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Magnetic anomalies in $La_{1.85}Sr_{0.15}CuO_4$ crystals under tilted fields

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Abstract

Magnetization curves of $La_{1.85}Sr_{0.15}CuO_4$ in fields slightly tilted from the *ab* plane exhibit an additional magnetization peak (AMP) in between the well-known first and second magnetization peaks. Measurements of the induction vector versus field reveals flux rotation from the *ab* plane towards the direction of the external field, beginning at the onset of the AMP. Characterization of the AMP and flux rotation as a function of temperature, time and tilting angle, shows a strong correlation between the two phenomena. This correlation is explained by considering variations in the magnetization caused by a tilt of the current flow plane associated with the flux rotation. Simulations of the magnetization curves based on the proposed model agree well with the experimental results.

Keywords: High temperature superconductors; $La_{1.85}Sr_{0.15}CuO_4$; Magnetization curves; Flux rotation; Magnetic anisotropy

1. Introduction

The layered structure of high temperature superconductors is a source of new magnetic phenomena that cannot be merely attributed to the anisotropy in the electronic effective mass. An example of such a phenomenon is the "lock-in" effect [1] observed when a small external magnetic field is applied at a small angle θ_H to the *ab* plane. It was shown [1,2] that there is a finite lock-in angle $\theta_0(H)$, such that when $\theta_H < \theta_0$, the flux lines run parallel to the planes, remaining "locked in" between the layers. Raising the external field decreases θ_0 below θ_H, causing flux rotation towards the direction of the external field. In this work we describe measurements of this flux rotation in $La_{1.85}Sr_{0.15}CuO_4$ (LSCO) and show that it is strongly correlated with the appearance of an additional magnetization peak (AMP) in between the well-known first and second peaks in the magnetization loop [3]. We argue that the AMP results from a tilt of the current plane from a "hard" to "easy" direction accompanied by the flux rotation [4].

Measurements were performed on a parallelepiped shaped $0.193 \times 0.122 \times 0.072$ cm^3 $La_{1.85}Sr_{0.15}CuO_4$ (LSCO) crystal ($T_c = 38$ K), grown by the traveling-solvent-floating-zone method [5]. 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 $\vec{H}$, for fields applied at different angles θ_H relative to the *ab* plane. A schematic diagram of the external magnetic field $\vec{H}$ and the induction $\vec{B}$ relative to the sample crystallographic axes is shown in the inset to Fig. 1. Measurements were performed after zero-field cooling the sample to the target temperature. The external field was swept from 0 up to 50 kOe and back down to zero in steps of 500 Oe.

2. Results and discussion

Fig. 1 shows the AMP, measured at $T = 20$ K, for θ_H between 9° and 19°. The first peak and the second peak (not resolved in this scale) are in the field range 0.1–0.3 and 30–50 kOe, respectively. As θ_H increases beyond 19°, the AMP shifts towards lower fields, becoming less and less pronounced and eventually disappears for $\theta_H \gtrsim 35°$. As temperature increases the AMP shifts monotonically to lower fields and its height decreases. At a constant temperature, the AMP shifts slowly with time towards lower fields.

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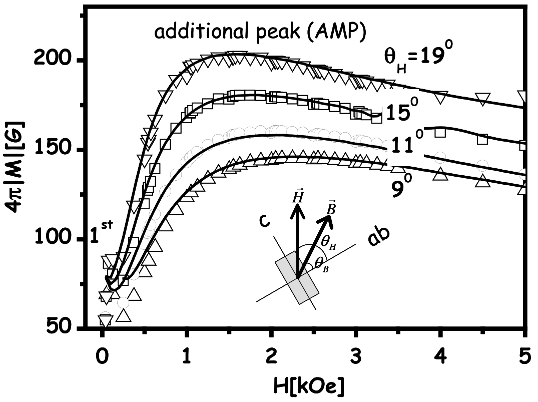

Fig. 1. M versus H measured in fields tilted at the indicated θ_H values. Solid curves are theoretical fits based on Eq. (1). Inset: Schematic diagram of the external magnetic field $\vec{H}$ and the induction $\vec{B}$ relative to the sample crystallographic axes.

