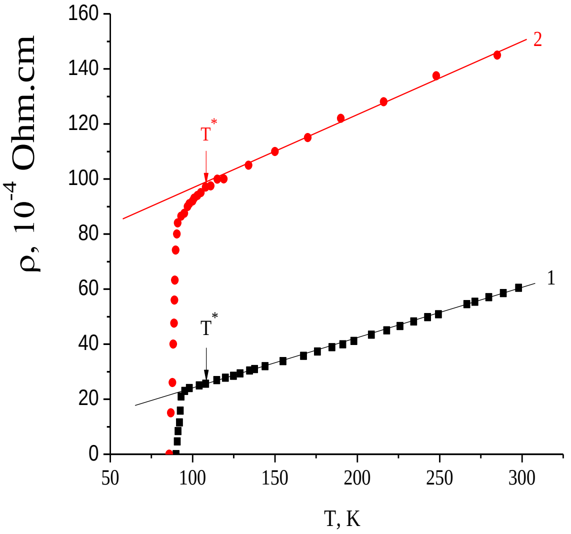

Fig. 1. Temperature dependences of the resistivity of samples Y1 is $YBa_2Cu_3O_{7-\delta}$ (1) and Y2 is $Y_{0,6}Cd_{0,4}Ba_2Cu_3O_{7-\delta}$ (2).

FLUCTUATION CONDUCTIVITY

The linear course of the temperature dependence of the specific resistance of samples Y1 and Y2 in the normal phase is well extrapolated by the expressions $\rho_{Y1n}(T) = (D + \kappa T + BT^2)$ and $\rho_{Y2n}(T) = (\rho_0 + \kappa T + BT^2)$ (here *D*, *B* and *k* are some constants). This linear relationship, extrapolated to the low temperature range, was used to determine excess conductivity $\Delta\sigma(T)$ according to:

$$\Delta\sigma(T) = \rho^{-1}(T) - \rho_n^{-1}(T). \qquad (1)$$

The analysis of the behavior of excess conductivities was carried out in the framework of the local pair model [4, 10].

Assuming the possibility of the formation of local pairs [3,4] in samples at temperatures below T*=107.57K (Y1) and T*=108.22K (Y2), the experimental results obtained near *Tc* were analyzed taking into account the occurrence of fluctuation Cooper pairs (FCP) above T_c in the framework of the theory of Aslamazov-Larkin (AL) [8].

The fig. 2 shows dependence of the logarithm of the excess conductivity of the samples Y1 (1) and Y2 (2) on the logarithm of the reduced temperature $\varepsilon = (T/T_c - 1)$. According to the theory of AL, as well as Hikami –Larkin (HL) developed for HTSC [10], in the region of $T > T_c$ (but near T_c), the fluctuation coupling of charge carriers occurs, leading to the appearance of fluctuation conductivity (FC). In this region, the temperature dependence of excess conductivity on temperature is described by the expressions:

$$\Delta\sigma_{AL3D} = C_{3D}\,\{e^2/[32\hbar\xi_c(0)]\}\varepsilon^{-1/2}, \qquad (2)$$

$$\Delta\sigma_{AL2D} = C_{2D}\,\{e^2/[16\hbar d]\}\varepsilon^{-1}, \qquad (3)$$

respectively for three-dimensional (3D) and two-dimensional (2D) region. The scaling coefficients C are used to combine the theory with experiment [4].

Thus, by the angle of inclination α of dependences ln (Δσ) as a function of $\varepsilon = \ln(T/T_c - 1)$ (see fig. 3), we can distinguish 2D (tgα = -1) and 3D ($tg\alpha$ = - 1/2) regions of phase transition. It can also determine the crossover temperature T_0 (the transition temperature from $\Delta\sigma_{2D}$ to σ_{3D}) and the tangents of the slopes of the dependences $\Delta\sigma(T)$ corresponding to the exponents ε in equations (2) and (3). The corresponding values of the parameters 2D and 3D regions determined from the experiment for sample Y1 are 2D (tgα = -1.04) and 3D (tgα = -0.44) and for Y2 are 2D (tgα = -1.1) and 3D (tgα = -0.49).

