JOURNAL OF APPLIED PHYSICS **101**, 09G115 (2007)

Time relaxation of flux rotation and dimensional crossover in $La_{1.85}Sr_{0.15}CuO_4$

Y. Bruckental,[a] A. Shaulov, and Y. Yeshurun
Institute of Superconductivity, Department of Physics, Bar-Ilan University, Ramat-Gan 52900, Israel

(Presented on 9 January 2007; received 23 October 2006; accepted 18 December 2006; published online 7 May 2007)

Vector magnetization measurements in $La_{1.85}Sr_{0.15}CuO_4$ under a steady field **H** tilted relative to the *ab* plane show that the induction **B** rotates toward **H** with time. The rate of rotation as a function of temperature exhibits two peaks separated by a dip around 12 K. Measurements of the remnant induction show that for temperatures below ~12 K, **B** rotates towards the *c* axis, whereas for temperatures above ~12 K, **B** rotates towards the *ab* planes. We argue that these data are consistent with a two-dimensional and a three-dimensional behavior below and above the dimensional crossover temperature, ~12 K, respectively. © *2007 American Institute of Physics*.

[DOI: 10.1063/1.2712293]

I. INTRODUCTION

The cuprate high temperature superconductors are characterized by a short coherence length ξ_c which at low temperatures may even become smaller than the spacing d between the superconducting Cu-O layers. When ξ_c is sufficiently smaller than d, the system exhibits a quasi-two-dimensional (quasi-2D) behavior.[1,2] As temperature increases, ξ_c increases, and for $\xi_c(T^*) \sim d/\sqrt{2}$ a crossover to a three-dimensional (3D) behavior occurs at crossover temperature T^* given by[2]

$$T^* = T_c[1 - 2\xi_c(0)^2/d^2]. \quad (1)$$

A variety of experimental techniques—such as torque,[3,4] vector magnetization,[5] and transport measurements[6]—were used in order to detect the 2D-3D crossover in various superconductors. In a recent work,[7–9] we demonstrated an approach to study the 2D-3D crossover in $La_{1.85}S_{0.15}CuO_4$ (LSCO), utilizing the flux rotation effect and its associated magnetization peak. This anomalous magnetization peak appears between the well-known first and second peaks when the external field slightly deviates from the *ab* plane.[7,10] It was shown[8,9] that this additional peak is developed as a result of flux rotation towards **H**. For a fixed tilting angle, at low fields the flux is "locked in" between the superconducting layers. As the field increases beyond a certain critical value, the flux starts rotating towards the external field direction. Our measurements of the critical field as a function of temperature revealed a remarkable crossover around 12 K. We demonstrated that this crossover temperature is consistent with the theoretically anticipated 2D-3D transition in $La_{1.85}Sr_{0.15}CuO_4$ (using the known values of ξ and d), and that the data below and above this temperature correspond to a 2D and a 3D behavior, respectively. We concluded that the flux rotation effect is sensitive to the system dimensionality and thus can serve as an indicator to the 2D-3D crossover.

In this paper we present results which further support this conclusion. We demonstrate magnetic measurements of the time relaxation of the flux rotation in the presence of a tilted field and rotation of the remnant flux after turning off the field. Both reveal a striking change in the behavior around 12 K. We argue that the data below and above 12 K correspond to the behavior of 2D and 3D systems, respectively.

II. EXPERIMENT

A parallelepiped shaped 0.72 × 1.22 × 1.93 mm^3 sample, with the largest dimension along the *c* axis, was cut from a single crystal of optimally doped $La_{1.85}Sr_{0.15}CuO_4$ (T_c=37 K), grown by the traveling-solvent floating-zone method.[11] Using a Quantum Design MPMS-5S superconducting quantum interference device (SQUID) equipped with a horizontal rotator, the magnetization components parallel to **H** (M_L) and perpendicular to **H** (M_T) were measured as a function of time and external field **H**, for fields applied at different angles θ_H relative to the *ab* plane. Measurements of the longitudinal and transverse components of the magnetization enable us to determine the magnitude and direction of the vectors **M** and **B**. A schematic representation of the external magnetic field **H** and the induction **B** relative to the sample is shown in Fig. 1(a).

Magnetic relaxation measurements were preformed after zero-field cooling followed by an increase of the field to its target value. Measurements of the relaxation of the remnant magnetization were performed after field cooling from above T_c in 500 Oe and turning off the field at the target temperature. In both measurements the relaxation of the magnetic moment was measured by taking 30 consecutive measurements of magnetization in time intervals of 60 s.

