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Current persistence and magnetic shielding properties of $Y_1Ba_2Cu_3O_x$ tubes

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We have studied the time and temperature dependence of trapped magnetic fields in ceramic tubes of the high-T_c superconductor $Y_1Ba_2Cu_3O_x$. The maximum field in a particular tube is largely a function of temperature, although decays of the form $t^{-\alpha}$ occur for fields at the maximum values. For fields away from the critical values, limits on the decay rates give $\rho \leq 10^{-16}$ Ω cm. These results are consistent with the superconductor being in a spin-glass-like state.

One of the first questions we asked ourselves after learning of the high-T_c superconductors[1,2] was "Do these materials support persistent currents?" In addition to being an interesting question from the point of view of the physics of these new materials, this is an important technological issue. The current-persistence question is complicated by the fact that the high-T_c superconductors have largely been prepared in the form of ceramics produced by sintering powdered components. Depending on the details of preparation these materials can exhibit rather pronounced variations in their properties as a result of their granular origin.[3] We have investigated the current persistence question in macroscopic structures made from such materials, specifically tubes made from the compound $Y_1Ba_2Cu_3O_x$.

The tubes were made by cold pressing prereacted material directly into the final shape in a special press at about 7.5 kbar, then sintering at about 940 °C for 12 h in pure oxygen, followed by cooling at 4 °C/min. Materials prepared in this manner had room-temperature resistivity of 2 to 3×10^{-3} Ω cm, with the midpoint of the resistive transition at about 91.5 K, and apparent zero resistence at 89 K. The sample, of inner and outer diameters 0.800 and 1.284 cm, respectively, and length 0.65 cm, was mounted in a variable-temperature cryostat with a Bell Model 921A cryogenic Hall probe of active area 2×10^{-3} cm^2 positioned in the center of the sample to measure the axial component of the field. Both the temperature and the external magnetic field were under computer control; this allowed well-parametrized field and temperature sweeps to be executed.

Figure 1 shows the results of cooling the sample well below T_c in various external fields below the effective[4] value of H_{c1}, 120 G, reducing the external field to zero, and then warming at a constant rate (13 mK sec^{-1}) while monitoring the central axial field of the tube. The trapped field is seen to be essentially temperature independent until the trace intersects and follows a "universal curve" that is a measure of the maximum field that can be trapped in a particular sample as a function of temperature. The trapped field at 20 K corresponds to a persistent current density of approximately 500 A cm^{-2}. The precise shape of the curve depends somewhat on the scan rate, since the trapped fields decay; however, for most *practical* purposes the curve is well defined. The time dependencies we observe, which are a function of how close the trapped field is to the critical value, are extremely interesting. If at a particular temperature the external field is reduced to zero from a value above the critical value, then the trapped field starts to decay. The decays are very well described over the whole range of time of our measurements (1 to 10^4 sec) by $t^{-\alpha}$ [since the total variation of B_{axial} is quite small, it is not possible to distinguish between a power law

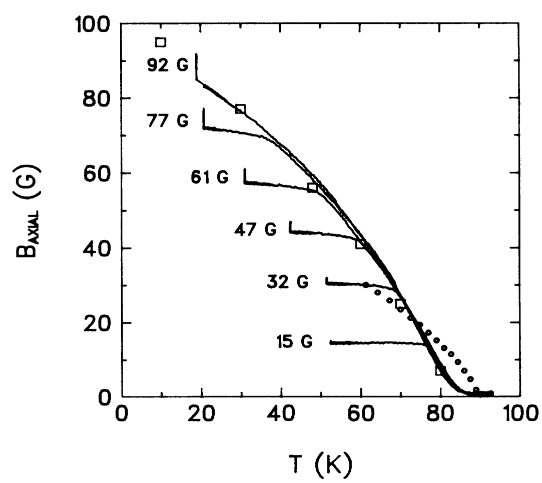

FIG. 1. Temperature dependence of the trapped magnetic field (indicating the temperature dependence of the critical current of the tube). These data are obtained by cooling the sample in an external field (indicated by the top of the vertical lines at the left), turning off the field, and measuring the trapped field while warming. The boxes indicate the positions of the breaks in the curves of Fig. 3. The circles show the trapped field observed after the ceramic tube was reheated at a slightly higher temperature (950 °C for 10.5 h). The material of the reheated tube showed nearly a full Meissner effect, and was thus "better" material; however, the maximum trapped fields were lower except near T_c.

and a function of the form $a - b\ln(t)$]. Figure 2 shows such a decay for $T = 30$ K. The values of a that we obtained are 0.0053, 0.0058, 0.0069, 0.010, and 0.034 at temperatures of 31, 40, 48, 60, and 77 K, respectively.

If, on the other hand, the sample is cooled in a field somewhat below the critical value for the temperature of interest, then the trapped field is generally constant to within experimental error. For our geometry, this translates to a resistivity of less than 10^{-16} Ω cm. This, however, is a misleading conclusion, as will be discussed later.

