Magnetic flux rotation anomalies in superconducting $La_{1.85}Sr_{0.15}CuO_4$

Y. Bruckental, A. Shaulov, and Y. Yeshurun

Institute of Superconductivity, Department of Physics, Bar-Ilan University, Ramat-Gan 52900, Israel

(Received 26 June 2007; revised manuscript received 20 December 2007; published 21 February 2008)

Vector magnetization measurements in $La_{1.85}Sr_{0.15}CuO_4$ under fields slightly tilted from the crystallographic *ab* plane reveal flux rotation with distinctive behavior around $T^* \approx 15$ K. The temperature dependence of the onset-field H^* for flux rotation and the dependence of H^* upon the tilting angle are markedly different below and above T^*, exhibiting pronounced anomalies in the crossover regime. Possible mechanisms for these anomalies, such as dimensional crossover in superconductivity or the anomalous behavior of the in-plane penetration depth due to coexistence of two superconducting gaps, are discussed.

DOI: 10.1103/PhysRevB.77.064512 PACS number(s): 74.25.Ha, 74.25.Qt, 74.72.Dn

The layered structure of the cuprate superconductors and their relatively short coherence length give rise to a range of unique anisotropic magnetic phenomena.[1–21] Among them is the so-called "lock-in" effect[3] observed when a small external field is applied at a small angle θ_H to the *ab* planes. It was predicted theoretically[3,7,9] and observed experimentally[4,6,8,11,12] that there is a finite lock-in angle θ_c, such that when $\theta_H < \theta_c$, the flux lines run parallel to the planes, remaining "locked in" between the layers. When either the applied field or the tilting angle exceeds their critical value, the flux starts rotating toward the direction of the external field forming an array of kinked vortices.[3,7,9,22,23] In this paper, we report on anomalous behavior of the onset field H^* for flux rotation, previously overlooked in studies of the lock-in effect in $La_{1.85}Sr_{0.15}CuO_4$ (LSCO) crystals.[11,12] Namely, we find that H^* exhibits a power-law dependence upon the tilting angle with a sharp jump in the exponent around 15 K. Also, the temperature dependence of H^*, measured for a constant tilting angle, exhibits a pronounced peak around the same temperature. In addition, the behavior of the remnant magnetization vector $\mathbf{M}_R$, after turning off a tilted field, also changes around T^*: $\mathbf{M}_R$ rotates toward the *c* axis at low temperatures crossing over to rotation toward the *ab* plane at high temperatures.[24] A similar anomaly previously observed in the relaxation of the remnant magnetization in $YBa_2Cu_4O_8$ (YBCO)[10] was interpreted as signifying a dimensional crossover from two dimensional (2D) to three dimensional (3D) superconducting behavior. We discuss the possibility that similar dimensional crossover mechanism is the origin of the flux rotation anomalies reported here in LSCO. A different approach to explain our data is attempted based on a recent discovery of anomalous behavior of the in-plane penetration depth λ_{ab} around T^*, recently revealed in muon-spin scattering measurements in $La_{1.83}Sr_{0.17}CuO_4$ (Ref. 25) and interpreted as caused by the coexistence of two superconducting gaps. Apparently, the anomaly in λ_{ab} per se cannot account for the flux rotation anomalies reported here, yet the question whether these phenomena have a common origin remains open.

A parallelepiped shaped $0.72 \times 1.22 \times 1.93$ mm^3 sample, with the longest dimension parallel to the crystallographic *c* axis, was cut from an optimally doped $La_{1.85}S_{0.15}CuO_4$ single crystal, grown by the traveling-solvent-floating-zone method.[26] For this sample, $T_c = 37$ K and the anisotropy ratio $g = 17$.[27] 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 enabled determination of both the magnitude and direction of the vectors $\vec{M}$ and $\vec{B}$. In a typical experiment, the sample was zero-field cooled to the target temperature, and an external field was then applied at a constant angle θ_H, and swept from zero up to 50 kOe and back to zero in steps of 500 Oe.