On basis of value the temperature of the crossover T_0, which corresponds to $\ln\varepsilon_0$, according to Fig. 2, it can determine the coherence length of local pairs along the *c* axis [11,12]:

$$\xi_c(0) = d\sqrt{\varepsilon_0}\,, \qquad (4)$$

here *d* is the distance between the inner conducting planes in Y-Ba-Cu-O [13], d ≈ 11.7Å. The values of $\xi_c(0)$ = 6.32 Å ($\ln\varepsilon_0 \approx -1.2318$) for Y1 and $\xi_c(0)$ = 3.18 ($\ln\varepsilon_0 \approx -2.755$) for Y2 are obtained correspondingly

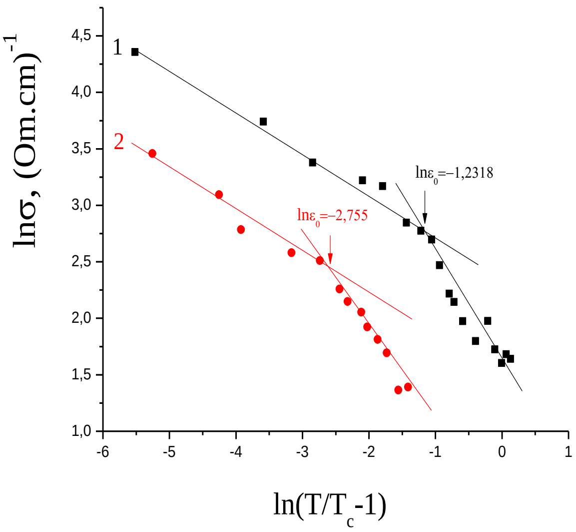

Fig. 2. The dependences of the logarithm of excess conductivity on logarithm (T/T_c-1) of samples Y1 (1) and Y2 (2). The solid lines are the calculations in the framework of the Aslamazov-Larkin theory.

ANALYSIS OF THE MAGNITUDE AND TEMPERATURE DEPENDENCE OF THE PSEUDOGAP

As noted above, in the cuprates at T<T*, the density of electron states of quasiparticles on the Fermi level decreases [14] (the cause of this phenomenon is not yet fully elucidated), which creates conditions for the formation of a pseudogap in the excitation spectrum and it leads ultimately to the formation of an excess conductivity. The magnitude and temperature dependence of the pseudogap in the investigated samples was analyzed using the local pair model, taking into account the transition from Bose-Einstein condensation (BEC) to the BCSh mode predicted by the theory [10] for HTSC when the temperature decreases in the interval T*<T <Tc. Note

that excess conductivity exists precisely in this temperature range, where fermions supposedly form pairs- the so-called strongly coupled bosons (SCB). The pseudogap is characterized by a certain value of the binding energy $\varepsilon_b \sim 1/\xi^2(T)$, causing the creation of such pairs [10,13], which decreases with temperature, because the coherence length of the Cooper pairs $\xi(T)=\xi(0)(T/T_c-1)^{-1/2}$, on the contrary, increases with decreasing temperatures. Therefore, according to the LP model, the SCB transform into the FCP when the temperature approaches T_c (BEC-BCSh transition), which becomes possible due to the extremely small coherence length ξ (T) in cuprates.

From our studies, we can estimate the magnitude and temperature dependence of PG, based on the temperature dependence of excess conductivity in the temperature interval from T* to T_c according to [3, 13]:

$$\Delta\sigma(\varepsilon)=\left\{\frac{A(1-T/T^*)[\exp(-\Delta^*/T)]e^2}{16\eta\xi_c(0)\sqrt{2\varepsilon_0^*\cdot sh(2\varepsilon/\varepsilon^*{}_0)}}\right\} \tag{5}$$

where the (1-T/T*) determines the number of pairs formed at T≤T*; and the exp (-Δ*/T) determines the number of pairs destroyed by thermal fluctuations below the BEC-BCSh transition temperature. The coefficient A has the same meaning as the coefficients C_{3D} and C_{2D} in (2) and (3).