One can obtain additional information by cooling the sample in zero field to some temperature below T_c and then monitoring the field on the axis of the tube as a function of an externally applied field. The resulting "shielding curves" for several temperatures are shown in Fig. 3. One sees substantial shielding up to a certain applied field, above which the external field penetrates into the central region, although shielding currents continue to flow. The shapes of the curves up to the break are well produced by a model in which the current density in the material cannot exceed a saturation value J_c. As the external field is increased from zero, surface currents are induced which shield the interior of the sample. Eventually, more of the tube must carry current to shield the interior, and the interface between saturated and zero current regions moves inward. To calculate the current distribution, the tube was modeled on a computer as a bundle of loops. Each loop had two states, "off" (zero current) or "on" (current I_{max}). To facilitate computation, the total current (i.e., number of loops turned on) was fixed. An interface between current carrying and quiescent regions was found, which minimized the variance in the external field that would be required to null the flux through the quiescent loops. A Monte Carlo sampling technique was used, switching states of suitable random pairs of loops in order to move the interface while conserving total current. The resulting flux-nulling field is the applied field that would produce the calculated current distribution. Repeating the calculation for different total currents, we obtained the current distribution (and hence the field at the probe) as a function of the applied field. An enlarged version of the $T < 20$ K curve from Fig. 3 is shown in Fig. 4 along with the results of the computer simulation. Also shown in the figure is the calculated current distribution for a particular value of the external field. The initial slope of 0.024 for B_{axial}/B_{ext} agrees well with the longitudinal shielding factor for a perfect superconductor in the shape

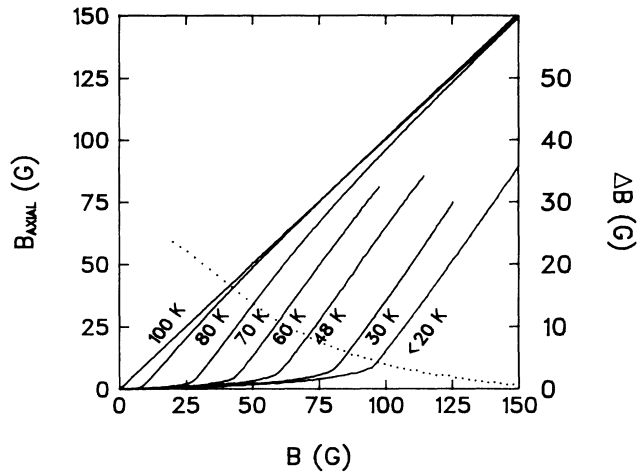

FIG. 3. The solid lines show the axial magnetic field (left scale) at the center of the tube as a function of the applied magnetic field (B_{app}) after cooling to the indicated temperatures in zero applied field. The dots illustrate $\Delta B \equiv B_{ext} - B_{axial}$ (right scale) vs $B_{avg} \equiv (B_{ext} + B_{axial})/2$ at 70 K indicating the magnetic field dependence of the saturation current density J_c.

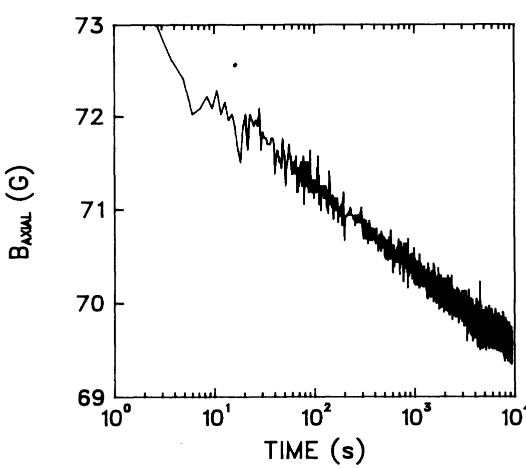

FIG. 2. Time dependence of the trapped magnetic field at 31 K (logarithmic scales).

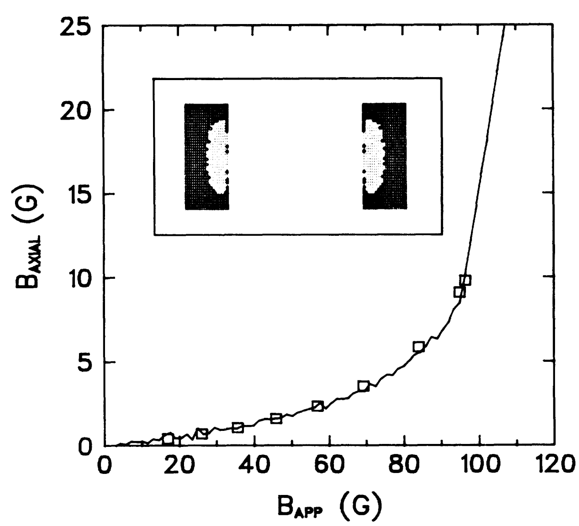

FIG. 4. An enlargement of the <20 K curve from Fig. 3. The boxes are from the model calculation described in the text with $(J_c)_{fitted} = 500$ A cm^{-2}. The inset depicts the current distribution in the tube determined by our model calculation for a trapped field of 57 G. The dark area is the region where the current in the loops are at their saturation value and the light area shows the region where the loops carry zero current.

of our sample, as determined by an independent measurement. The curvature is caused by the shortening of the effective length of the sample as more of it becomes current saturated.

