Decay of trapped flux in the high-T_c superconducting compound $Y_1Ba_2Cu_3O_{6.5+\delta}$

M. A.-K. Mohamed, W. A. Miner, J. Jung, J. P. Franck, and S. B. Woods
Department of Physics, University of Alberta, Edmonton, Canada T6G 2J1
(Received 8 October 1987; revised manuscript received 28 December 1987)

We have observed the decay of trapped flux in the superconducting compound $Y_1Ba_2Cu_3O_{6.5+\delta}$ with $T_c = 90$ K at liquid-nitrogen temperature (77 K). Measurements were done on samples in the form of a disk, a ring, and a cut ring. The results showed similar logarithmic decays with time for all samples, in good agreement with Anderson's flux-creep theory. This may indicate that our results were mainly due to microscopic vortex creep and not due to a macroscopic persistent current.

Since the discovery of the high-temperature superconductivity in the La-Ba-Cu-O system by Bednorz and Müller,[1] and later by Wu *et al.*[2] in the Y-Ba-Cu-O system, rapid and wide research has been done in this field, especially concerning future technological applications.

One of the most important features of superconductivity is the existence of a persistent current that gives the contribution to a trapped flux phenomenon or Meissner effect. Recently Skolnick *et al.*,[3] Chen, Xu, Bi, and Yang,[4] and Tjukanov *et al.*[5] reported the observation of a macroscopic persistent current in a ring-shaped sample of the $Y_{1.2}Ba_{0.8}CuO_{3-y}$, $Y_{0.6}Ba_{0.4}CuO_{3-y}$, and $YBa_2Cu_3O_x$ compounds, respectively, based on trapped flux measurements at liquid nitrogen temperature.

In this work, we present the results of measurements of trapped flux in a sample of the $YBa_2Cu_3O_{6.5+\delta}$ compound, shaped in the form of a disk, a ring, and cut ring. We have found that the flux measured results from the existence of microscopic current loops (vortices) in this material and the logarithmic decay of the flux with time could be understood on the basis of Anderson's flux-creep theory.[6]

The samples were prepared by the solid-state reaction method from metal oxides; Y_2O_3 (Morton Thiokol 99.99% pure), CuO (Fisher reagent grade), and $BaCO_3$ (Baker analyzed reagent grade). The powders were mixed, ground, and formed into a pellet of diameter 15 mm and approximately 3 mm thick, and reacted in air at 915 °C for 24 h. After reaction a pellet was reground, a new pellet formed and sintered in flowing O_2 for 7 h at 925 °C. The product was furnace cooled for 12 h at an initial rate 200 °C/h.

The trapped field was measured at liquid-nitrogen temperature with a dc Hall probe gaussmeter (sensitivity 0.01 G) together with a computer-controlled system, which allowed measurement of fast-trapped field decays. The system was programmed to collect data every $\frac{1}{8}$ s in the first 25 s, then every 4 min for about 30 h. The experimental setup is shown in Fig. 1. The external applied field was 800 G parallel to the ring axis, which gave a trapped field as high as 12 G. This field decayed rapidly to about 4.5 G, then slowly decreased with time with an average slope of 5% per decade.

The ring and cut ring were cut from the same disk-shaped sample to rule out any possible variations of the sample characteristics due to preparation technique. The measurements were made in the following order: (1) The trapped field was measured on the disk-shaped sample for the applied external field $H=0$ or $H \neq 0$, while cooling down to 77 K. (2) The ring of outside and inside diameter 15 and 6 mm, respectively, was cut from the disk, then the above measurements were repeated. (3) A radial slit approximately 0.3 mm wide was cut in the ring and the above measurements were repeated.

The experimental results are presented in Fig. 2. The curves show a fast initial decay in the first 10 s after

