Fluctuation conductivity in melt-textured YBaCuO samples under low magnetic fields

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Abstract. We have studied thermal fluctuations of the electrical conductivity in melt-textured YBa₂Cu₃O₇ (YBCO) samples under low magnetic fields. Measurements were performed either for current applied parallel or perpendicular to the c-axis and fluctuation conductivity was studied in the proximity of the superconducting transition. Two melt processed samples were prepared with different concentrations of Y₂Ba₁Cu₁O₅ (Y₂11) phase. For the sample with lower concentration, 3D-Gaussian and genuine critical 3D-XY-E fluctuation regimes were identified in the conductivity parallel to the ab plane and a regime beyond 3D-XY was also observed. The 3D-XY-E scaling was also identified in the fluctuation conductivity along the c-axis. In the sample with higher concentration of the Y211 phase, disorder effects are relevant. The results indicate that the superconducting state in YBCO has a three-dimensional character, and suggest the presence of a sub-dominant order-parameter component that has an appreciable projection along the c-axis.

1. Introduction

Thermodynamic fluctuation regimes are observed in transport properties of the high-T_c cuprates (HTSC’s), below and above the critical temperature [1].

Owing to the millimeter size of the melt-textured samples along the c-axis, direct conductivity measurements parallel to this orientation may be accomplished using the four-contact method. A relatively small number of investigations have been done on the effects of fluctuations in the
conductivity along the c-axis of the HTSC and, in this scenario, melt-textured YBCO represents an interesting system to study anisotropic effects in the electrical conductivity.

In this paper we report measurements of fluctuation conductivity as a function of the temperature under low applied magnetic fields in melt-textured YBCO samples with different Y211 phase contents. Conductivity measurements were performed parallel to the ab plane and along the c-axis. Our experiments show that 3D-XY fluctuations [2] occur in the conductivity along the c-axis. This result indicates that the superconducting state in YBCO has a three-dimensional character.

2. Experimental details and method of analysis

We prepared two melt-textured YBCO samples by the top-seeding technique [3,4]. The nominal contents of Y211 particles added to the precursor composite were 17 and 30 wt%. The respective samples were labeled TS-17 and TS-30. Conductivity measurements were performed as a function of temperature within the configurations H//ab or H//c for currents J//ab and J//c, where ab refers to the orientation of the atomic Cu-O2 planes. Several values of the field were applied in the range 0 to 500 Oe. The measurements were performed using a low-frequency low-current ac technique.

The conductivity measurements were analyzed in terms of the quantity \( \chi_\sigma = -d(\ln \Delta \sigma)/dT \) [5], where \( \Delta \sigma \) is the fluctuation conductivity, from which we obtain \( \chi_\sigma^{-1} = \lambda/(T - T_c) \). Then, it is possible to determine \( T_c \) (critical temperature) and \( \lambda \) (critical exponent) by identifying linear segments in plots of \( \chi_\sigma^{-1} \) vs. \( T \). The uncertainties tend to become very small near \( T_c \), since a large fraction of the total conductivity in this temperature region is due to fluctuations, and the exponents could be estimated with errors around 10%. More details about this method are given in Ref. [6].

3. Results

3.1. Current parallel to the ab plane (J // ab)

Figure 1(a) shows the in-plane resistive transition in zero applied field for the TS-17 sample, represented as \( \chi_{\sigma(ab)}^{-1} \) vs. \( T \). This result reproduces observations in a single-crystalline YBCO sample [6]. A temperature region dominated by three dimensional (3D)-Gaussian fluctuations is evidenced by
the exponent $\lambda_c \cong 0.5$ [7]. Approaching $T_c$, a crossover occurs to a regime characterized by the exponent $\lambda_{XY} \cong 0.33$, predicted by the 3D-XY-E scaling theory [2]. Further approaching $T_c$, a scaling ‘beyond 3D-XY’ denoted by the exponent $\lambda_{3D} = 0.17$ is clearly observed. This regime is destabilized under the application of quite low fields.

The figure 1(b) shows the results for the TS-30 sample in zero applied field. Disorder at the microscopic level, induced by the Y211 particles, modifies the fluctuation conductivity in the normal phase and only the 3D-Gaussian exponent may be observed. This regime is stable until 500 Oe.