The onset of flux rotation was detected in our experiments by measuring the component M_{ab} of the magnetization vector parallel to the *ab* plane versus the component H_{ab} of the external field along the same direction. As long as the flux is locked in between the planes, this measurement overlaps with the magnetization curve measured for field applied parallel to the *ab* plane; a deviation from the latter curve indicates the onset of flux rotation. We note that in our sample geometry flux rotation toward the *c* axis due to geometrical effects[28,29] is excluded as the sample dimension along the *c* axis is the longest.

The concept of our measurements is illustrated in Fig. 1 which shows M_{ab} vs H_{ab}, measured in $La_{1.85}S_{0.15}CuO_4$ at $T = 10$ K, for different tilting angles θ_H. Apparently, for low

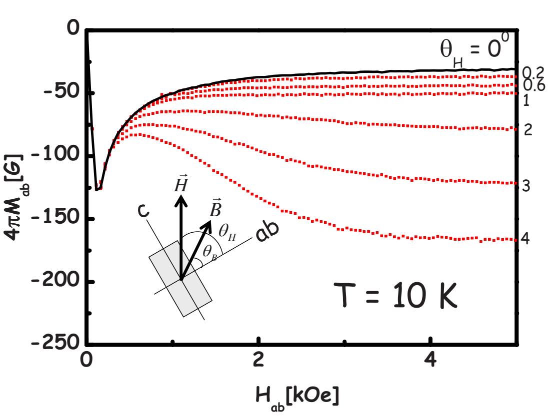

FIG. 1. (Color online) M_{ab} vs H_{ab} for the indicated tilting angles of the external field relative to the *ab* plane. Inset: Schematic diagram of the external magnetic field and induction vectors relative to the sample crystallographic axes.

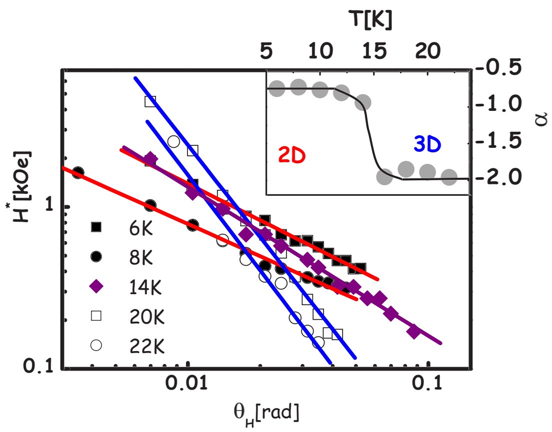

FIG. 2. (Color online) Log-log plot of the onset field for flux rotation H^* vs the field tilting angle θ_H measured at 6 K (bold square), 8 K (bold circles), 14 K (bold diamonds), 20 K (open square), and 22 K (open circles). Inset: The slope $\alpha = d(\log H^*)/d[\log(\theta_H)]$ vs temperature. The line is a guide to the eye.

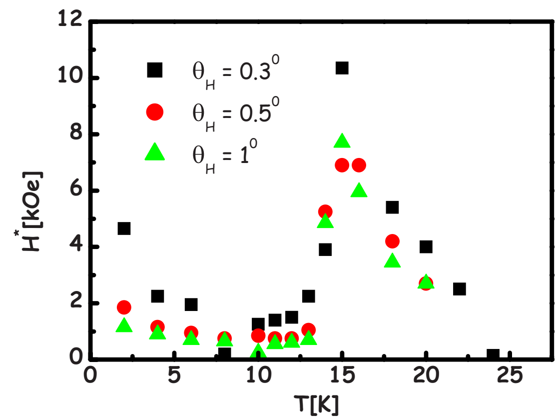

FIG. 3. (Color online) H^* vs temperature for external field applied at 0.3° (squares), 0.5° (circles), and 1° (triangles) relative to the *ab* plane.

