Gaussian and critical fluctuations in the electrical conductivity of YBa$_2$Cu$_3$O$_{7.8}$ with chemically introduced disorder

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Abstract. We have studied experimentally by electrical magnetoconductivity measurements the influence of the site disorder, introduced by chemical doping, on the superconducting pairing transition of the YBa$_2$Cu$_3$O$_{7.8}$ superconductor. The measurements were performed in YBa$_2$Cu$_3$O$_{7.8}$ and YBa$_{1.9}$Sr$_{0.1}$Cu$_3$O$_{7.8}$ single crystals with low magnetic fields applied either parallel or perpendicular to the superconducting Cu-O atomic planes. The in-plane electrical conductivity results show the systematic occurrence of tree-dimensional Gaussian (3D), tree-dimensional XY (3DXY) and beyond tree-dimensional XY fluctuation regimes, as the temperature is decreasing toward the $T_c$ of our samples. We propose that the observed beyond tree-dimensional XY fluctuation regime is precursory to a weak first-order superconducting transition driven by antiferromagnetic excitations related to the pseudo gap phenomenon. The experimental results shows that chemical introduced disorder, by Sr doping, does not hardly affect the stability of the beyond tree-dimensional XY fluctuation regimes in the YBa$_2$Cu$_3$O$_{7.8}$ superconductor when $H \leq 600$Oe are applied.

1. Introduction

The nature of superconducting state of the high $T_c$ superconducting cuprates (HTSC) is characterized by a short coherence length of Ginsburg-Landau (GL) order parameter. In this scenario, structural disorder, like oxygen vacancies, which are present in the most pure crystals of HTSC, affects the GL order parameter and the nature of superconducting transition of these materials. On the other hand, scientific investigations focus on the effects from point like structural disorder on the superconducting pairing transition of the HTSC is scarce [1-3].

An alternative way to introduce point like disorder into a superconducting system is to partially substitute a chemical element of the compound structure. For instance, the partial substitution of Ba for Sr, in YBa$_2$Cu$_3$O$_{7.8}$ increases the disorder in the structure of this material [4,5]. It is evidenced by a dramatic increased NQR linewith [4]. The Sr substitution also induces a variation of structural parameters, causing a charge distribution. Bond valence sum calculations and nuclear quadrupole resonance measurement indicate a transfer of holes from oxygen to copper atoms in the CuO$_2$ planes and from copper to oxygen in the chains [4]. The linear decrease of $T_c$ as Sr doping level arises may be due to the increased site disorder [5]. The doping with Sr are responsible for increases of $J_c(H,T)$ and
even the development of a second peak [6,7] and enhancement of superconducting granularity in this system [1-3].

In this communication, we report on field-dependent fluctuation conductivity measurements in homogeneous YBa$_2$Cu$_3$O$_7$-δ [YBCO] and in the doped YBa$_{1.9}$Sr$_{0.1}$Cu$_3$O$_7$-δ [YB(Sr)CO] single crystals. We focus on the investigation of the effects from chemically introduced disorder on the electrical fluctuations conductivity regimes in the vicinity $T_c$ of the YBa$_2$Cu$_3$O$_7$-δ superconductor.

2. Experimental techniques and method of analysis

The single crystal samples of the studied systems were grown by the self-flux method [3]. The crystals were analyzed by X-ray diffraction. The obtained lattice parameters are in agreement with values reported in the literature for well oxygenated samples [2,4].

In-plane resistivity versus temperature measurements were performed with a low current-low frequency AC technique using a lock-in amplifier as a null detector. Constant magnetic fields in the range 0 – 600 Oe were applied in the configuration $H$ parallel to ab-planes ($H//ab$) and $H$ parallel to c-axis ($H//c$). During the measurements the temperature was swept (down) very slowly (0.05 K/min) and measured with a Pt thermometer having a resolution better than 2.10$^{-3}$ K. The resistive data points, $\rho(T)$ are spaced closely enough in order to allow a precise numerical calculation of the temperature derivative of the resistivity, $d\rho/dT$, for details see figure 1 [2,3,8].

We separate the contributions of thermal fluctuations to the measured conductivity by using a method based on the Kouvel-Fischer analysis of critical phenomena [8]. Their contribution can be estimated by subtracting from extrapolated linear resistivity, defined by the data well above $T_c$, the effectively measured resistivity. The possibly experimental uncertainty inherent to the adoption to this method [9] is minimized by the high density of the experimental $\rho(T)$ data recorded at the temperature scale correspondent to the normal state resistivity of our samples [3,8].