The flux rotation phenomenon is illustrated in Fig. 2, showing the angle θ_B between $\vec{B}$ and the *ab* plane, as a function of H, for the same θ_H values as shown in Fig. 1. The lock-in effect is demonstrated in this figure in the data corresponding to θ_H values of 9° and 11°; in the low field range (0–500 Oe), $\vec{B}$ is parallel to the *ab* plane, i.e., flux is trapped in this plane. As the external field increases, flux 'leaves' the *ab* plane and rotates towards the direction of $\vec{H}$. The rotation begins at lower fields as θ_H increases. Analysis of the data in the low field range shows that the onset of the AMP and the field indicating the beginning of flux rotation coincide. Measurements of the temperature and time dependence of θ_B reveal a similar behavior as observed for the AMP, namely the rotation starts at lower fields as temperature increases and, at a constant field and angle, $\vec{B}$ rotates with time towards the direction of $\vec{H}$.

The data described above indicate strong correlation between the AMP and the flux rotation process. We explained this correlation by taking into account variations in $\vec{M}$ caused by a tilt of the current flow plane associated with the flux rotation. As a consequence of the anisotropic effective mass, currents have both "easy" and "hard" flow planes, parallel and perpendicular to the *ab* plane, respectively. Thus, a change of θ_B from 0° to θ_H with increasing field corresponds to a change of the current flow from a hard plane towards an easy plane, leading to an increase in M. On the other hand, the current, and thus, the magnetic moment, intrinsically reduce as the field increases. A competition between these two effects creates a peak in the magnetization curve identified as the AMP.

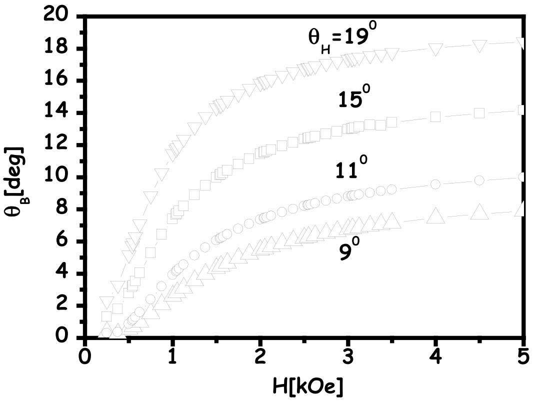

Fig. 2. Illustration of flux rotation phenomenon as a function of the external field H, applied at the indicated values of θ_H.

Simulations of the AMP based on this model are described by the solid lines in Fig. 1. These curves were calculated in the following way: the field dependence of the angle $(\theta_H - \theta_B)$ between $\vec{B}$ and $\vec{H}$ was taken from the experimental data described in Fig. 2. The intrinsic field dependence of M was determined from the descending branch of the hysteresis loops, where the AMP is absent. Theoretical fits yield $M \propto H^{-0.15}$ for a large range of tilting angles. The magnitude of $\vec{B}$ was taken as the component of $\vec{H} + 4\pi\vec{M}$ along the $\vec{B}$ direction, where we took into account an increase of the magnetization component along $\vec{B}$ by a factor $\varepsilon = \sqrt{(\cos(\theta_B)/\gamma)^2 + \sin^2\theta_B}$, in accordance with the 3D scaling law [6], where γ is the anisotropy ratio. This yields:

$$B = H\cos(\theta_H - \theta_B) - \varepsilon C[\varepsilon H\cos(\theta_H - \theta_B)]^{-0.15}, \tag{1}$$

where C is a constant. Knowledge of $\vec{B}$ and $\vec{H}$ allows calculation of $\vec{M}$. The calculated M versus H (solid curves in Fig. 1) yield excellent fits to the experimental data, using $C = 1530$ G for a large range of angles. Small deviations are observed only at low fields corresponding to very small θ_B where the 3D scaling law may not be applied because of possible formation of 'kinked' or crossed lattices vortex structures where Josephson vortices are involved.

In conclusion, the AMP is a result of two competing effects: a magnetization increase due to a tilt in the current flow plane to an easy direction accompanied by the flux rotation, and magnetization decrease due to current reduction with increasing field. Simulations of the AMP based on this model show a good agreement with the measured data for a wide range of tilting angles.

Acknowledgements

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