fields the measured curves for $\theta_H \neq 0$ overlap with that measured for $\theta_H=0$, manifesting the lock-in effect. Deviations from this curve mark the beginning of flux rotation. Note that these deviations also mark the onset of an additional magnetization peak (AMP)[7,27] in between the well known first and second peaks. (The second peak, not shown in the figure, appears in the field range of 50 kOe.) In fact, the direction corresponding to $\theta_H=0$ was obtained with an accuracy of 0.10° as one for which no AMP could be detected when the field was ramped up to 50 kOe. We refer to the $\theta_H=0$ curve in Fig. 1 as the "master curve" to which all other curves are compared. It is evident from the figure that as the tilting angle θ_H increases, deviations from the master curve occur at decreasing fields. We define the onset-field H^* for flux rotation as the first field for which the relative deviation from the master curve exceeds 2%. The data of Fig. 1 thus allow determination of H^* as a function of θ_H at a given temperature. The flux rotation above H^* signals the penetration of pancakelike vortices in the layer, one for each kink, which undergo pinning. We note that H^* can be measured only during field ascend, as for $H < H^*$ the vortices penetrate to the sample along the *ab* planes and deviation from this direction for $H > H^*$ can be detected. In contrast, during field descend, the induction vector does not return to the *ab* planes due to the pinning effects.

Figure 2 presents a log-log plot of H^* as a function of θ_H, measured at different temperatures. Evidently, H^* exhibits a power-law dependence on θ_H, $H^* \propto \theta_H^{\alpha}$, with a dramatic crossover in the exponent α when the temperature is scanned through 15 K. This crossover is better illustrated in the inset of Fig. 2, which depicts α vs T. One clearly observes a crossover from $\alpha \approx -3/4$ at low temperatures to $\alpha \approx -2$ at high temperatures, with a crossover region around 15 K.

A remarkable anomaly around the same temperature is also observed in the temperature dependence of H^* measured for a constant θ_H, as shown in Fig. 3, for $\theta_H=0.3°$, 0.5°, and 1°. Evidently, H^* exhibits a nonmonotonic behavior: It decreases slowly with temperature up to ~10 K, rising abruptly around 15 K, and subsequently decreasing rapidly toward a zero value.

The data of Figs. 2 and 3 reveal two distinct temperature regimes, below and above $T^* \approx 15$ K, in which the temperature dependence of the onset field for flux rotation H^* and the dependence of H^* upon θ_H are markedly different. A clue for the interpretation of these anomalies was provided by measurements of the remnant magnetization vector $\mathbf{M}_R$, obtained after turning off the initial tilted external field.[24] The inset of Fig. 4 shows the time dependence of θ_B after switching off a field of 500 Oe titled at 15°, measured at 12, 14, 22, and 26 K. It is clearly seen that at 12 and 14 K, the flux rotates toward the *c* axis, while at 22 and 26 K, it rotates toward the *ab* plane. In order to identify the crossover regime between these two behaviors, we present in the main panel of Fig. 4 the normalized relaxation rate of θ_B, $\beta = \partial\theta_B/\partial \ln t$, as a function of temperature for $\theta_H=10°$ and