For simplicity, the above model assumed that the saturation current density J_c was independent of field, which is only approximately true. In fact, past the break region a plot of $\Delta B \equiv B_{\text{ext}} - B_{\text{axial}}$ vs $B_{\text{avg}} \equiv (B_{\text{ext}} + B_{\text{axial}})/2$ (see Fig. 3)[5] gives a fairly accurate measure of the field dependence of J_c: the difference between B_{ext} and B_{axial} is an approximate measure of the total current in the ring, and B_{avg} is an approximation to the average field seen by the ring. Well past the break point, where $B_{\text{axial}} \simeq B_{\text{ext}}$, the error in approximating J_c by ΔB becomes small.

We also measured the magnetic field dependence of the magnetization of other samples, which were prepared at the same time and in the same manner as our tube. These measurements showed spin-glass-like behavior as predicted by Ebner and Stroud[6] and previously observed by Müller *et al.* in La_2CuO_{4-y}:Ba. This spin-glass-like behavior occurs in a composite superconductor in which the superconducting grains are coupled together by Josephson tunneling or the proximity effect into closed loops. These support screening supercurrents in response to an external magnetic field. The system is "frustrated" and so there are many supercurrent-carrying states of nearly equal energy. At low temperature, energy barriers between these states tend to inhibit hops from one state to another. The supercurrent loops are analogous to the magnetic moments in a spin-glass and hence the superconductor has spin-glass-like properties.

In many ways the properties of our ceramic samples bear great similarities to the behavior observed many years ago by Kim, Hempstead, and Strnad,[7] and explained by Anderson[8] in their classic work on critical persistent currents in hard superconductors at fields above H_{c1}. However, our work is at fields less than H_{c1} and the underlying physics is quite different; Kim *et al.* were concerned with a critical state resulting from flux penetration, whereas in our samples the magnetic field does not penetrate the superconducting grains.

In the spin-glass-like state the maximum trapped field is determined by the critical current of the weak links. The temperature dependence of the trapped field is due to the change in the critical currents with temperature. We have not attempted to fit the observed temperature dependence to some function because we do not know the distribution of coupling strengths which is required to predict the functional form. The field dependence of J_c is due to suppression of the critical current of the weak links joining the grains by the applied magnetic field. Rosenblatt, Peyral, and Raboutou[9] analyzed a network of phase coherent, randomly oriented Josephson junctions in order to calculate the magnetic field dependence of the critical currents of a bulk granular superconductor (grain size$\gg$penetration depth). Their simplified model gave $J_c \propto 1/B$ for large B, which has the right tendency but is too slow a variation to explain our results.

We can account for the decay of the trapped field as follows: as in our computer model, we think of the tube as being made up of a number of annular current loops where each loop contains many weak links. The current in one loop cannot exceed the saturation value (which depends on the weak links in the loop) and is closely linked to the current in all the other loops and by their interconnections. When the trapped field is on the "universal curve" of Fig. 1, the current in every loop is at its saturation value. If the saturation current of one loop decreases in some thermally activated process, this forces the current in all the other loops to adjust, and results in a net decrease in the trapped field. In the process of this adjustment, the current in some of the other current loops would exceed their saturation value and therefore decrease, again forcing the current in all the other loops to readjust, and so on. This simplified picture is equivalent to the actual microscopic situation; the procedure of cooling in a field and turning it off prepares the system in a higher-energy metastable state. Following this, the system decays toward the ground state through thermally activated hops to states of nearly equal energy.

Sompolinsky and Zippelius,[10] in a mean-field caculation, suggested that the decay of the magnetization of a spin glass should go like $t^{-\alpha}$. Models of hierarchical dynamics[11,12] indicate that the decay should be of the stretched exponential form $\exp[-(t/\tau)^{\beta}]$. The time dependence that we observe for the decay of the trapped field is decidedly nonexponential and corresponds to the prediction of Sompolinsky and Zippelius.

To return to the question of the apparent current persistence in tubes with fields slightly below the critical values, we believe that in that case the system has been prepared in such a way that the current loops toward the outside of the tube are not initially driven to carry the saturation current allowing them to partly suppress the effect of the decay of the innermost loops which do carry the maximum possible current. Eventually, as the currents in the inner loops decay and the shielding currents increase, the system will be forced into the state where all loops carry their saturation current. At this point, the central field will start to decay, taking up more or less the decay curve it would have had if the original external field had been larger than the critical value. We have, in fact, observed curves that are flat for roughly one hour and then start to decay.

In conclusion, we have measured the persistence and shielding properties of tubes made from sintered powders of $Y_1Ba_2Cu_3O_x$, and explained our results in terms of the spin-glass-like behavior of a superconducting composite. The trapped magnetic fields (and corresponding "persistent" currents) decay as $t^{-\alpha}$, consistent with Sompolinsky and Zippelius's prediction for a spin glass. The critical current densities drop very quickly with magnetic field, showing an unusual dependence. It is of both fundamental and technical importance to try to understand these properties.

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