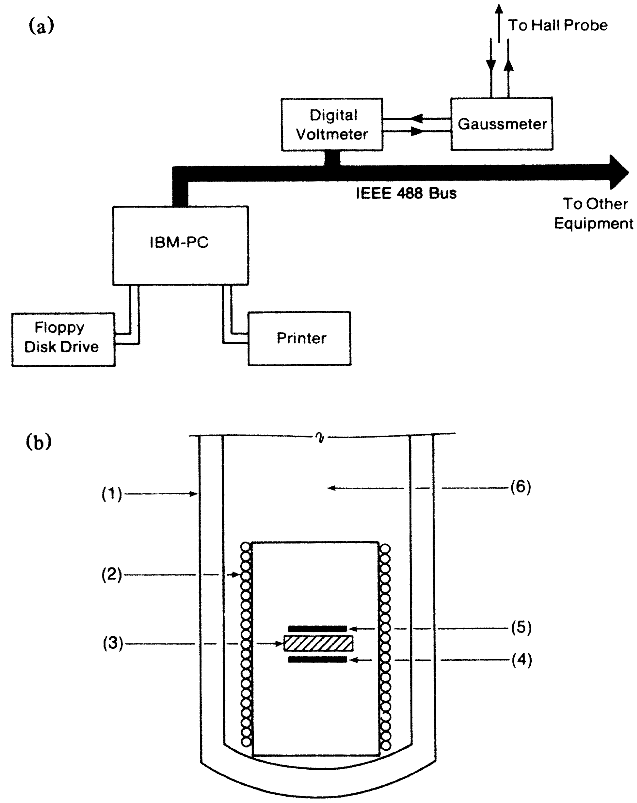

FIG. 1. Experimental setup: (a) Computer-controlled system used for trapped field measurements; (b) cryostat used: (1) glass Dewar, (2) solenoid, (3) sample, (4) and (5) dc Hall probes, (6) liquid-nitrogen surface.

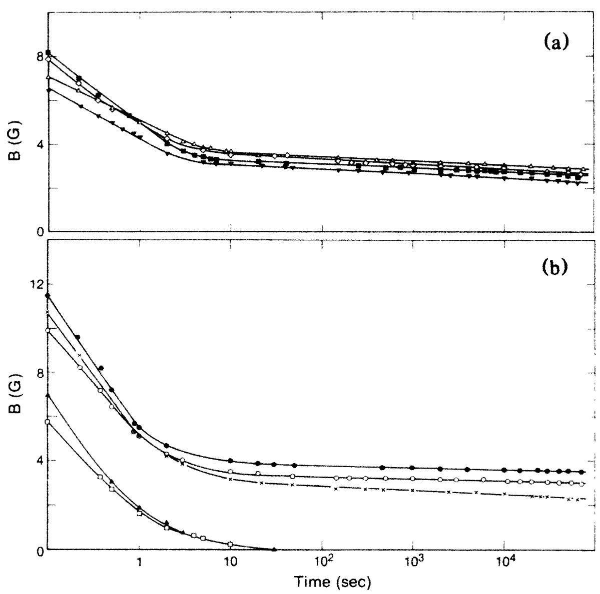

FIG. 2. Trapped field B as a function of time for samples of different geometry: (a) ring (▼, ◇); cut ring (■,△); (b) disk (●,○); ring (×); empty sample holder (▲,□). The samples denoted by symbols (▼,■) were cooled at $B^{ext}=0$, and those denoted by (◇,△) at $B^{ext} \geq 300$ G.

switching the external field off, followed by a slow decay region measured up to 80000 s. Similar fast initial decay, measured using torque technique, was also reported by Giovanella, Collin, Rounault, and Cambell[7] in the $La_{1.85}Sr_{0.85}CuO_4$ compound. The measurements repeated with an empty sample holder revealed that the fast decay might be due to a decay of an induced current in the solenoid core caused by the rapid change of the applied external field[8] [Fig. 2(b)]. The results for the disk-, ring-, and cut-ring-shaped samples are qualitatively similar. However, the slope of the slow decay line for the disk-shaped sample is smaller (about 3% per decade) than for the ring-shaped sample (about 6% per decade). This difference could be explained by a persistent current circulating in the ring, but the similarity in the results for the ring-, and cut-ring-shaped samples rules out this possibility.

The results are very similar to the flux decay measurements in type-II superconductors by Kim, Hempstead, and Strnad.[9] These results can be interpreted on the basis of Anderson's flux-creep theory.[6] According to this theory, flux pinned in type-II superconductors [by the creation of microscopic persistent current loops (vortices)] can jump over barriers by a thermal activation process. This process may lead to a logarithmic decay of trapped field δB with time t, according to the following relation:

$$\delta B = F(B,g) k_B T \ln t \ ,$$

where $F(B,g)$ is a function of the trapped field B, and the constant g depends on sample geometry and microstructure. k_B is the Boltzmann constant and T is temperature.