The solution of equation (5) gives the value of Δ*:

$$\Delta^*(T)=T\cdot\ln\left\{\frac{A(1-T/T^*)e^2}{\Delta\sigma(T)16\eta\xi_c(0)\sqrt{2\varepsilon_0^*\cdot sh(2\varepsilon/\varepsilon^*{}_0)}}\right\} \tag{6}$$

where $\Delta\sigma$ (*T*) is the experimentally determined excess conductivity.

Fig. 3 shows the dependence of logarithm of the excess conductivity of samples Y1 and Y2 on the inverse temperature. The choice of such coordinates is due to the strong sensitivity of the linear region $ln\Delta\sigma$ (1/T) to the value of $\Delta^*(T_c)$ in equation (5), which allows to estimate this parameter with high accuracy (this is necessary to find the coefficient A) [3,13,15]. The dependences $ln\Delta\sigma$(1/T) were calculated according to the method approved in [12]. As can be seen from fig. 3 (curves 1 and 2), in this case, the values $ln\Delta\sigma$ (1/T) calculated for both samples with parameters: A=82.4 ± 0.1, T* = 107.57K, ξ_c (0) = 6.32 Å (Y1) and A = 5.53 ± 0.1, T*=108.22K, ξ_c (0) = 3.18 Å (Y2) are in good agreement with the experimental data.

The temperature dependence and the value of the pseudogap parameter Δ*(T) (fig. 4) were calculated on the basis of equation (6) with the parameters given above. As noted in [3, 4, 13], the value of the coefficient *A* is selected from the condition of coincidence of the temperature dependence of $\Delta\sigma$ (equation (5), assuming Δ*= Δ*(T)) with experimental data in the region of 3D fluctuations near T_c. According to [13, 16], the optimal approximation for the HTSC material is achieved with values of $2\Delta^*(T_c)/k_BT_c \approx 5\div7$.

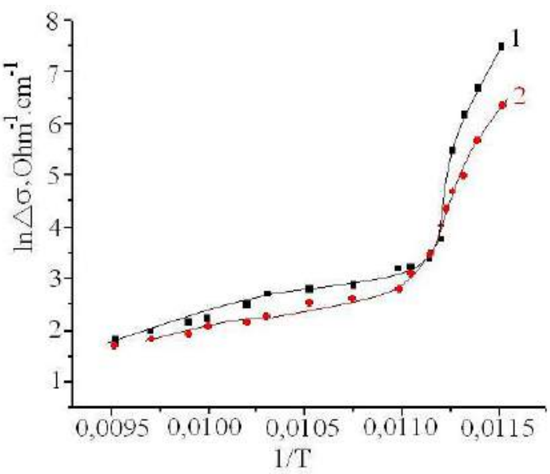

Fig. 3. The dependences of logarithm of excess conductivity on inverse temperature: 1-Y1; 2-Y2; solid lines are approximations of eq. (3) with the parameters given in text.

For sample Y1, the values $2\Delta^*(T_c)/k_BT_c = 5$, and for Y2 $2\Delta^*(T_c)/k_BT_c = 4{,}5$ have been obtained. As a result, the values of A = 82.4 and $\Delta^*(T_c)$ = 92.62 • 2.7 = 250.07K; for Y2 A = 5.53 and $\Delta^*(T_c)$ = 89.23 • 2.5 = 223.075K have been obtained, and it consistent with the experimental data (fig. 4).

