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Measurements of the fluctuation magnetization around T_C in a $YBa_2Cu_3O_7$ crystal: Determination of the critical-region width

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Abstract

We present measurements of the fluctuation-induced magnetization around the superconducting transition in a $YBa_2Cu_3O_7$ single crystal. The data were analyzed in terms of the Ginzburg–Landau theory for multilayered superconductors. The simultaneous analysis in the low magnetic field region above T_{C0} and in the high magnetic field region around $T_C(H)$ allowed us to obtain accurate information on the critical region width (which was found to be in excellent agreement with the prediction of the Ginzburg criterion) and also on the ratio of Josephson couplings between the different superconducting layers.

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1. Introduction

Thermal fluctuations of vortices and Cooper pairs have been an important research topic since the discovery of the high temperature superconductors (HTSC) [1]. One of the issues which has attracted more attention is their behavior in the critical region around the superconducting transition. The Ginzburg–Landau theory in the lowest Landau level approximation (or GL-LLL theory) predicts that in this region several observables present an scaling behavior [2], that was soon observed experimentally [3]. Since then, new important contributions have been reported: for instance, Tesanovic et al. [4] developed a non perturbative approach to the GL equations which allowed to calculate the explicit scaling functions for both two- and three-dimensional fluctuations. In spite that, in principle, this should allow a much more convincing comparison with the experiments [5], some important aspects remain still open. An example is the long-standing discussion concerning the extension and topology of the regions in the superconducting phase diagram where the GL-LLL and the 3D-XY theories for the critical fluctuations hold [6].

In this paper, we present new measurements of the fluctuation-induced in-plane (for $H \perp ab$ planes) magnetization ΔM_{ab} in the critical region of a high quality $YBa_2Cu_3O_7$ (Y-123) single crystal. These data are complemented with ΔM_{ab} measurements in the low magnetic field region above T_{C0}. The combined analysis of the experimental data in these two regions of the phase diagram allowed us to obtain reliable information about the applicability of the GL-LLL theory to the critical region. In particular, we found that the critical region width is in excellent agreement with the prediction of the so-called field dependent Ginzburg criterion [7]. As a complementary result, we obtained information on the ratio of Josephson couplings between the different layers in these multilaminar HTSC compounds.

2. Experimental details and results

The Y-123 single crystal was grown by using the self-flux growth method, and annealed in pure O_2 for ~1 week at 425 °C. Polarized-light optical microscopy revealed the

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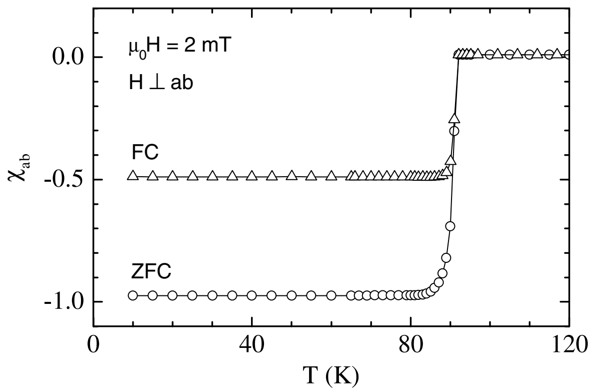

Fig. 1. Temperature dependence of the FC and ZFC magnetic susceptibility for a low applied magnetic field. These data are already corrected for demagnetizing effects.

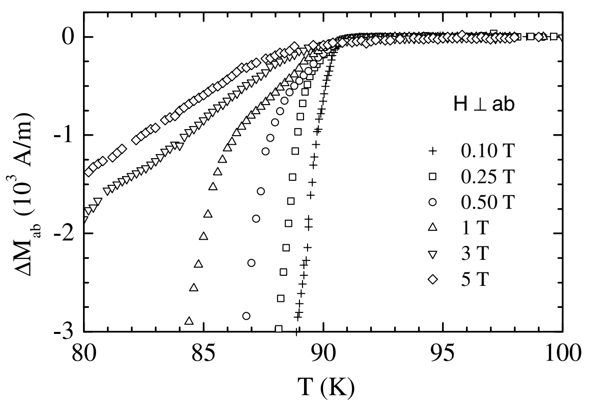

Fig. 2. Temperature dependence of the fluctuation magnetization around T_{C0} for different applied magnetic fields.

presence of micro twins in the *ab* plane, but X-ray diffraction confirmed the excellent alignment of the *c*-axis and discarded the presence of impurity phases. The magnetization measurements were made with a commercial SQUID magnetometer (Quantum Design, model MPMS). As magnetic characterization, in Fig. 1, we present the temperature dependence of the field-cooled (FC) and zero-field-cooled (ZFC) magnetic susceptibilities under a 2 mT magnetic field perpendicular to the *ab* planes. The sharp superconducting transition ($\Delta T_{C0}/T_{C0} \sim 0.02$) and the relatively high Meissner fraction confirm the good structural and stoichiometric quality of the crystal [8].

