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Surface impedance measurements in $La_{1.8}Ba_{0.2}CuO_{4-y}$

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Surface impedance measurements at 102 GHz are reported for the high-T_c superconductor $La_{1.8}Ba_{0.2}CuO_{4-y}$. In the superconducting state the temperature dependence of the surface resistance R_s is in agreement with a Bardeen-Cooper-Schrieffer form and magnitude of the gap $\Delta(T)$. A distribution of gap values was found which is consistent with the smeared transition in the dc resistivity.

The high transition temperature of oxide superconductors[1] based on La_2CuO_4 and similar materials has led to suggestions of novel types of mechanisms for superconductivity with possible consequences for the thermodynamic and electrodynamic properties in the superconducting state. Recent optical experiments suggest the development of a single-particle gap over the entire Fermi surface which is suggestive of conventional BCS pairing. The magnitude of the gap, however, remains controversial. The evaluation of the single-particle gap from the measurement of the temperature dependence of various quantities such as the specific heat, thermal expansion, thermal conductivity, or ultrasonic attenuation is difficult because of the high transition temperatures, and nuclear magnetic resonance experiments have not been performed to date.

Several optical experiments[2] have been performed in order to evaluate the gap, and its dependence on the temperature and magnetic field; however, all encountered serious problems associated with small particle sizes, sample inhomogeneities, and the small penetration depth of the radiation. This also explains the large variations in the evaluations of $2\Delta_0/kT_c$.

Experiments using small particles[2] compressed between supportive windows were analyzed assuming theories valid for small particles. This led to $2\Delta_0=2.5kT_c$ which is less than the BCS relation, but a considerable distribution of gaps was suggested. Sulewski *et al.*[3] found that $2\Delta_0/kT_c=1.3-1.9$, while others[4] arrive at values of $2\Delta_0/kT_c=2.5$ and 3.2, respectively. Although these values are smaller than what follows from the BCS relation, recent tunneling measurements[5] indicate a gap substantially larger than $3.5kT_c$.

We have conducted surface impedance measurements in order to measure the magnitude and temperature dependence of the gaps. Such experiments were useful earlier to explore the electrodynamics of conventional BCS superconductors.

The material was prepared as described by standard techniques. The weighed amounts of finely ground La_2O_3, $BaCO_3$, and CuO were fired at 900 °C for 5 h, then ground and fired for 9 h. After the second heat treatment, the mixture was pulverized and pressed into a pellet at 2500 lbs. pressure. The pellet was subsequently sintered for 17 h at 1050 °C. X-ray diffraction patterns indicate a single phase with lattice parameters reported by others. The dc resistivity indicated by the full line in Fig. 1, shows a superconducting transition at $T_c=25.6$ K (midpoint) with a width $\Delta T_c=6.7$ K (90%–10%); the transition temperature is in broad agreement with those found earlier by others, and the width of the transition is also comparable.

The relatively broad transition indicates that either the material develops the superconducting state only progressively within a temperature interval of $\Delta T_c \sim 7$ K, or that more and more superconducting paths are formed with decreasing temperature. In the case of the former, a correction to the relative fraction of the superconducting volume has to be made by using the dc resistivity as a measure of the volume fraction. If the percolation picture is more appropriate, no such correction is necessary since the high-frequency measurement is less sensitive to percolation effects. In the following we will assume that there is a distribution of transition temperatures in our specimen, and this is responsible for the absence of a sharp resistive transition. The width (90%–10%) $\Delta T_c=6.7$ K and the average transition temperature $T_c=25.6$ K. These values were arrived at by inspecting the dc resis-

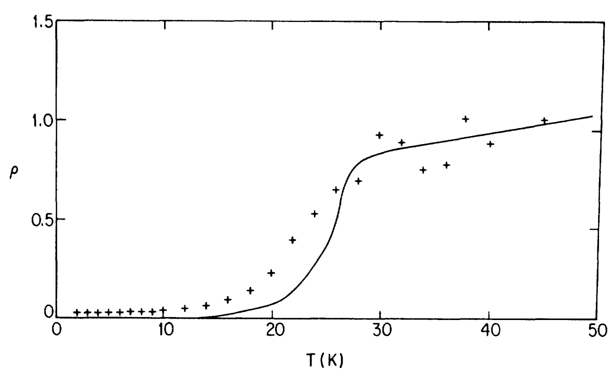

FIG. 1. Temperature dependence of the normalized resistivity measured at dc (solid line) and 102 GHz (crosses). The microwave resistivity is given as $\rho \sim [R_c+1/\gamma(\Delta f_s-\Delta f_c)]^2$, where R_c is the surface impedance of copper, and γ is the geometrical constant appearing in Eq. (1) for the end plate of the cavity. Δf_s and Δf_c are the widths of the cavity resonance with the sample and copper end plates. The microwave data were normalized to the dc resistivity at 200 K.

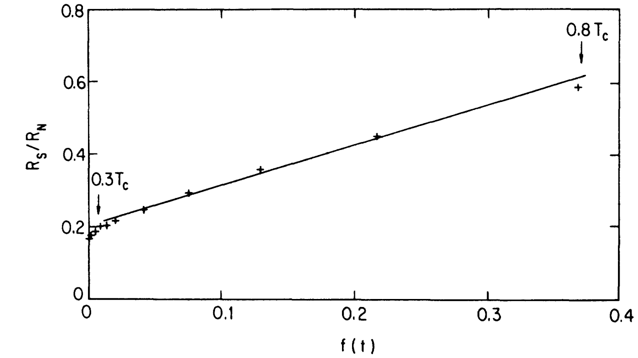

FIG. 2. Temperature dependence of R_S/R_N in the superconducting state, plotted as a function of the reduced temperature $f(t)$. The full line is Eq. (2) with $A=1.1$.