III. RESULTS

A. Flux rotation in the presence of a tilted field

Figure 1(b) shows the time dependence of the angle θ_B between **B** and the *ab* plane for an external field H=2 kOe

---

[a] Electronic mail: bruckey@mail.biu.ac.il

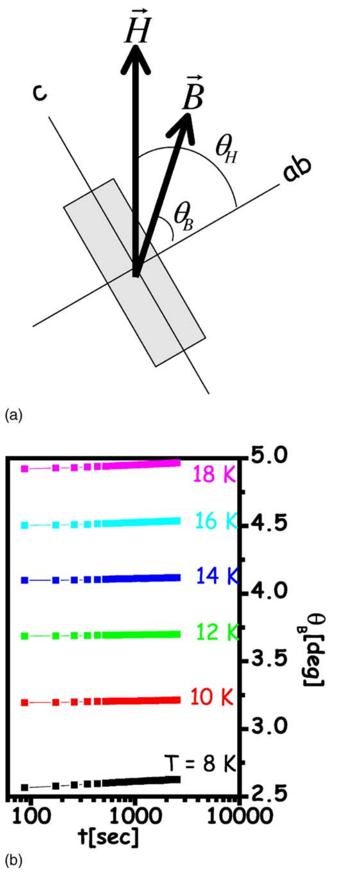

FIG. 1. (Color online) (a) Definition of directions. (b) Time dependence of the angle θ_B for an external field $H=2$ kOe [after zero-field cooling (ZFC)] tilted at an angle $\theta_H=9°$ at the indicated temperatures.

tilted at an angle $\theta_H=9°$ at the indicated temperatures. Evidently, θ_B has a logarithmic dependence on time, thus justifying definition of a rotation relaxation rate as $\alpha=d\theta_B/d\ln t$, where a positive α indicates relaxation towards the *ab* plane and a negative α indicates relaxation towards the *c* axis. Figure 2 shows the dependence of α on temperature deduced from the data of Fig. 1. Apparently α exhibits two peaks separated by a dip around 12 K.

B. Remnant flux rotation

The inset of Fig. 3 shows the time dependence of θ_B after switching off a field of 500 Oe titled at 15°, measured at 8 and 26 K. It is clearly seen that at 8 K the flux rotates toward the *c* axis while at 26 K it rotates towards the *ab* plane. In order to identify the crossover regime between these two behaviors, we present in Fig. 3 α as a function of temperature for $\theta_H=10°$ and 15°. Apparently, the onset of the change in the behavior of α occurs around 12 K. A change in the sign of α occurs around 20 K.

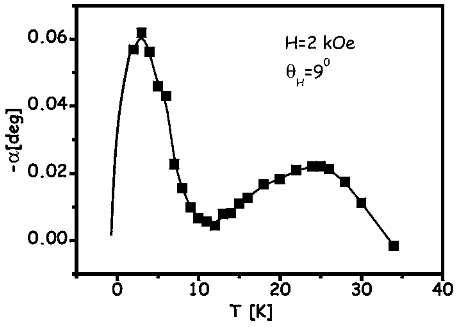

FIG. 2. Rate of flux rotation as a function of temperature for an external field of 2 kOe tilted at 9° to the *ab* plane (bold circles). The bold line is a guide to the eyes.

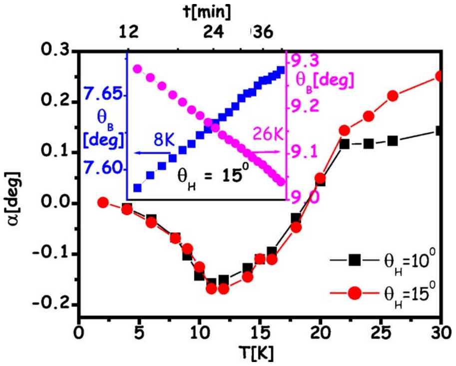

FIG. 3. (Color online) Rate of remnant flux rotation as a function of temperature measured after a field $H=500$ Oe, applied at 10° (squares) and 15° (circles) relative to the *ab* plane, was removed. Inset: The tilting angle of **B** as a function of time measured at 8 K (squares) and 26 K (circles). Note that at low temperatures the flux rotates toward *c*, whereas at high temperatures it rotates toward *ab*.

IV. DISCUSSION

The above two experiments (together with other experiments reported elsewhere[7–9]) show a clear crossover in the measured data around 12 K. We assert that it is related to a 2D-3D crossover in LSCO. The crossover temperature can be estimated using Eq. (1). Taking $\xi_c(0)\approx 0.3-0.4$ nm, $d\approx 0.66$ nm, and $T_c=37$ K we find that T^* is in the range of 10–20 K. We note that partial field penetration[12] and geometrical effects[13,14] may cause a peak in the relaxation rate and flux rotation towards the *c* axis at low temperatures, respectively. However, in our measurements we verified full field penetration by magnetization curves and magneto-optical measurements. In addition, the *c* axis in our sample is along the largest dimension, eliminating the possibility of a geometrical effect. In the following we show that the measured data below and above ~12 K are indeed consistent with 2D and 3D behaviors, respectively.

A. Flux rotation in the presence of a tilted field

Usually, the temperature dependence of the relaxation rate exhibits a nonmonotonic behavior with a single peak. The common explanation[15] for such a peak is as follows: At low temperature, the relaxation rate increases with temperature due to thermally activated flux creep. At high enough temperature, where the flux creep is very fast, only the "tail" of the relaxation process is measured for a given experimental time window. As a result, a reduced relaxation rate is measured and a peak is observed. Surprisingly, in Fig. 2 we see two peaks in the curve of α versus temperature. This indicates the existence of two regimes of relaxations with a crossover region around 12 K.

