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Dimensional crossover in $La_{1.85}Sr_{0.15}CuO_4$

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Abstract

We exploit the magnetic flux rotation effect under tilted fields, and its associated magnetization peak, to study the temperature induced crossover from a 2D to 3D behavior in $La_{1.85}Sr_{0.15}CuO_4$. Measurements of the peak field versus temperature show a pronounced anomaly around the theoretical 2D–3D crossover temperature (~12 K). Analysis of the data on both sides of this anomaly shows two distinct regimes corresponding to a 2D and 3D behavior.

Keywords: High-temperature superconductors; $La_{1.85}Sr_{0.15}CuO_4$; Dimensional crossover; Flux rotation

1. Introduction

The layered structure of high-temperature superconductors (HTS) and their relatively small coherence length cause these materials to be highly anisotropic magnetically, and under certain conditions to approach a two-dimensional (2D) behavior expected for a stack of decoupled superconducting film planes [1,2]. The two dimensional regime (2D) is well described by the Lawrence–Doniach (LD) model [1], which reduces to the Landau–Ginzburg (LG) anisotropic 3D model when the transverse coherence length crosses the interlayer spacing. The common criterion for the 2D–3D crossover is $\xi_c = d/\sqrt{2}$ where ξ_c is the coherence length along the *c*-axis and *d* is the distance between layers [3]. Since, the coherence length diverges as the temperature approaches the transition temperature T_c, a detectable crossover temperature T^* separating the 2D and 3D regimes is expected in HTS. A variety of experimental techniques were used in order to detect the 2D–3D crossover, including torque [4,5] and vector magnetization [6] measurements with field oriented close to the *ab* planes, and transport measurements [7]. In all these measurements, deviations from the 3D GL model with decreasing temperature have been interpreted as a crossover to the 2D regime.

In this paper, we study the 2D–3D crossover in $La_{1.85}Sr_{0.15}CuO_4$ employing a unique method, which exploits the additional magnetization peak (AMP), appearing in between the well-known first and second magnetization peaks, when the external field is slightly tilted from the *ab* plane [8,9]. In a previous paper [9], we showed that the origin of this peak is flux rotation from the *ab* plane towards the field direction, which causes a tilt of the current flow plane towards an easy direction (*ab* plane), giving rise to magnetization increase. As explained below, the flux rotation effect is sensitive to the system dimensionality, and thus the AMP can serve as an indicator to the 2D–3D crossover.

Parallelepiped shaped samples with dimensions $0.193 \times 0.122 \times 0.072\ cm^3$ were cut from a single crystal of optimally doped $La_{1.85}S_{0.15}CuO_4$ ($T_c = 38$ K), grown by the traveling-solvent-floating-zone method [10]. Using a Quantum Design MPMS-5S SQUID magnetometer equipped with a horizontal rotator, the magnetization components M_L and M_T parallel and perpendicular to $\vec{H}$, respectively, were measured as a function of the external field *H*, for fields applied at different angles θ_H relative to the *ab* plane. Measurements of M_L and M_T enable us to determine the magnitude and direction of the vectors $\vec{M}$ and $\vec{B}$. A schematic diagram of the external magnetic field

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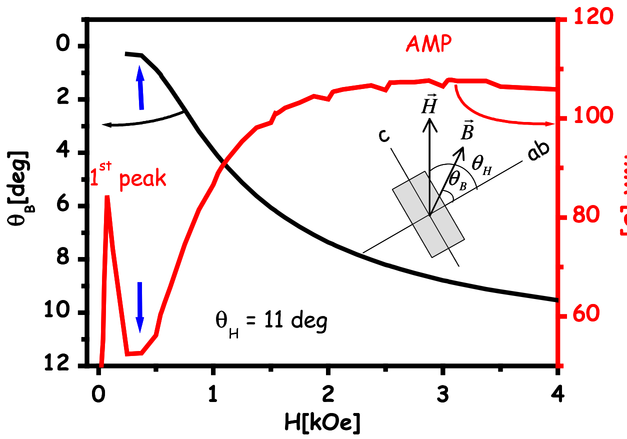

Fig. 1. Field dependence of M and θ_B, both measured in a field tilted at 11° to the ab plane.