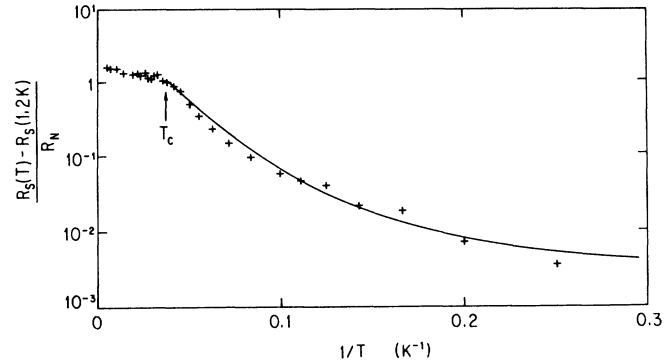

FIG. 3. Low-temperature data of $[R_S(T)-R_S(1.2\text{ K})]/R_N$. The solid line is Eq. (4) with $\Delta_0=45$ K and $\Gamma=2.0$ K.

tivity shown in Fig. 1.

The surface impedance was measured using a cylindrical copper cavity which resonates in the TE_{011} mode at a frequency of 102 GHz. By sweeping the frequency of the microwave source, it is possible to record the resonance with a signal averager. The width of the resonance at half the power is given by

$$\Delta f=\sum_i \gamma_i R_i \ , \qquad (1)$$

where the R_i are the surface impedances of the various conductors that make up the cavity, and the γ_i are a set of constants which can be calculated from the geometry. If there are any additional losses in the cavity such as that due to radiation from the coupling holes, they must also be added on to Eq. (1).

After the sample was polished, it was clamped to the bottom of the cavity, and the resonant width was measured from room temperature down to 1.2 K. The experiment was repeated with the sample replaced by a copper end plate. It is possible to eliminate any contributions to Eq. (1) that are not due to the sample by subtracting the half-widths from the two runs. One ends up with an expression for the impedance relative to that of copper.

Next we analyze our experimental data. A detailed theory of the surface impedance is involved, and the relation between R_S/R_N and the parameters of the BCS theory, where S and N refer to the superconducting and normal states, depends on the relation between the penetration depth, coherence length, and normal-state electron mean free path.[6] Detailed frequency-dependent measurements would be required to establish which limit is appropriate for the sintered specimen used by us. Consequently, in this Rapid Communication we focus only on the temperature dependence of the surface resistance. In nearly all of the cases where the BCS theory is appropriate, the temperature-dependent surface resistance was found to follow the empirical form[7,8]

$$\frac{R_S}{R_N}=At^4(1-t^2)(1-t^4)^{-2}=Af(t) \ , \qquad (2)$$

with $t=T/T_c$, in the temperature interval $0.3T_c<T<0.85T_c$. Consequently, we have fitted our experimental results to Eq. (2) and such a fit is displayed in Fig. 2. While Eq. (2) is *not* a consequence of the BCS theory, a functional form close to $f(t)$ follows from the temperature-dependent gap given by the BCS theory. Consequently, Fig. 2 strongly indicates that the gap in $La_{1.8}Ba_{0.2}CuO_{4-y}$ has a BCS-like temperature dependence.

The Gorter-Casimir two-fluid model is obviously in clear conflict with observations at low temperatures where various parameters follow an exponential temperature dependence. Because the penetration depth and coherence length are expected to be temperature independent well below T_c, R_S/R_N is expected to have the form of

$$\frac{R_S}{R_N}\sim\exp\left(-\frac{\Delta}{kT}\right) \qquad (3)$$

if the gap is well defined, and has no gap anisotropy nor a distribution of values.

As discussed earlier, the absence of a sharp transition is modeled by a distribution of gap energies. The surface impedance with a Lorentzian distribution of gaps $P(\Delta)$ is given by

$$\frac{R_S}{R_N}\sim\int_0^\infty P(\Delta)\exp\left(-\frac{\Delta}{kT}\right)d\Delta$$
$$=\int_0^\infty \frac{1}{\Gamma^2+(\Delta-\delta)^2}\exp\left(-\frac{\Delta}{kT}\right)d\Delta \ , \qquad (4)$$

with the approximate BCS form for $\delta=\Delta_0(1-T/T_c)^{1/2}$. A fit to this expression is displayed in Fig. 3 with a gap $\Delta_0=45$ K and $\Gamma=2.0$ K. Similar appropriate fits are obtained at somewhat larger or smaller ($\pm 20\%$) gap values. We have not treated Γ as a free parameter when fitting the microwave data. Instead, Γ was selected so that the distribution of energy gaps $P(\Delta)$ is consistent with the measured dc resistivity. We conclude, therefore, that $2\Delta_0/kT_c\approx 3.5$, and that our experiments are in good accord with a superconductor whose electrodynamic properties can be well accounted for by the BCS theory.

We note that our experiments cannot distinguish between an anisotropic gap or a gap distribution as discussed above. More extended experiments at various frequencies, including measurements of the reactive part of the impedance are underway.

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