The observation of a higher and a narrower peak at low temperatures indicates that the relaxations in the low temperature regime are stronger and the collective pinning energy is smaller as compared to the high temperature regime. This is in accordance with the measurements described in Refs. 8 and 9, which also reveal less effective pinning in the low temperature regime. A less effective pinning is expected in the 2D regime as the order parameter at the core of the vortex has a finite value, in contrast to an Abrikosov vortex where the order parameter is zero in the core.

B. Remnant flux rotation

Our measurements of the remnant flux rotation in LSCO resemble those performed previously in $YBa_2Cu_3O_7$ (YBCO) (Ref. 5) and $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) samples.[16] The remnant flux in BSCCO tends to rotate towards the *c* direction while in YBCO it rotates towards the *c* axis at low temperatures and towards the *ab* plane at high temperatures. Zech *et al.*[5] interpreted these results as a consequence of a dimensional crossover. The crossover temperature in BSCCO is close to T_c, therefore only the behavior of a 2D system (i.e., rotation of the remnant towards the *c* axis) is observed. However, in YBCO and LSCO the crossover temperature is noticeably below T_c and therefore a change in the direction of rotation towards the *ab* plane is observed after crossing to the 3D regime. This change of behavior may be explained as follows: In the 2D regime the tilted vortex consists of a stack of separated pancakes located in the superconducting planes. When external field is removed, the interaction between these pancakes align them one on top of the other along the *c* axis. However, in the 3D regime the continuous vortex energetically prefers to be aligned along the *ab* plane due to the reduction of the order parameter in this direction.

V. CONCLUSION

We demonstrated that time relaxation of flux rotation is sensitive to the dimensionality of the system. At low temperatures, in the 2D regime, the rate of flux rotation is larger and the remnant flux rotates towards the *c* axis. At high temperatures, in the 3D regime, the flux rotation is relatively slow and the remnant flux rotates towards the *ab* plane.

ACKNOWLEDGMENTS

We thank Professor B. Ya. Shapiro and Professor B. Rosenstein for helpful discussions. This research is supported by the Israel Science Foundation Program for Centers of Excellence (Grant No. 8003/02) and the Heinrich Hertz Minerva Center for High Temperature Superconductivity.

[1] W. E. Lawrence and S. Doniach, Proceedings of the 12th International Conference on Low Temperature Physics, 1970 (Keigaku), p. 361.
[2] R. A. Klemm, A. Luther, and M. R. Beasley, Phys. Rev. B **12**, 877 (1975).
[3] D. E. Farrell, J. P. Rice, D. M. Ginsberg, and J. Z. Liu, Phys. Rev. Lett. **64**, 1573 (1990).
[4] V. Vulcanescu, G. Collin, H. Kojima, I. Tanaka, and L. Fruchter, Phys. Rev. B **50**, 4139 (1994).
[5] D. Zech, H. Keller, M. Warden, H. Simmler, B. Stauble-Pumpin, P. Zimmermann, E. Kaldis, and J. Karpinski, Phys. Rev. B **48**, 6533 (1993).
[6] R. Marcon, E. Silva, R. Fastampa, and M. Giura, Phys. Rev. B **46**, 3612 (1992).
[7] Y. Bruckental, A. Shaulov, and Y. Yeshurun, Phys. Rev. B **73**, 214504 (2006).
[8] Y. Bruckental, A. Shaulov, and Y. Yeshurun, Physica C (in press).
[9] Y. Bruckental, A. Shaulov, and Y. Yeshurun, Phys. Rev. Lett. (submitted).
[10] Yu. V. Bugoslavsky, A. L. Ivanov, V. A. Kovalsky, and A. A. Minakov, Physica C **257**, 284 (1996).
[11] T. Kimura, K. Kishio, T. Kobayashi, Y. Nakayama, N. Motohira, K. Kitazawa, and K. Yamafuji, Physica C **192**, 247 (1992).
[12] V. V. Moshchalkov, A. A. Gippius, A. A. Zhukov, H. H. Nyan, V. I. Voronkova, and V. K. Yanovskii, Physica C **165**, 62 (1990).
[13] F. Hellman, E. M. Gyorgy, and R. C. Dynes, Phys. Rev. Lett. **68**, 867 (1992).
[14] A. A. Zhukov, G. K. Perkins, Y. V. Bugoslavsky, and A. D. Caplin, Phys. Rev. B **56**, 2809 (1997).
[15] Y. Yeshurun, A. P. Malozemoff, and A. Shaulov, Rev. Mod. Phys. **68**, 911 (1996).
[16] M. Tuominen, A. M. Goldman, Y. C. Chang, and P. Z. Jiang, Phys. Rev. B **42**, 8740 (1990).