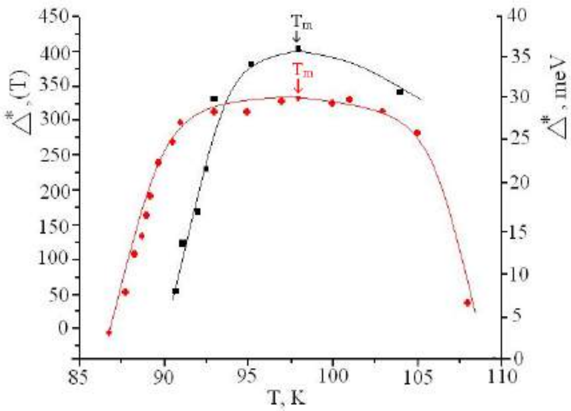

Fig. 4. Temperature dependences of the calculated pseudogap of samples Y1 (1) and Y2 (2) with the parameters given in the text. The arrows show the pseudogap maximum values.

The temperature dependences of Δ^*(T) obtained on the basis of equation (6) are shown in fig. 4. The maximum values of the pseudogap for Y1 $\Delta^*_m \approx$ 34.56 meV ($\Delta^*(T_m)$ ≈402.66 K, T_m=97.98K) for Y2 $\Delta^*_m \approx$ 28.5 meV ($\Delta^*(T_m)$≈330,13 K, T_m≈98.22 K) are determined.

From the presented data in fig. 4, it is also seen that as *T* decreases, the pseudogap value first increases, then, after passing through a maximum, decreases. This decrease is due to the transformation of the SCB in the PCF as a result of the BEC-BCSh transition, which accompanied by an increase in excess conductivity at $T \rightarrow T_c$. Such a behavior of Δ* with decreasing temperature was first found on YBCO films [3.13] with different oxygen contents, which seems to be typical of cuprate HTSC [13]. Thus it can be concluded that in investigated $Y_{0,6}Cd_{0,4}Ba_2Cu_3O_{7-\delta}$ and $YBa_2Cu_3O_{7-\delta}$ it is possible the local pair formation of charge carriers at $T>>T_c$, which creates conditions for the formation of a pseudogap [13,16] the subsequent establishment of the phase coherence of the fluctuating Cooper pairs at $T<T_c$ [17].

CONCLUSION

The investigation of the effect of partial substitution of Y bu Cd on the mechanism of excess conductivity in Y-Ba-Cu-O polycrystals showed that partial substitution of Y by Cd leads to a decrease in the critical temperatures of the $Y_{0,6}Cd_{0,4}Ba_2Cu_3O_{7-\delta}$ (Y2) sample compared to $YBa_2Cu_3O_{7-\delta}$ (Y1) (respectively T_c (Y2)=89.23K and T_c (Y1)= 92.628K). In this case, the resistivity of the sample $Y_{0,6}Cd_{0,4}Ba_2Cu_3O_{7-\delta}$ in the normal phase at 300 K increases (2 times) compared to $YBa_2Cu_3O_{7-\delta}$. At the same time, there is an expansion of the temperature regions of PG and FCP, as well as a decrease in the coherence length of Cooper pairs.

Studies and analysis have shown that the excess conductivity $\Delta\sigma$(T) in $Y_{0,6}Cd_{0,4}Ba_2Cu_3O_{7-\delta}$ in the temperature range $T_c<T<T^*$ is satisfactorily described in the framework of the model of local pairs [3,14].

The analysis result of the pseudogap state by the method of excess conductivity confirms that the model of local pairs in this case is applicable to both samples.

At $T\rightarrow T_c$, the behavior of $\Delta\sigma$(T) of both samples obeys to the Aslamazov – Larkin theory for 2D and 3D fluctuations [8, 11]. Thus, before the transition to the superconducting state, the region of superconducting fluctuations is always realized in the form of a FCP, in which $\Delta\sigma$(T) is described by equation (2) for 3D superconductors (that is, before the SP transition, the HTSC transition is always three-dimensional).

Thus, it can be assumed that in $YBa_2Cu_3O_{7-\delta}$ and $Y_{0,6}Cd_{0,4}Ba_2Cu_3O_{7-\delta}$ PG forms by converting the *d*-wave SC energy gap in CuO_2 planes into the corresponding gap of the fluctuation Cooper pairs above T_c.

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