Pairing and Coherence Transition in $La_{1.82}Sr_{0.18}CuO_4$ Strongly Two-Dimensional Superconductor

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We report conductivity fluctuation measurements in the $La_{1.82}Sr_{0.18}CuO_4$ high temperature superconducting material. The conductivity fluctuation analysis was performed by utilizing the concept of the logarithmic derivative of the conductivity excess. Close and above the critical temperature T_c, we experimentally determine the occurrence of Gaussian and critical fluctuation regimes. Systematic measurements of conductivity as a function of temperature were performed for several values of transport current j. Fluctuation analysis close to the zero resistivity temperature T_{c0} was performed and we clearly identified a characteristic exponent, which is analyzed by the dynamical scaling theory and considering a percolation-like transition in a frustrated and disordered system. The observation of a glass-like behavior in our experiments permits to interpret our results as corresponding to a vortex-glass regime.

Keywords: Fluctuations; Transport properties; Granularity

I. INTRODUCTION

High temperatures, small coherence length and strong anisotropy enhance the thermal fluctuation effects in high temperature superconductors (HTS). Most studies in R-123 [1], Bi-based [2] and Hg-based [3] HTS, reveal that the superconducting transition occurs in a process with two steps. When temperature is decreased, the superconducting long range order is first reached into the individual grains of polycrystalline systems. This coherence in the amplitude of the order parameter has place for a temperature value according with the bulk critical temperature T_c, and is currently known as pairing transition [4]. Close and above T_c, the Aslamazov-Larkin fluctuations [5] follow a quasi-universal behavior, which are strongly related with Gaussian and genuinely critical fluctuations. Below T_c, near the zero resistance state, the fluctuation effects are enhanced by the granular-like disorder. This *paracoherent* regime precedes the denominated coherence transition [6], which is characteristic of inhomogeneous systems.

The aim of this work is to synthesize and analyze the fluctuation effects above and below T_c in the HTS $La_{1.82}Sr_{0.18}CuO_4$. We study carefully the resistive transition in presence of several applied current densities, as specified in section II. Using the logarithmic derivative of the conductivity excess, we analyze the experimental data and identify the critical regimes in the normal state and near the zero resistance state.

II. EXPERIMENTAL TECHNIQUES

Polycrystalline samples of $La_{1.82}Sr_{0.18}CuO_4$ were synthesized by the recognized solid-state reaction recipe. A stoichiometric mixture of high purity (99.99%) chemical constituents La_2O_3, SrO and CuO was mixed thoroughly, palletized and calcined at temperature of 960 ^oC for 12 h. The calcined material was reground, pressed as circular discs and sintered at 920 ^oC for 24 h in oxygen atmosphere. Structural analysis of samples were performed by x-ray diffraction (XRD), which reveal that this oxide crystallized in a tetragonal perovskite with cell parameters *a=b=3,79(4) Å* and *c=13,31(8) Å*. Conductivity measurements were carrying out by using the conventional four probes DC technique. The temperature was monitored by means a Pt-100 sensor. We determine that this material evidenced a normal-superconductor bulk transition at $T_c = 34,5K$. In order to study the coherence transition in this strongly granular and disordered system, transport current densities of 0.055, 0.555, 0.833, 1.111, 2.222 and 3.331 A/m^2 were applied.

III. ANALYSIS METHOD

The analysis of results for the fluctuation contribution on magnetoconductivity is performed by assuming that the conductivity excess is given by [1]

$$\Delta\sigma = \sigma - \sigma_R, \quad (1)$$

where $\sigma = \sigma(T) = \frac{1}{\rho(T)}$ is the measured conductivity and $\sigma_R = {}^1\!/_{\rho_R}$ is the regular term extrapolated from the high-temperature behavior, as shown in Fig. 1. Notice that the feature of the normal resistivity as a function of temperature is approximately linear, which permits to perform an easy linear extrapolation to determine ρ_R. According to the Aslamazov-Larkin (AL) proposal, the fluctuation magnetoconductivity diverges as a power law of the type

$$\Delta\sigma(T) = A\varepsilon^{-\lambda}, \quad (2)$$

where A is a constant, $\varepsilon = \frac{T-T_c}{T_c}$ represent the reduced temperature and λ is the critical exponent. Analogously to the Kouvel-Fisher method of analysis of critical phenomena

[7], the logarithmic temperature derivative of $\Delta\sigma$ is given by $\frac{d}{dT}\ln(\Delta\sigma)$. Then, the inverse of logarithmic temperature derivative is defined as

$$\chi_\sigma = -\frac{d}{dT}\ln(\Delta\sigma) = \frac{1}{\Delta\sigma}\frac{d(\Delta\sigma)}{dT}. \quad (3)$$

By substituting equation (2) in (3) it is obtained that

$$\frac{1}{\chi_\sigma} = \frac{1}{\lambda}[T - T_c]. \quad (4)$$

Thus, obviating more complex procedures of adjustment, simple identification of linear temperature behavior in plots of χ_σ^{-1} as a function of T allows simultaneous determination of critical temperature T_c of fluctuation regime and the corresponding critical exponent, λ. At $T < T_c$, by using the same analysis method, we denote the critical exponents related with the *paracoherent-coherent* transition as λ_p and the critical temperature as T_{c0}.

