UPPER LIMIT ON THE RESISTIVITY OF $La_{1.85}Sr_{0.15}CuO_4$

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The stability of a shielding current in a hollow cylinder of $La_{1.85}Sr_{0.15}CuO_4$ has been studied with a superconducting quantum interference device (SQUID). From the observed lack of decay of the current an upper limit of 3×10^{-17} Ω cm has been established on the resistivity at 4.2 K.

There has recently been intense interest in the superconducting properties of La- and Y-based oxides [1–5]. Samples of the lanthanum-based materials typically show a resistive transition in which the resistivity drops from the order of 1 mΩ cm to an upper limit set by the sensitivity of the measuring equipment at a value 4 or 5 orders of magnitude smaller. Thus, the upper bounds on the resistivity reported to date are typically 10^{-8} Ω cm or higher, values comparable with the low-temperature resistivity of copper with a residual resistance ratio of about 10^2 or less. Similar upper limits have been established on the resistivity of the yttrium-based materials below the superconducting transition temperature [6].

The purpose of this short communication is to report an experiment that establishes a lower limit on the lifetime of a shielding supercurrent in a ring of $La_{1.85}Sr_{0.15}CuO_4$, and thereby establishes an upper limit on the resistivity of approximately 3×10^{-17} Ω cm at 4.2 K.

The experimental configuration is shown in fig. 1. A solenoid consisting of 136 turns of 75 μm diameter insulated niobium wire is wound on a teflon form; the dimensions of the solenoid are listed in table 1. The coil form is attached to a silicon chip on the reverse side of which there is a thin-film planar dc SQUID [7] (superconducting quantum interference device). The body of the SQUID consists of a square washer with an outer length of 0.9 mm and inner length of 0.18 mm. The center of the SQUID is aligned approximately along the axis of the solenoid. A hollow cylinder of the material under investigation can be inserted coaxially into the coil form. The output from the SQUID is determined by a second dc SQUID in a flux-locked loop. The whole assembly is enclosed in a niobium shield and immersed in liquid helium at 4.2 K.

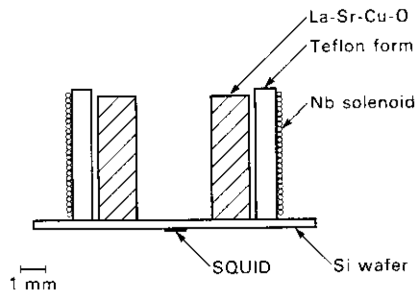

Fig. 1. Experimental configuration.

In the absence of any sample, we measured the mutual inductance M between the solenoid and the SQUID by injecting a known current I and counting the number of flux quanta $\Phi_0 \equiv h/2e$ entering the SQUID. In a preliminary experiment to investigate its effect on the mutual inductance, we inserted a hollow lead cylinder into the solenoid; the dimen-

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sions of the cylinder are listed in table 1. In the presence of the Pb cylinder, the mutual inductance between the solenoid and the SQUID was reduced to a value M_{Pb} approximately 7 times smaller than M (see table 1). This reduction in mutual inductance arised from the screening current that is established around the cylinder when a magnetic field is applied by the solenoid. A fraction of the applied magnetic flux leaks around the end of the cylinder and enters the SQUID. By monitoring the stability of the flux in the SQUID as a function of time, one can infer the stability of the screening current in the cylinder.

Finally, we replaced the Pb cylinder with the $La_{1.85}Sr_{0.15}CuO_4$ sample, which was prepared as follows: $SrCO_3$, La_2O_3, and CuO were dissolved in nitric acid and precipitated as oxalates. The material was fired at 800°C in air, ground, and pressed into pellets. The pellets were fired for 13 h at 900°C and 4 h at 1100°C, and finally annealed for 7 h at 900°C in air. Measurements of the Meissner effect in this material using a SQUID-based susceptometer yielded an expulsion of approximately 45% of the ideal value. The diamagnetic transition was found to have an onset temperature of 37 K, a midpoint of 33 K, and a width (10%–90%) of 5 K. The sample was formed in a right circular cylinder approximately 4.8 mm high with a diameter of about 5.9 mm. A hole approximately 2.9 mm in diameter was carefully drilled along the axis of the cylinder. The mutual inductance between the solenoid and the cylinder, M_{La}, was approximately 12 times less than the value in the absence of the cylinder. The difference between M_{Pb} and M_{La} arises from a slight difference in the separation between the cylinders and the silicon chip. We note that the major reduction in mutual inductance necessarily implies that a current is established around the cylinder. Suppose the sample were to consist of a collection of superconducting grains not connected by at least one superconducting path around the ring. The magnetic field from the solenoid would enter the interior of the cylinder and the presence of the material would have only a minor effect on the flux threading the SQUID loop, the size of which (0.18 mm) is much less than the inner diameter of the cylinder (2.9 mm).

