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Anelastic relaxation in the high-T_c superconductor $YBa_2Cu_3O_{7-x}$

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The first measurement of anelastic relaxation in a vibrating sample of $YBa_2Cu_3O_{7-x}$ is reported. A marked drop in the dissipation is observed below T_c, from which a strong electron-phonon interaction is inferred. It is found that the Bardeen-Cooper-Schrieffer theory with a gap of $\Delta/K_B = 240$ K can explain this drop. The data also suggest the occurrence of a phase transition at 235 K.

Anelastic relaxation measurements are a powerful tool with which to investigate structural imperfections, classical and quantum diffusion of atoms, phase transformations, and electron-phonon interactions in solids.

In metals, a strong contribution to the sound absorption is due to the interaction of the elastic wave with the conduction electrons. If the metal exhibits superconductivity this absorption markedly decreases below T_c because the normal electrons condense into Cooper pairs. For this reason ultrasonic attenuation measurements have been widely used to test the Bardeen-Cooper-Schrieffer (BCS) theory and evaluate the energy gap. Because this contribution to the elastic energy dissipation coefficient Q^{-1} is proportional to the frequency f of the elastic wave, the drop in Q^{-1} below T_c in the traditional superconductors is marked in the MHz range (ultrasonic attenuation measurements) but hardly seen in the kHz and Hz range (internal friction in vibrating samples).

The role played by the electron-phonon interaction in the new superconductors is much debated at present; consequently, it is important to perform sound absorption experiments in a wide range of frequencies in order to evaluate the strength of the electron-phonon coupling and to test the various models.

We present the first measurement of anelastic relaxation from a resonating sample (Q^{-1} and f measurement) in the high-T_c superconductor $YBa_2Cu_3O_{7-x}$.

The sample was obtained using Y, CuO, and $BaCO_3$ as starting materials. An excess of $BaCO_3$ and CuO with respect to the stoichiometric $YBa_2Cu_3O_{7-x}$ composition was used to improve the superconducting properties of the material.[1] The mixture was first fired at 950 °C in air for 16 h, and then finely ground, pressed into ingots, sintered in flowing O_2 at 980 °C for 19 h, and slowly cooled to room temperature. The anelastic relaxation measurements were conducted by electrostatic excitation of two flexural modes of the sample (1.8 and 6.5 kHz).

Figures 1(a) and 1(b) present the concomitant measurements of resonant frequency f and internal friction Q^{-1} on cooling from 300 to 60 K. The crosses represent the data from two subsequent runs on the first vibration mode, which were followed by two runs on the second mode (closed squares). These measurements were carried out after a few runs to find the best experimental conditions.

At 235 K the frequency shows an inflection; concomitantly, the internal friction displays a spike (in the first mode) centered at 230 K followed by a drastic decrease.

Around 165 K a small peak is visible, which seems to shift in temperature with frequency, as occurs in thermally activated relaxation processes; however, because it is not well pronounced, we will not discuss it.

On further cooling, a marked decrease is observed in the Q^{-1} curve below the onset temperature T_c^{on} of the normal-superconducting transition (Fig. 2), whereas the frequency curve displays an upward inflection at T_c^{on} followed by a decrease. Measurements in this temperature range presented lesser experimental difficulties, as is seen from the smaller dispersion of data.

Between the runs for the first and second vibration modes the electrical resistance was measured with the four-probe method (Fig. 2). The obtained temperature of the onset of the transition and that of zero resistance are $T_c^{on} = 94$ K and $T_c^0 = 86$ K.

The frequency-independent decrease of the internal friction and the concomitant inflection of frequency at the same temperature (235 K) for both vibration modes are characteristic of a phase transformation. In fact, abrupt changes of Q^{-1} and f curves are observed at the onset of diffusion-controlled,[2] martensitic, and ferromagnetic transitions.[3] However, from the present measurement it is not possible to specify the nature of the presumed transformation at 235 K in $YBa_2Cu_3O_{7-x}$. Indeed, in $La_{1.85}Ba_{0.15}CuO_4$ there has been observed a tetragonal-

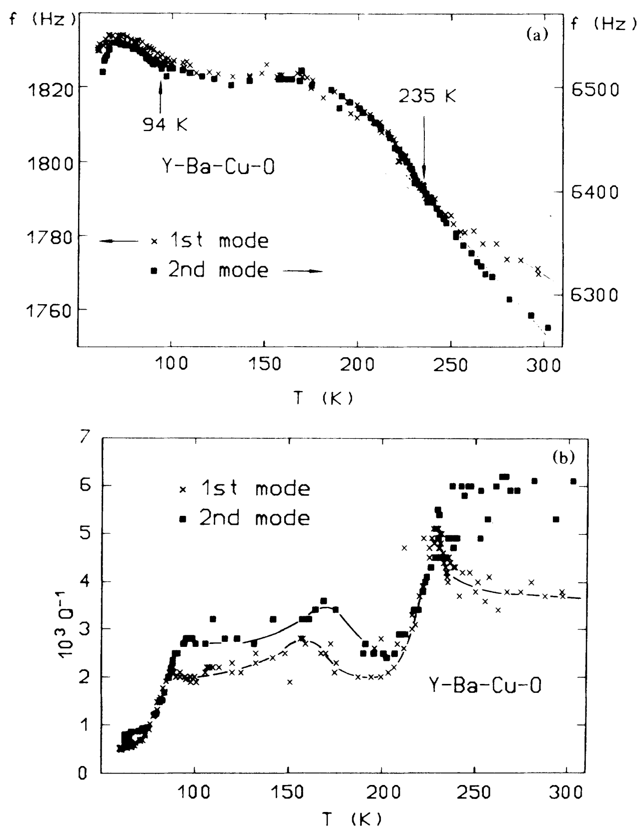

FIG. 1. (a) Resonant frequency and (b) elastic energy dissipation as a function of temperature.