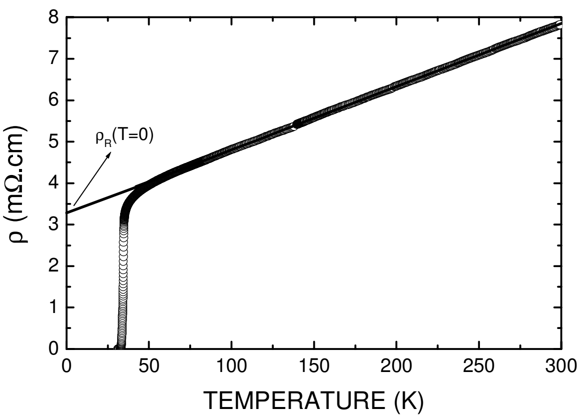

FIG. 1: Resistive transition and regular resistivity behavior extrapolated from the normal behavior.

IV. RESULTS AND DISCUSSION

Figure 2 shows the characteristics resistivity, $\rho(T)$, temperature derivative, $d\rho(T)/dT$, and logarithmic derivative, χ_σ^{-1}, as a function of T close to T_c. It is evident that the transition occurs in a two steps process. Figs. 2(a) and 2(b) permit to separate two good differenced regimes: first, for high temperature, we observe one sharp maximum in $d\rho(T)/dT$, which is related with intra-granular fluctuations (fluctuations in the amplitude of the order parameter). These characteristic fluctuations define the so called *pairing transition* [8]. The temperature value of this maximum is close to the bulk critical temperature value T_c. For low temperature region a hump, as a shoulder, is discerned in the temperature derivative of resistivity. This regime corresponds to inter-granular fluctuation [6], which is known as *paracoherent state*. At the temperature value T_{c0} the electrical resistivity vanishes and the phase of the order parameter acquired long range order between the grains of the system. This critical temperature characterizes the *coherence transition*. Fig. 2(c) exemplifies the analysis method described in section III to obtain the critical exponents from equation (4).

Figure 3 shows the fluctuation regimes in the normal state, obtained from the analysis of the experimental data. Three Gaussian fluctuation regions were clearly identified above T_c, in the plot of $\chi_\sigma^{-1}(T)$. These were labeled by the indices λ_{2D}, λ_{3D-2D} and λ_{3D}, as specified in table I. We interpreted the characteristic regimes on the basis of the Aslamazov-Larkin theory [5], which proposes that the critical exponents are related with the dimensionality d of the fluctuation system, through the expression

$$\lambda = 2 - \frac{d}{2}. \quad (5)$$

The exponents λ_{2D} and λ_{3D} correspond to homogeneous 2D and 3D regimes. As showed in table I, the exponent λ_{3D-2D} do not corresponds to an integer dimensionality. It was demonstrated by Char and Kapitulnik [9] that the fluctuation system can be to develop in a space with fractal topology. In this case, the fluctuation exponent is given by

$$\lambda = 2 - \frac{\tilde{d}}{2}, \quad (6)$$

where $\tilde{d}$ describes the fractal dimensionality of the fluctuation network.

By assuming that the coherence length of the fluctuation regimes varies as in the Ginzburg-Landau theory, $\xi_c(T) = \xi_c(0)\varepsilon^{-\frac{1}{2}}$, where $\xi_c(0)$ represents the coherence length at T=0, we determine the correlation length for the fluctuation regimes along the c crystallographic axis. As show in table I, the correlation length for the homogeneous 3D regime, corresponds with the c lattice parameter. It is possible to infer that this 3D Gaussian regime, determines the spatial limit for the obtainment of long range order of the superconductivity in the material bulk.

Closer to T_c, a fourth power law region is observed in Fig. 3. This regime, which is labeled as λ_{CR}, is expected to be describes by the 3D-XY model, and corresponds to genuine critical fluctuations [1]. The critical exponent for fluctuation conductivity is given by

$$\lambda_{CR} = \nu(2 + z - d + \eta), \quad (7)$$

where ν is the critical exponent for the coherence length, z represents the dynamical critical exponent, d is the dimensionality of the system and η is the exponent for the order-parameter correlation function. Renormalization calculations

TABLE I: Gaussian exponents, dimensionalities, reduced temperatures and coherence lengths for the fluctuation regimes.