Our results (Fig. 2) are in very good agreement with this equation for $t > 10$ s. The slope of the function $\delta B = f(\ln T)$ is given by $F(B,g)k_B T$ which depends on sample geometry and microstructure only, for constant temperature and initial trapped field. In the present work, we can assume, taking into account very good reproducibility of the results, that the initial trapped fields were almost the same for all measurements. The microstructure did not alter, since all three different sample geometries were made out of the same disk-shaped sample. Following these arguments, one may attribute the observed difference in logarithmic decays for the disk- and ring-shaped samples to the difference in geometry only. For the ring-shaped sample the boundary area is larger than for the disk-shaped one, so the probability for a vortex to leak out through a boundary is larger for the ring than for the disk. This might explain why the decay rate for the ring is larger than that for the disk. In the case of the cut ring, the geometry is essentially the same as for the original ring, so the decay rate is very close to that of the continuous ring.

Some recent experimental results for the magnetic properties of high T_c oxides have been interpreted in terms of a superconducting glass state.[5,10] The superconducting loops in this state are connected by Josephson junctions that are responsible for the glassy behavior. Analysis of the behavior of high T_c materials, which have a very short coherence length, shows that the superconducting loops in these materials are typically much smaller than the grain size.[11] It is expected that only above magnetic fields $H_c^J \sim 200$–800 G and at $T < T_c$ will glassy behavior such as nonequilibrium flux trapping be visible.[11] It is notable in our experiments that although the applied field was often in the region of H_c^J, the largest amounts of flux involved in the slow decay corresponded to $B < 12$ G. As Mota *et al.*[12] remarked in connection with their results for similar logarithmic time dependence of flux decay in powder samples of La-Sr-Cu-O and La-Ba-Cu-O compounds, this value is deep in the reversible weak random-phase region and not in the superconducting glass-phase region. Morgenstern, Müller, and Bednorz[11] who have done numerical calculations for the superconducting glass model point out that it is appropriate to expect $M(t) \sim \ln t$ for the weak random-phase region, but they have not performed dynamical simulations in this region.

In conclusion, we have observed the decay of trapped flux in samples of the $YBa_2Cu_3O_{6.5+\delta}$ compound. Measurements were done on samples in the form of a disk, a ring, and a cut ring. The decay was logarithmic in time, in good agreement with Anderson's flux-creep theory.[6] The results indicate that the observed trapped field decay in the ring-shaped sample are not due to a macroscopic persistent current circulating in a ring.

The research was supported by grants from the National Science and Engineering Research Council of Canada.

[1]J. G. Bednorz and K. A. Müller, Z. Phys. B **64**, 189 (1986).
[2]M. K. Wu, J. R. Ashburn, C. J. Torng, P. H. Hor, R. L. Meng, L. Gao, Z. J. Huang, Y. Q. Wang, and C. W. Chu, Phys. Rev. Lett. **58**, 908 (1987).
[3]M. S. Skolnick, M. K. Saker, D. S. Robertson, J. S. Satchell, L. J. Reed, J. Singleton, and D. M. S. Baggaby, J. Phys. C **20**, L435 (1987).
[4]W. J. Yeh, L. Chen, F. Xu, B. Bi, and P. Yang, Phys. Rev. B **36**, 2414 (1987).
[5]E. Tjukanov, R. W. Cline, R. Krahn, M. Hayden, M. W. Reynolds, W. N. Hardy, J. F. Carolen, and R. C. Thompson, Phys. Rev. B **36**, 7244 (1987).
[6]P. W. Anderson, Phys. Rev. Lett. **9**, 309 (1962).
[7]C. Giovanella, G. Collin, P. Rounault, and I. A. Cambell, Europhys. Lett. **4**, 109 (1987).
[8]C. P. Bean, R. W. DeBlois, and L. B. Nesbitt, J. Appl. Phys. **30**, 1976 (1959).
[9]Y. B. Kim, C. F. Hempstead, and A. R. Strnad, Phys. Rev. Lett. **9**, 306 (1962); Phys. Rev. **129**, 528 (1963).
[10]K. A. Müller, M. Takashige, and J. G. Bednorz, Phys. Rev. Lett. **58**, 1143 (1987).
[11]I. Morgenstern, K. A. Müller, and J. G. Bednorz, Z. Phys. B **69**, 33 (1987).
[12]A. C. Mota, A. Pollini, P. Visani, K. A. Müller, and J. G. Bednorz, Phys. Rev. B **36**, 4011 (1987).