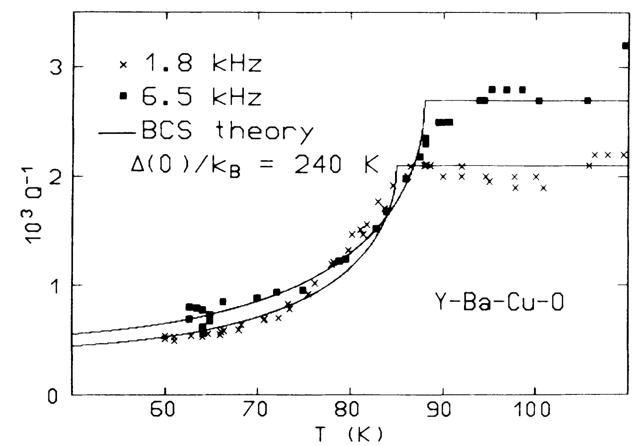

FIG. 3. Fit of the BCS theory to the experimental elastic energy dissipation with the parameters reported in the text.

to-orthorhombic phase transition at 180 K by neutron scattering[4] and a drastic decrease in the sound velocity at 24 MHz, from room temperature to 150 K, which the authors attribute to a structural transformation.[5] Moreover, antiferromagnetic ordering in La-Sr-Cu-O below 230 K has been observed by magnetic susceptibility.[6]

The most relevant result of the present experiment is the concomitant decrease of electrical resistance and internal friction at the superconducting transition. This strongly suggests that the dissipation, which above T_c exceeds the low-temperature background, is ascribable to electrons. Its magnitude ($\sim 1.5\times 10^{-3}$) at the frequencies used (kHz) is surprising, considering that the dissipation in metals and semiconductors in the same temperature and frequency range is more than two orders of magnitude smaller.

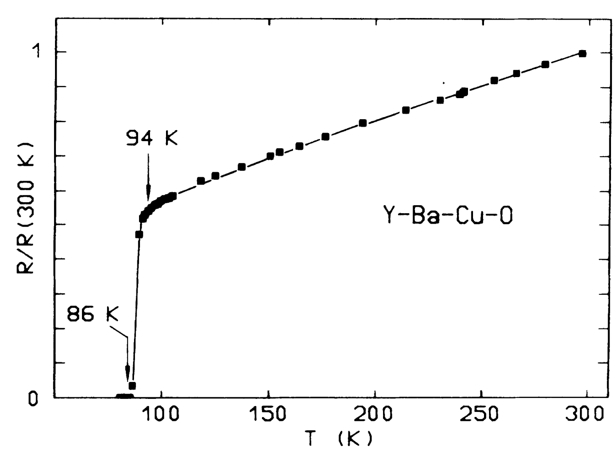

Fig. 2. Temperature dependence of the normalized resistance of the specimen.

The Q^{-1} drop below T_c recalls that of the traditional superconductors, which has been explained by the BCS theory, and therefore we tried to interpret our data in the same way. According to the BCS theory, the ratio of the energy dissipation in the superconducting and normal state in the low-frequency limit is[7]

$$Q_s^{-1}/Q_N^{-1}=2/\{1+\exp[\Delta(T)/k_BT]\} \ .$$

For the energy gap Δ we used the following numerical estimate:[8]

$$\Delta(T)/\Delta(0)=1.82(1-\vartheta)^{1/2} + (1-\vartheta)(-0.82+0.09\vartheta+0.3175\vartheta^2) \ ,$$

with $\vartheta=T/T_c$.

Assuming that the dissipation coefficient Q_N^{-1} due to the electron-phonon interaction in the normal state is constant around T_c, we found for the best fit to our data the curves reported in Fig. 3. The fit gave $\Delta(0)k_B=240$ K for both frequencies, $T_c=85$ K, $Q_N^{-1}=1.7\times 10^{-3}$, $Q_b^{-1}=0.4\times 10^{-3}$ for the first vibration mode, and $T_c=88$ K, $Q_N^{-1}=2.3\times 10^{-3}$, $Q_b^{-1}=0.5\times 10^{-3}$ for the second one, Q_b^{-1} being a background dissipation. The best fit gave two slightly different transition temperatures, having mean value $T_c=86.5$ K, practically coinciding with the measured zero-resistance temperature (Fig. 2). It is likely that the fit presented here could be improved taking into account possible material inhomogeneities and anisotropies of the energy gap. An estimate of Δ(0) from farinfrared conductivity measurements gave 290 K,[9] a value close to our result.

With regards to frequency, the upward inflection at T_c^{on} followed by a marked decrease is qualitatively different from the monotonic decrease starting at T_c usually found in superconductors.[10]

The analysis carried out here shows that the BCS theory can adequately explain some features found in $YBa_2Cu_3O_{7-x}$, also considering the ratio $2\Delta/k_BT_c=5.5$, which is not too different from the values found in the traditional superconductors.

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