In Fig. 2, we present the temperature dependence of the fluctuation in-plane magnetization ΔM_{ab} around the transition for field amplitudes ranging from 0.1 to 5 T. These data are already corrected for the normal-state contribution, which is almost constant (~320 A/m) in the region ~120–200 K.

3. Theoretical background and analysis

For magnetic field amplitudes high enough to confine the Cooper pairs in the lowest Landau level (LLL), the fluctuations acquire an one-dimensional character along the magnetic field direction. This fact increases the importance of the fluctuations in a temperature region around the transition which grows with the magnetic field as given by the so-called field-dependent Ginzburg criterion, which for 3D materials like Y-123 may be written as [7]

$$\frac{|\Delta T_C|}{T_C} \leqslant 2\varepsilon_G^{1/3}\left(\frac{H}{H_{C2}(0)}\right)^{2/3}, \tag{1}$$

where $H_{C2}(0)$ is the upper critical magnetic field for $H \perp ab$ extrapolated to $T = 0$ K, and ε_G is the Ginzburg reduced temperature, which limits the critical region for $H = 0$ [9]. The magnetization in this region presents a scaling behavior in the variables [2]

$$m \equiv \frac{\Delta M_{ab}}{(HT)^{2/3}} \tag{2}$$

and

$$t \equiv \frac{T - T_C(H)}{(HT)^{2/3}} = \frac{T - T_{C0}[1 - H/H_{C2}(0)]}{(HT)^{2/3}}. \tag{3}$$

In the weak magnetic field limit for temperatures above T_{C0}, the fluctuation-induced magnetic susceptibility for bilayered superconductors has been calculated by Ramallo et al. [10], from a generalization of the Lawrence–Doniach (LD) functional. For $H \perp ab$ and in the weak magnetic field limit ($H \ll H_{C2}(0)$) is given by

$$\frac{\Delta\chi_{ab}}{T} = -N_{\rm eff}(\varepsilon)\frac{A_S}{\varepsilon}\left(1 + \frac{B_{LD}}{\varepsilon}\right)^{-1/2}, \tag{4}$$

where $A_S = \pi\mu_0 k_B \xi_{ab}^2(0)/3\phi_0^2 s$ is the Schmidt diamagnetism, $B_{LD} = (2\xi_c(0)/s)^2$ is the LD parameter, $\xi_{ab}(0)$ and $\xi_c(0)$ are the coherence length amplitudes perpendicular and, respectively, parallel to the *ab* planes, $\varepsilon = |T - T_{C0}|/T_{C0}$ is the reduced temperature, *s* the superconducting layers periodicity length, and $N_{\rm eff}$ the effective number of planes in *s*. If the Josephson coupling between closer planes is much bigger than between the more distant planes ($\gamma_1/\gamma_2 \gg 1$) then the biplanes will behave as an unique plane without internal structure and $N_{\rm eff} \sim 1$. On the other hand, if $\gamma_1/\gamma_2 \approx 1$ then $N_{\rm eff}$ will have a ε-dependent value given by [10],

$$N_{\rm eff}(\varepsilon) = 2\sqrt{\frac{1 + 4\xi_c^2(0)/s^2\varepsilon}{1 + 8\xi_c^2(0)/s^2\varepsilon}}. \tag{5}$$

The fluctuation induced in-plane diamagnetism above T_{C0} for a low magnetic field [i.e., for $H \ll H_{C2}(0)$] is presented in Fig. 3. The solid line is the best fit of Eq. (4) to the experimental data in the region bounded by the arrows, for the two γ_1/γ_2 scenarios commented above and with $\xi_{ab}(0)$ and $\xi_c(0)$ as free parameters. The resulting values for both coherence lengths are summarized in Table 1.

In Fig. 4 it is presented the scaling of the $\Delta M_{ab}(T)_H$ data in the critical region. To construct the scaling variable for the temperature (Eq. (3)) we used the well known