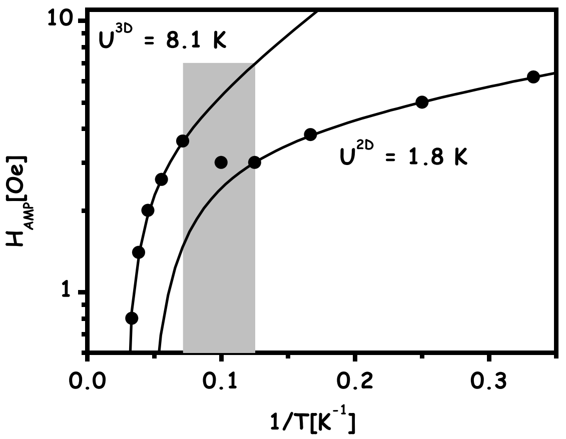

Fig. 2. AMP field vs. inverse temperature. Shaded area indicates the 2D–3D crossover region. Solid lines are theoretical fits.

$\vec{H}$ and the induction $\vec{B}$ relative to the sample crystallographic axes is shown in the inset to Fig. 1. After the sample was zero-field cooled to the target temperature an external field was applied at a constant angle to the ab planes, and swept from 0 up to 50 kOe and back down to zero in steps of 500 Oe.

2. Results and discussion

Fig. 1 compares the field dependence of M and θ_B, both measured in a field tilted at $\theta_H = 11°$ to the ab plane. The θ_B vs. H curve in the figure demonstrates the "lock in" and flux rotation effects. For fields up to ~400 Oe flux remains "locked" parallel to the ab plane. For larger fields flux rotates towards the field direction. A comparison of $M(H)$ and $\theta_B(H)$ curves in Fig. 1 shows that the onset of the AMP and the beginning of deviation of $\vec{B}$ from the ab plane occurs at the same field (about 400 Oe). In the following we show that the temperature dependence of the AMP can provide information on the dimensionality of the system.

Clearly, the onset of flux rotation corresponds to a field H for which the lock-in angle $\theta_0(H)$ is just below θ_H. As shown by Kwok et al. [11], θ_0 exhibits different field dependence, depending on the dimensionality of the system. In the absence of pinning associated with defects, they showed that $\theta_0 \sim [(1 - T/T_c)/H]^{0.5}$ and $\theta_0 \sim [(1 - T/T_c)/H]\ln(d/\xi_c)$, for 3D and 2D systems, respectively. These relations can be inverted to provide the dependence of the onset field of rotation on temperature for different θ_H. To account for pinning effects, we further introduce a thermal activation factor $\exp(U/kT)$, leading to the following expressions for the peak field H_{AMP} in 2D and 3D systems:

$$H^{3D}_{AMP} = c(1 - T/T_c)\exp(U^{3D}/kT) \tag{1}$$

$$H^{2D}_{AMP} = c_1(1 - T/T_c)[1 + c_2\ln(1 - T/T_c)]\exp(U^{2D}/kT) \tag{2}$$

where c, c_1, c_2 are constant parameters and U is the activation energy for flux rotation. Based on these results one expects different temperature dependence for the onset of the AMP in the 2D and 3D regimes. Thus, measurements of the AMP as a function of temperature should reveal 2D–3D crossover.

Fig. 2 shows the AMP field as a function of inverse temperature for field applied at 11° to the ab planes. An anomalous non-monotonic behavior is evident in the range 10–14 K. The theoretically calculated 2D–3D crossover fall in this region, as for $La_{1.85}Sr_{0.15}CuO_4$, $\xi_c \approx 0.3$–0.4 nm, $d \approx 0.7$ nm and $T_c = 38$ K, yielding $T^* = (1 - 2\xi_c(0)^2/d^2)T_c$ in the range of: $T^* = 10$–20 K. The solid curves in Fig. 2 are fits to Eqs. (1) and (2) for the 3D and 2D regimes. This fits yield $U^{2D} = 1.8$ K, $U^{3D} = 8.1$ K for the activation energy for the thermally activated flux rotation in the 2D and 3D regimes, respectively. This result implies that it is easier to rotate fluxons in a 2D than in a 3D system. This is plausible because in a 2D system flux penetrates into the ab plane as a Josephson vortices; the pinning force associate with them is small compared to Abrikosov vortices since in Josephson vortices the order parameter has a finite value even at the core of the vortex.

Acknowledgements

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