When the current in the solenoid was increased to about 250 μA and then reduced to zero, the flux in the SQUID returned to its original value (to within $10^{-2}\Phi_0$). For higher currents, the flux did not return to its original value, indicating that some flux was trapped in the cylinder.

We established a lower limit on the lifetime of the shielding current circulating in the cylinder using the following argument. With no sample in the coil, a current I produces a flux $\Phi = MI$ in the SQUID. With the sample in place, for times much shorter than the decay time of the shielding current a flux $\Phi_{La} = M_{La}I$ is produced. Let us suppose for the sake of argument that the cylinder has a small but non-zero resistivity. Then after a long time the shielding currents will have decayed and we will find approximately the same flux $\Phi = MI$ in the SQUID as in the absence of the cylinder. We approximate the time dependence of the flux in the SQUID as

$$\Phi(t) \approx (1 - e^{-t/\tau})(\Phi - \Phi_{La}) + \Phi_{La} . \quad (1)$$

Here $\tau = L/R$, L is the inductance of the cylinder and R is the resistance for a current circulating around the cylinder. The time rate of change of the flux for $t \ll \tau$ is therefore

$$d\Phi(t)/dt \approx (\Phi - \Phi_{La})/\tau . \quad (2)$$

In a typical experiment I was increased to about 230 μA. This produced a flux $\Phi_{La} \approx 24\Phi_0$ in the SQUID, and would have resulted in $\Phi \approx 290\Phi_0$ if the

Table 1
Dimensions of solenoid and of LaSrCuO and Pb cylinders. The mutual inductance between the solenoid and the SQUID is also shown with and without the cylinders.

	Height (mm)	Inner diameter (mm)	Outer diameter (mm)	Mutual inductance (nH)
LaSrCuO	4.8	2.9	5.9	$M_{La} = 0.21$
Pb	4.2	2.7	5.4	$M_{Pb} = 0.37$
solenoid	5.1	8.0	8.6	$M = 2.52$

sample had not been present. The output of the SQUID was monitored for approximately 2 min during which time [‡1] it changed by less than $10^{-2}\Phi_0$. Hence $d\Phi/dt < 8\times10^{-5}\Phi_0/s$. From eq. (2) we calculate that $\tau > 3\times10^6$ s and thus $R < 6\times10^{-16}$ Ω, where we have used an estimated inductance $L\approx 2nH$. In order to estimate the resistivity we assume the currents flow uniformly throughout the sample. Although this assumption obviously neglects skin depth effects, it provides a *conservative* upper limit on the resistivity. With the LaSrCuO sample, the area was about 0.075 cm^2 and the length (along the outer surface) was about 1.8 cm. We thus find $\rho < 3\times10^{-17}$ Ω cm. Since the room temperature resistivity of the sample was approximately 4×10^{-3} Ω cm, the observed residual resistance ratio was greater than 10^{14}. For comparison, the upper limit on the resistivity of conventional superconductors [8] is about 10^{-23} Ω cm.

In concluding, we note this experiment does not prove the entire sample supports a current with a decay time greater than 3×10^6 s, but rather that there is at least one closed path of length greater than about 9 mm that does so. Since the total cross-sectional area of one or more such loops is less than the cross-sectional area of the wall of the cylinder, the limit on the resistivity would actually be more stringent for those regions carrying the current than the value we have quoted. We are continuing our experiments to lower the upper limit on the resistivity by monitoring the flux for longer times at a higher SQUID sensitivity, and to extend the measurements to temperatures approaching the transition temperature.

[‡1] The quoted sensitivity and time were chosen somewhat arbitrarily to lower the existing upper limit on the resistivity by at least 8 orders of magnitude.

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