Regime	λ	d	ε	ξ_c (Å)
λ_{2D}	0.95±0.02	2.0	$0.347 \leq \varepsilon \leq 0.391$	$3.7 \leq \xi \leq 3.9$
λ_{3D-2D}	0.73±0.04	2.5	$0.086 \leq \varepsilon \leq 0.140$	$6.1 \leq \xi \leq 7.9$
λ_{3D}	0.54±0.07	3.0	$0.028 \leq \varepsilon \leq 0.032$	$12.9 \leq \xi \leq 13.7$

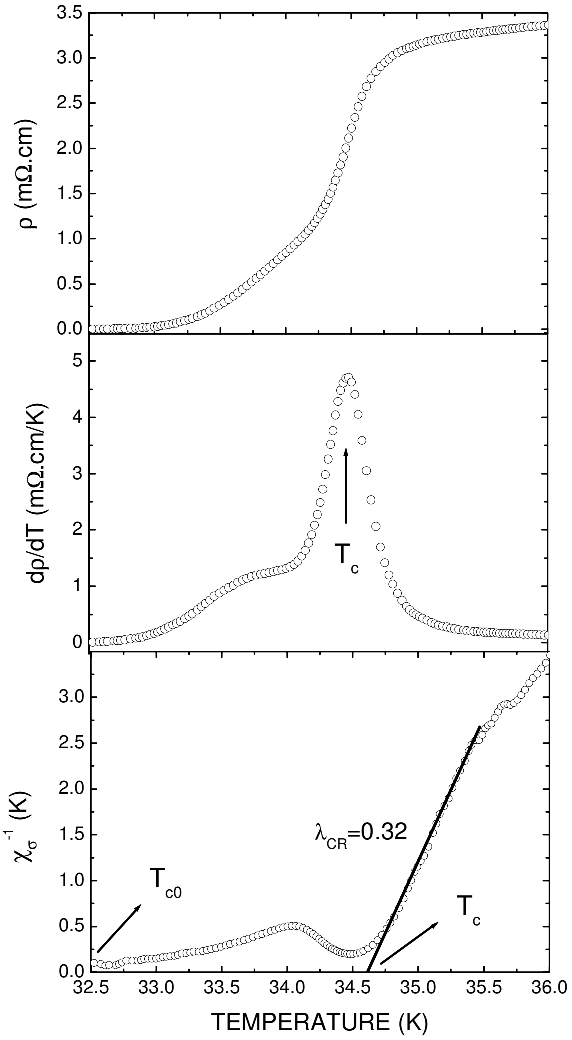

FIG. 2: Superconducting transition in $La_{1.82}Sr_{0.18}CuO_4$: (a) resistivity, $\rho(T)$, (b) temperature derivative, $d\rho(T)/dT$, and (c) logarithmic temperature derivative, χ_σ^{-1}.

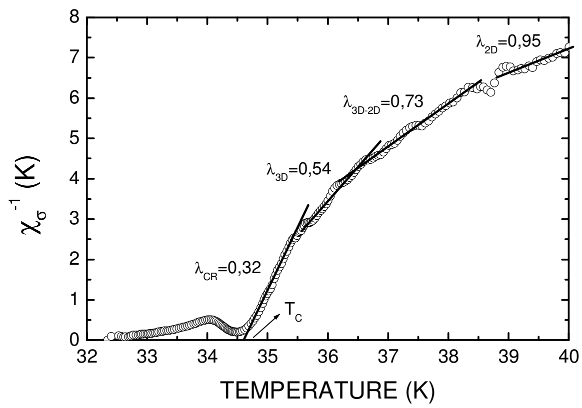

FIG. 3: Fluctuation regimes identified in χ_σ^{-1} as a function of temperature.

for the 3D-XY model supply the values ν=*0.67* and η=*0.03* [1]. Our result λ_{CR}=*0.32±0.08*, implies that $z = 1.5$, which is in agreement with the model-E (dynamical universality class for the superfluid transition in ^{4}He and for extreme type II superconductors [10]).

As shown in Fig. 4, below T_c, in the approach to the zero resistance state, we observe a characteristic scaling in $\chi_\sigma^{-1}(T)$ curves, for experimental data, in absence of magnetic field and for several values of transport current density. This result has the characteristic feature of the high temperature superconductors for low applied magnetic fields [1,8].

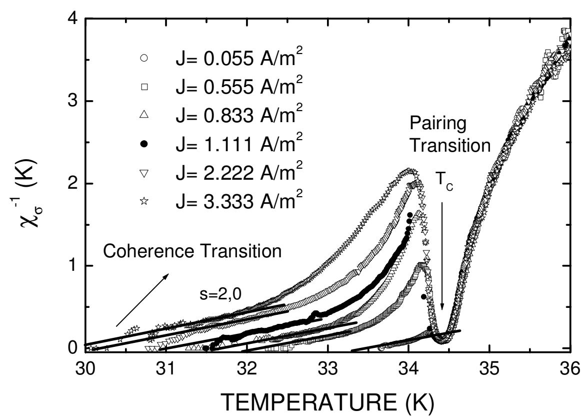

FIG. 4: Scaling regime, which is characteristic of the coherence transition for several transport current densities.