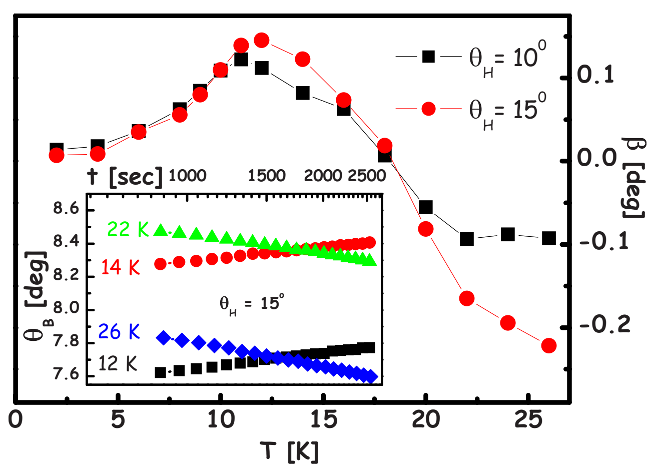

FIG. 4. (Color online) Rate of remnant flux rotation as a function of temperature measured after a field $H=500$ Oe, applied at 10° (squares) and 15° (circles) relative to the *ab* plane, was removed. Inset: The tilting angle of **B** as a function of time measured at 12 K (squares), 14 K (circles), 22 K (triangles), and 26 K (dimonds). Note that at low temperatures the flux rotates toward *c*, whereas at high temperatures it rotates toward *ab*.

15°. Apparently, the onset of the change in the behavior of the relaxation occurs around T^* and a change in the sign of the relaxation rate occurs around 18 K. A similar behavior of the remnant magnetization was previously observed in YBCO.[10] While in $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO),[30] the remnant flux always tends to rotate toward the c direction, in YBCO it rotates toward the c axis at low temperatures and toward the ab plane at high temperatures. This behavior was associated with a dimensional crossover from 2D to 3D in YBCO.[10] The crossover temperature in BSCCO is close to T_c; therefore, only the behavior of a 2D system (i.e., rotation of the remnant toward 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 toward the ab plane is observed after crossing to the 3D regime. This change in the rotation direction is explained as follows: In the 2D regime, the tilted vortex consists of a stack of separated pancakes located in the superconducting planes. When the external field is removed, the interaction between these pancakes align them one of 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.

Interpretation of $T^* \approx 15$ K as signifying a crossover temperature from 2D to 3D behavior in $La_{1.85}Sr_{0.15}CuO_4$ is plausible, as the common criterion for the 2D-3D crossover is $\xi_c = d/\sqrt{2}$,[31,32] where ξ_c is the coherence length along the c axis and d is the distance between adjacent layers.[31] Inserting $\xi_c = \xi_c(0)(1-T/T_c)^{-1/2}$, one finds for the 2D-3D crossover temperature $T^* = T_c[1-2\xi(0)^2/d^2]$. Identifying $T^* \approx 15$ K as the 2D-3D crossover temperature and taking $d \approx 0.66$ nm and $T_c = 37$ K yield $\xi_c(0) = 0.36$ nm, in the range of previously reported values for $\xi_c(0)$ in $La_{1.85}Sr_{0.15}CuO_4$.[33,34]

We discuss now the possibility that the anomalies presented in Figs. 2 and 3 are also associated with a dimensional crossover. The data of Fig. 2 indicate a power-law dependence of H^* upon θ_H and a sharp crossover in the temperature dependence of the exponent α around 15 K from $-3/4$ to -2. A power-law dependence of H^* upon θ_H is theoretically predicted[3,4,7,22,23] for both 2D and 3D regimes. However, our experimental observation of a crossover in the exponent α cannot be presently supported theoretically. The temperature dependence of H^*, depicted in Fig. 3, stems mainly from the magnetic field in-plane penetration depth, λ_{ab},[3,4,22,23] ($H^* \propto \lambda_{ab}^{-2}$). Thus, the slow decrease of H^* with temperature in the low-T regime merely reflects the slow increase of λ_{ab} at low temperatures. Similarly, the sharp decrease of H^* at high temperatures reflects the fast increase of λ_{ab} as the temperature approaches T_c. In fact, the theory predicts $H^* \propto (1-T/T_c)$ for a 3D system, whereas experimentally we do observe an approximate linear decrease terminating, however, well below T_c. We note that Vulcanescu *et al.*,[11] based on torque measurements in a similar LSCO crystal, reported a similar decrease of H^* with temperature down to zero around 25 K. However, data for temperatures below 15 K are lacking in their work and thus the large anomaly reported here was overlooked. The vanishing of H^* around 25 K was interpreted in Ref. 11 as signifying a 2D-3D crossover. In contrast, we suggest that the 2D-3D