Assuming that excess electric conductivity $\Delta\sigma(T)$ diverges when the temperature approaches $T_c$ from above according to the power law

$$\Delta\sigma(T) = A(T - T_c)^{-\lambda},$$

where $A$ is a critical amplitude and $\lambda$ is a critical exponent. Then we calculate the temperature derivative of ln[$\Delta\sigma(T)$] and plot $[\chi_\sigma(T)]^{-1}$, obtaining

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

The existence of asymptotically critical fluctuation regimes becomes evident if a linear behavior of the data over considerable temperature intervals occurs in this plot and its temperature axis extrapolation yields the best evaluation of the paring critical temperature, $T_c$, see figure 2.

3. Results and discussion

The upper panels of figure 1 displays the superconducting resistive transition of the YBCO and YB(Sr)CuO samples to the $H//ab$ configuration. In order to make a closer examination of these superconducting resistive transitions we displayed in the lower panels of figure 1 its respective resistive temperature derivatives, $d\rho/dT$. It can be observed that $d\rho/dT$ data of the YBCO crystal is characterized by a single sharp peak that is barely affect by magnetic field. In contrast, the $d\rho/dT$ data of the YB(Sr)CO crystal is characterized by a single sharp peak followed by a satellite or a hump, at lower temperature scale. The satellite or hump is strong affected by the magnetic field. Similar behavior of $\rho(T)$ and $d\rho/dT$ was observed to the $H//c$ configuration.

These features, described in the last paragraph, characterizes the YBCO sample as a homogeneous superconductor and the YB(Sr)CO sample as a granular superconductor. The YB(Sr)CO granularity
can be a result of random distribution of oxygen rich superconducting regions that possibly are embedded in a weaker superconducting or no superconducting background material probably resulting from the Sr chemical doping.

![Graphs showing resistive transitions and temperature derivatives](image)

**Figure 1.** The characteristic resistive transitions (upper panels) and temperature derivatives (lower panels) of the YBa$_2$Cu$_3$O$_{7-\delta}$ [YBCO] and YBa$_{1.9}$Sr$_{0.1}$Cu$_3$O$_{7-\delta}$ [YB(Sr)CO] single crystals to $H \parallel ab$.

The upper temperature peak, $T_P$, in figure 1, marks the occurrence of the first step in the resistive transition of a granular superconductor. $T_P$ is well to correspond closely but not exactly to the pairing transition temperature $T_C$ within the superconducting grains, see figure 2. The second stage is related to superconducting grain coupling process and the establishment of a coherence transition where the zero resistance temperature, $T_0$, not represented in the figure 1, takes place only when grain coupling diverges and extends over the whole sample. In particular, the flux flow contributions on the superconducting magnetoresistivity transition of our samples are relevant at this second stage ($T < T_C$) and are specially intensified to the $H \parallel c$ configuration, but is important to remark that the focus of this paper is to study the magnetic field stability of the critical fluctuation regimes to $T > T_C$.

In figure 2 is shown a representative $[\chi_s(T)]^{-1}$ result for the pure YBCO and YB(Sr)CO single crystals when no magnetic field is applied. As the temperature approaches $T_c$ from above, a sequence of linear temperature behaviours may be seen for both samples. Farther from $T_c$, the regimes characterized by the exponents $\lambda_G = 0.50 \pm 0.03$, in the YBCO sample, and $\lambda_G = 0.49 \pm 0.03$, in the YB(Sr)CO sample, are due to 3D-Gaussian fluctuations. Decreasing the temperature, a crossover occurs to a genuine critical region at the Ginzburg temperature $T_G$ of our samples [3,8]. Two power
law regimes for the fluctuation conductivity are identified within the critical interval. Just below the Gaussian region, the regimes labeled by the exponents $\lambda_{XY} = 0.34 \pm 0.02$, in the YBCO sample, and $\lambda_{XY} = 0.30 \pm 0.03$, in the YB(Sr)CO sample, are characteristic of 3D-XY-E scaling [3,8]. The asymptotic fluctuation regimes corresponds to $\lambda_A = 0.17 \pm 0.02$, in the YBCO sample, and $\lambda_A = 0.17 \pm 0.03$, in the YB(Sr)CO sample. Its respective temperature axis extrapolation provides the $T_C = 93.72$ K for YBCO and $T_C = 91.52$ K for YB(Sr)CO. The overall behaviour depicted in figure 1 reproduces rather well previous observations in an YBCO crystal [3,8].

The fluctuation conductivity in superconductors is expected to diverge at $T_c$ as [8]

$$\lambda = \nu (z - 1 - \eta),$$

(3)

where $\nu$ is the critical exponent for the order parameter correlation length, $z$ is the dynamical exponent and $\eta$ is a small exponent related to the order parameter correlation function. In the mean-field 3D-Gaussian region, $\nu = 0.5$, $z = 2$ and $\eta = 0$. Then, from equation (3) one obtains $\lambda = 0.5$. For the 3D-XY-E model, $\nu = 0.67$, $\eta \approx 0.0$ and $z = 1.5$. Substituting these values in equation (3) one calculates $\lambda \approx 0.33$, which is in agreement with the experimentally observed $\lambda_{XY}$. The full dynamic 3D-XY-E scaling was observed in YBCO by several authors [3,8,10].