For the analysis of this fluctuation regime, we assume that $\Delta\sigma$ is given by equation (2), but using the critical exponent s and the reduced temperature $\varepsilon = \frac{T-T_{c0}}{T_{c0}}$. Thus, the critical exponent s for the fluctuation conductivity is given by equation (7) for a system with relevant disorder. For the percolation-like transition of granular superconductors [11], and in other disordered and frustrated systems [12], it has been proposed that ν=*1.3*. For $d = 3$ and assuming that η=*0*, the value $s = 2$

would be correspond to a vortex-glass-like behavior, with $\nu=2$ and $z = 3$ [13]. This picture is consistent with the expectations from the 3D-XY model for disordered systems [14]. The observation of glass-like behavior in our experiments at zero applied fields suggests that frustration arises from possible current generated self-field, which may attain non-negligible values near current constrictions in these granular samples.

V. CONCLUSION

We performed conductivity fluctuation measurements in the $La_{1.82}Sr_{0.18}CuO_4$ high temperature superconducting material. Close and above T_c, the conductivity fluctuation analysis reveal the occurrence of two fluctuation regimes characterized by the critical exponents $\lambda_{3D} = 0.54$ and $\lambda_{2D} = 0.95$, respectively. These regions were interpreted as corresponding to 3D and 2D Gaussian regimes, respectively. Another intermediate regime was identified, which is related with fluctuations develop in spaces with fractal topology between three and two dimensionalities. A genuinely critical fluctuation region with $\lambda_{CR} = 0.32$ was identified closer to T_c. This exponent value corresponds to a critical dynamic exponent, which is characteristic of the known as 3D-XY-E-model. This is the dynamical universality class for the superfluid transition in ^{4}He and also for extreme type II superconductors. Systematic measurements of $\Delta\sigma$ as a function of temperature where performed for several values of transport current j. Fluctuation analysis close to T_{c0} was performed and we clearly identified a characteristic exponent $\lambda_p = 2.0$, which is analyzed by the dynamical scaling theory and considering a percolation-like transition in a frustrated and disordered system. The observation of a glass-like behavior in our experiments permits to interpret our result as corresponding to a vortex-glass regime. This is indeed suggestive of a percolation-like transition associated to the connective nature of the granular array in cuprate high temperature superconductors. The vortex feature was attributed to current loops around the grains of material. These loops produce vortices of the Josephson type, which frustrate the granular system in similar form of low magnetic fields.

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[1] P. Pureur, R. Menegotto Costa, P. Rodrigues Jr., J. Schaf, and J. V. Kunzler, Phys. Rev. B **47**, 11420 (1993).
[2] R. Menegotto Costa, P. Pureur, L. Ghivelder, J. A. Campá, and I. Rasines, Phys. Rev. B **56**, 10836 (1997).
[3] J. Roa-Rojas, P. Pureur, L. Mendonça-Ferreira, M. T. D. Orlando, and E. Baggio-Saitovich, Supercond. Sci. Technol. **14**, 898 (2001).
[4] R. Menegotto Costa, P. Pureur, M. Gusmão, S. Senoussi, and K. Behnia, Solid State Commun. **113**, 23 (2000).
[5] L. G. Aslamazov, A. I. Larkin, Sov. Phys. Solid State **10**, 875 (1968).
[6] C. Lebeau, A. Raboutou, P. Peyral, and J. Rosenblatt, Physica B **152**, 100 (1988).
[7] J. S. Kouvel, S.E. Fisher, Phys. Rev. **136**, A1626 (1964).
[8] J. Roa-Rojas, R. Menegotto Costa, P. Pureur, and P. Prieto, Phys. Rev. B**61**, 12457 (2000).
[9] K. Char, A. Kapitulnik, Z. Phys. B **72**, 253 (1988).
[10] J. Lindmar, M. Wallin, C. Wengel, S. M. Girvin, and A.P. Young, Phys. Rev. B **58**, 2827 (1998).
[11] H. Kawamura, M. S. Li, Phys. Soc. Jpn. **66**, 2110 (1997).
[12] I. A. Campbell, Phys. Rev. B **37**, 9800 (1988).
[13] C. Wengel and A. P. Young, Phys. Rev. B **56**, 5918 (1997).
[14] A. R. Jurelo, I. Abrego Castillo, J. Roa-Rojas, L. M. Ferreira, L. Ghivelder, P. Pureur, P. Rodrigues Jr., Physica C**311**, 133 (1999).