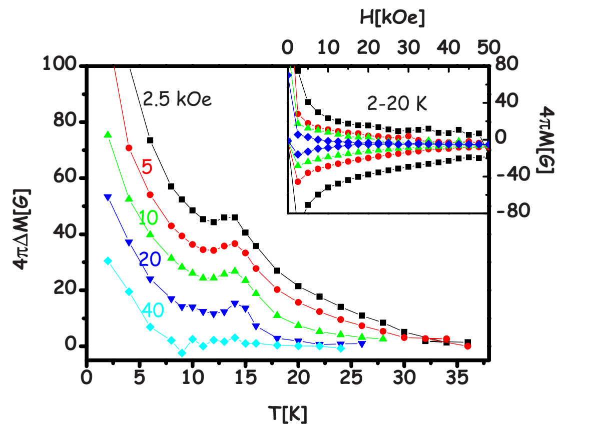

FIG. 5. (Color online) Temperature dependence of $\Delta M_{ab} \propto J_c^{ab}$ for different fields, as deduced from magnetization curves. Inset: Magnetization curves for $\vec{H}$ parallel to the ab plane, measured at 2 K (squares), 6 K (circles), 14 K (triangles), and 20 K (diamonds).

crossover occurs already around 15 K as indicated by the pronounced anomaly in $H^*(T)$ at this temperature. The finite value of H^* above 15 K is consistent with previous observations of a lock-in effect well above T^*, ascribed to the modulation of the vortex core energy in the quasi-3D regime.[4,22] The lock-in effect (and thus H^*) vanishes only at high temperatures, deep in the 3D regime, where the core energy modulation becomes insignificant.

Of special interest in Fig. 3 is the sharp rise of H^* to large values in the crossover regime. In a scenario of 2D-3D crossover, this implies that the lock-in effect can be more pronounced in the quasi-3D regime than in the 2D regime. Although there is no theory for the behavior of $H^*(T)$ in the crossover regime, these data may be understood considering the fact that in the crossover region the coreless Josephson vortices are replaced by Abrikosov vortices that are more effectively pinned due to their core energy. The enhanced intrinsic pinning of the Abrikosov vortices in the ab plane is demonstrated in Fig. 5 which presents the temperature dependence of the width of the hysteresis loops, $4\pi\Delta M$. The width, proportional to the persistent current J_c, is deduced from the hysteresis loops shown in the inset to the figure for different fields applied parallel to the ab plane. The absence of AMP in these curves indicates that $\vec{H}$ is parallel to the ab plane within 0.1°, as explained above. The anomalous increase in J_c around 15 K indicates enhanced intrinsic pinning in this temperature region. Note that the anomalous increase around 15 K is *independent of the field*, consistent with our interpretation of a temperature induced dimensional crossover around this temperature.

The flux rotation anomalies may be associated with an anomaly observed recently in muon-spin rotation (μSR) measurements[25] in $La_{1.83}Sr_{0.17}CuO_4$. This anomaly was assigned to an inflection point in the temperature dependence of λ_{ab}^{-2} around 10–15 K and was interpreted as suggesting the presence of two superconducting gaps or two order parameters. However, an inflection point in λ_{ab}^{-2} vs T cannot explain the nonmonotonic behavior of H^* shown in Fig. 3. Nevertheless, the apparent coincidence of the flux rotation anomalies reported here and the anomaly observed in the μSR measurements call for further investigation.

In summary, the onset field H^* for flux rotation in LSCO exhibits pronounced anomalies around $T^* \approx 15$ K whose origin is still unclear. Although there are some indications that the underlying mechanism is a 2D-3D crossover in the superconducting behavior, a theoretical challenge remains to explain the details of these anomalies, especially the crossover in the exponent α and the jump of H^* to large values in the crossover regime. A possible relationship between the crossover around 15 K reported here and the recently observed anomaly in μSR measurements around the same temperature is particularly intriguing.

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.

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