Figure 2. Plots of the $[\chi_{\sigma}(T)]^{-1}$ data for our YBa$_2$Cu$_3$O$_{7-\delta}$ [YBCO] and YBa$_{1.9}$Sr$_{0.1}$Cu$_3$O$_{7-\delta}$ [YB(Sr)CuO] samples. The $\lambda_A$ and $\lambda_{XY}$ exponents corresponds to critical fluctuations regimes. The $\lambda_G$ labels a 3D Gaussian regime. The straight lines are fittings to equation (2).

Figure 3 magnifies the $[\chi_{\sigma}(T)]^{-1}$ data in the narrow fluctuation regime beyond 3D-XY for all the studied systems. Measurements were performed in the presence of the quoted magnetic fields for $H \parallel c$ and $H \parallel ab$. The results in YBCO and YB(Sr)CO samples show that the external field tends to destabilize the super-critical regime so that the 3D-XY-E scaling is recovered around $H = 600$ Oe. The destabilization effect is more accentuated in $H \parallel c$ than $H \parallel ab$ field configurations.

The low values found for the conductivity critical exponent in the asymptotic regime immediately above $T_c$ raises the possibility that the superconducting transition in YBCO is weakly first-order. A first-order and discontinuous transition would be characterized by the exponent $\lambda = 0$. Thus, the observed regimes beyond 3D-XY-E may be interpreted as precursor to the ultimate first-order
transition in this HTSC. An interesting possibility is that the first-order transition is approached within a slowing down of the dynamics. Equation (3) shows that $\lambda = 0$ is reached when \( z \approx 1 \). Thus, considering that the static exponents \( \nu \) and \( \eta \) keep the values of the 3D-XY model, the asymptotic conductivity exponents $\lambda_{XY} \approx 0.33$, $\lambda_A \approx 0.17$ are obtained when we substitute in equation (3) the sequence \( z = 3/2 \) and \( 5/4 \), respectively. If this picture is valid, one might expect to observe still smaller exponents in the asymptotic conductivity regime of YBCO.

The mechanism that drives the superconducting transition in YBCO first-order is unknown. In a classical paper, Halperin, Lubensky and Ma, see reference [11], proposed that a superconducting transition may be driven first-order because of fluctuations of the electromagnetic field. However, the small magnitude of the blackbody radiation is too small to render the effect experimentally observable in an extreme type-II superconductor as YBCO. Recently, the influence of antiferromagnetic (AF) fluctuations was proposed by Ferreira, Continentino and Marino [12] as an alternative mechanism to render a superconducting transition weakly first-order. These authors studied the coupling between a two-component superconducting order-parameter and a metallic AF field within the Ginzburg-Landau

\[ \text{Figure 3. Plots of the } [\chi_\sigma(T)]^{-1} \text{ data for our single-crystal samples, showing the evolution of the asymptotic critical regime under several magnetic fields applied parallel and perpendicular to c-axis. The exponent values label fits to equation (2).} \]
theory including quantum corrections to one-loop order. In particular, they consider the case where two separate but in close proximity quantum critical points (QCP) occur along the carrier concentration axis. Due to proximity of the AF ground state, the superconducting QCP is shifted towards the magnetic QCP so that AF spin fluctuations may strongly affect the superconducting state. In particular, the magnetic fluctuations may drive the superconducting transition weakly first-order, as much as the fluctuations of the electromagnetic field in reference [11]. Calculations in reference [12] strictly applies to $T = 0$. However, in non-zero temperatures AF fluctuations related to the so-called pseudogap phenomenon are believed to play a relevant role in the normal phase of the HTSC [13]. Thus, one may conceive that a tendency to first-order behaviour occurs in the superconducting transition of the HTSC. This might explain the observation of the critical regimes beyond 3D-XY-E in the fluctuation conductivity of our samples.

On the other hand, from figure (3), it is evident that the fluctuations regimes dynamics observed above the paring transition in our YB(Sr)CO sample evolve with applied magnetic filed quite similarly as observed in our YBCO sample. This observed behavior suggests that chemical introduced disorder effects, like charge transfer [4] and chemical pressure [4], introduced by Sr doping, are irrelevant to the fluctuations regimes in YBCO.

In summary, we present fluctuation conductivity measurements in pure and doped YBCO single crystals that reveal the occurrence of critical regimes beyond 3D-XY-E that we attribute to the proximity of a weak first-order transition induced by AF excitations related to the pseudogap phenomenon and that chemical introduced disorder, by Sr doping, does not affect the stability of the 3D Gaussian and critical fluctuations regimes in the vicinity $T_c$ of the YBa$_2$Cu$_3$O$_{7-\delta}$ superconductor.

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