3.2. Current parallel to the $c$-axis ($J // c$)

The $c$-axis resistivities are metallic in the normal phase, and we could extract the $c$-axis fluctuation conductivity using the same procedure as for the in-plane component. Figure 2 depicts the $c$-axis $\chi_{\sigma(c)}^{-1}$ vs. $T$ data for the TS-17 sample in zero magnetic field. A straight line behavior could be identified only in the asymptotic regime close to $T_c$. Interestingly enough, the value found for the exponent matches the one predicted by the 3D-XY-E model when magnetic fields up to 100 Oe are applied in this sample. The $c$-axis resistivity in the whole measured range is shown in the inset.

For the TS-30 sample only the 3D-Gaussian regime was observed. This regime is unaffected by the applied magnetic fields and the results are very similar to results obtained for the $J // ab$ configuration.

4. Discussion

Our results are very different for the two studied samples. The TS-17 sample shows strong planar anisotropy and the data in this case are representative of the intrinsic behavior of YBCO. On the other hand, the large amount of the Y211 phase added to the TS-30 sample weakens the anisotropy and induces effects of disorder in the fluctuation conductivity near the transition.
In the TS-17 sample we observe critical conductivity fluctuations, described by the 3D-XY-E model, for both current orientations. This result shows that superconducting state in YBCO is a genuine three dimensional and anisotropic phenomenon. The validity of the 3D-XY-E model for both conductivity components is consistent with the description of YBCO as a Fermi liquid system. This conclusion is reinforced by the observation of 3D-Gaussian fluctuation regimes. The critical scaling regime ‘beyond 3D-XY’ observed in the TS-17 sample was suggested to be precursor of the ultimate weak first-order character of the superconducting transition in YBCO [6]. A significant work to describe the weakly first-order transition was proposed by Halperin, Lubensky, and Ma [8]. The fluctuation conductivity results in the TS-30 sample are severely affected by disorder introduced by the Y211 phase, but also confirm the 3D character of the transition in YBCO. The applicability of the 3D-XY-E thermodynamics indicates that the superconductivity in YBCO can be described by a single two-component order parameter of \(d\)-type or anisotropic \(s\)-type symmetry.

Our data also reveal a subtle splitting of the superconducting transition that may implies the occurrence of some hybridization in the pairing wave function. Comparing the critical temperatures extrapolated from the 3D-XY-E and Gaussian regimes for the \(J//ab\) and \(J//c\) configurations in the TS-17 sample, we find that the critical temperature for the \(J//c\) orientation exceeds by 0.5 K the critical temperature for the \(J//ab\) orientation. This result is independent of the applied magnetic field. This difference is much larger than our experimental resolution and can be credited as an intrinsic property of YBCO. This surprising result suggests that the superconductivity first stabilizes perpendicularly to the Cu-O \(_2\) atomic planes. This result may indicate that oxygen \(p_z\) and copper \(3d_{x^2-y^2}\) orbitals, which have relevant projection along the \(z\) axis, are decisive for describing the superconductivity in YBCO. The same value for the difference \(T_c(c) - T_c(ab)\) was found in a YBCO single-crystal [9]. On the other hand, no such difference was found in the disordered TS-30 sample.

5. Conclusions

Fluctuations of the electrical conductivity in two melt-textured YBCO samples with different Y211 phase inclusions were investigated. The results for the sample with smaller concentration of Y211 phase are credited to the YBCO intrinsic behavior. In this sample 3D-Gaussian and 3D-XY-E regimes were observed in the in-plane fluctuation conductivity. An asymptotic regime described by a scaling beyond 3D-XY-E that is characterized by a small critical exponent was also observed. Genuine critical 3D-XY-E and 3D-Gaussian regimes were evidenced in the \(c\)-axis fluctuation conductivity for the sample with the lowest content of Y211 phase. This important result indicates that the superconductivity in YBCO has a three-dimensional character. We found that \(T_c(c)\) exceeds \(T_c(ab)\) by 0.5 K. This interesting result suggests the presence of a sub-dominant order-parameter component in YBCO having a considerable projection along the \(c\)-axis. On the other hand, disorder destroys the genuine critical fluctuation conductivity regimes and only the 3D-Gaussian contribution was observed in the sample with larger content of the Y211 phase.

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