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MAGNETIC AND THERMAL MEASUREMENTS ON HIGH-$T_c$ (La$_{0.9}$Ba$_{0.1}$)$_2$CuO$_{4-y}$

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We have measured the magnetic moment of (La$_{0.9}$Ba$_{0.1}$)$_2$CuO$_{4-y}$ as a function of temperature and magnetic field and have found the onset of superconductivity at a temperature $T_c \approx 35$ K. From the magnetic field dependencies, we have shown that the sample is a type-II superconductor with $\kappa \approx 11$. Specific heat measurements yield a finite electronic specific heat coefficient of $\sim 6$ mJ/mole-K at 4 K and a Debye temperature of only 330 K, suggesting that a strong electron-phonon interaction may be responsible for the high $T_c$ in our sample.

Recently, high $T_c$ La-(Ba,Sr)-Cu-O superconductors have been intensively investigated. Bednorz and Muller$^1$ have measured the temperature dependence of the resistivity of Ba$_{1.7}$La$_{4.26}$Cu$_{0.6}$O$_{6-\gamma}$ and have found a superconducting onset temperature $T_{c0} \approx 35$ K followed by the disappearance of resistivity below $T_D \approx 12$ K. Chu et al.$^4$ have obtained $T_{c0} \approx 35$ K and $T_D \approx 14$ K for their La$_{1-x}$Ba$_x$CuO$_{4-\gamma}$ with $x = 0.15$ and 0.20, and at a pressure of 12 kbar. $T_{c0}$ increases to 52.3 K and $T_D$ to 25 K. Very recently, they have improved the quality of their sample and have obtained an excellent sample (La$_{0.9}$Ba$_{0.1}$)$_2$CuO$_{4-\gamma}$, which has the K$_2$NiF$_2$ crystal structure with $T_{c0} = 44$ K and $T_D = 28$ K, but, at 10 kbar, $T_{c0} = 45$ and $T_D = 40$ K. This value of $T_D$ is the highest among the La-(Ba,Sr)-Cu-O system. Therefore, it is of great interest to investigate the magnetic properties of this material for the purpose of providing more information on this new type of high $T_c$ material.

A Quantum Design SQUID susceptometer has been employed to measure the sample magnetization $M$ as a function of applied field and temperatures. We obtain the susceptibility by $\chi = \Delta M/\Delta H$. Figure 1 shows our results as a function of temperature. The susceptibility becomes negative below $T_D = 31$ K. However, it starts to decrease at $T_{c0} \approx 35$ K (not shown). At 2 K, $\chi = 3.3 \times 10^{-3}$ emu/cm$^3$, which is 42% of perfect diamagnetism, indicating bulk superconductivity in the sample. In order to observe the Meissner effect, we have measured the magnetization as the sample was cooled in a

![Fig. 1. Temperature dependence of the magnetic susceptibility $\chi$ of La$_{1.8}$Ba$_{0.2}$CuO$_{4-\gamma}$ defined from $dM/dH$ ($H = 0$), where $M$ is the magnetization.](image-url)
MAGNETIC AND THERMAL MEASUREMENTS ON HIGH- \( T_c \) \( (\text{La}_{0.9}\text{Ba}_{0.1})_2\text{CuO}_{4-y} \)

Figure 2 shows the temperature dependence of \( M \) at \( H_{\text{COOL}} = 30, 45, 60, 75 \) and 90 G. As shown, \( M \) is negative below \( T_0 \), and it increases with increasing \( H_{\text{COOL}} \). The inset exhibits the field dependencies of \( M \) at 2 and 15 K, both of which clearly indicate that \( M \) is not linear in \( H_{\text{COOL}} \).

**Fig. 2.** Magnetization of \( \text{La}_{1.8}\text{Ba}_{0.2}\text{CuO}_{4-y} \) as a function of temperature on field cooling for different applied magnetic fields. The inset shows the field cooled magnetization values for \( T = 2 \) K, 15 K as a function of the applied field.

The magnetization as a function of applied magnetic field is shown in Figs. 3 and 4 for two different ranges of applied field. Each of these \( M \) vs. \( H \) curves displays a peak, whose shape is reminiscent of behavior typical for a type-II superconductor. From these peaks (Fig. 3), we obtain the lower critical field, \( H_c \). Its temperature dependence is shown in Fig. 5, and is quite different from that of a conventional type-II superconductor. By linearly extrapolating \( M \) at high fields to \( M = 0 \) in Fig. 4, we obtain the upper critical field \( H_{c2} \). Its temperature dependence is depicted in Fig. 5 and is again unexpected for a type-II superconductor. From \( H_{c1} \) and \( H_{c2} \), we can deduce the coherence length \( \xi = 6.7 \) nm, the thermodynamic critical field \( H_c = 4900 \) G, and the Ginzburg-Landau parameter \( \kappa = 11 \) at 2 K.

**Fig. 3.** Magnetic moment \( M \) vs. magnetic field \( H \) (\( H < 700 \) G) at various temperatures for \( \text{La}_{1.8}\text{Ba}_{0.2}\text{CuO}_{4-y} \). The position of the maximum defines the lower critical field \( H_{c1} \).

**Fig. 4.** Magnetic moment \( M \) vs. magnetic field \( H \) (\( H > 1 \) kG) at various temperatures for \( \text{La}_{1.8}\text{Ba}_{0.2}\text{CuO}_{4-y} \).

**Fig. 5.** Upper and lower critical fields of \( \text{La}_{1.8}\text{Ba}_{0.2}\text{CuO}_{4-y} \) as a function of temperature.
As shown in Fig. 6, the susceptibility above $T_{co}$ is $1.2 \times 10^{-4}$ emu/mole and nearly independent of temperature. We thus identify this as the Pauli susceptibility $\chi_p$. Using the free-electron model, $\chi_p = 3\mu_B^2/\pi(\hbar/\varepsilon)^2$, we obtain the electronic specific heat coefficient $\gamma = 8.5 \text{ mJ/mole-K}^2$. Another (La$_{0.9}$Ba$_{0.1}$)$_2$CuO$_{4-y}$ sample (J-6-3) with 10% diamagnetic signal gives $\chi_p = 3.06 \times 10^{-5}$ emu/mole (see Fig. 6), yielding $\gamma = 2.23 \text{ mJ/mole-K}^2$. For another sample, (La$_{0.8}$Sr$_{0.2}$)$_2$CuO$_{4-y}$ (SL-6), with 63% of perfect diamagnetism and $\chi_p = 5.11 \times 10^{-5}$ emu/mole, we have $\gamma = 3.7 \text{ mJ/mole-K}^2$. In comparison, we find our present sample has the highest $\gamma$ value. Because of our use of the free-electron model, we only expect the $\gamma$ values to be moderately accurate.

For comparison, we have made specific heat measurements. For this purpose, approximately 55 mg of the (La$_{0.9}$Ba$_{0.1}$)$_2$CuO$_{4-y}$ powder with 10% perfect diamagnetism (sample J-6-3) was pressed into a pellet to improve the sample thermal conductivity. The specimen was mounted on the platform of a small sample calorimeter with a small amount of Wakefield thermal compound. The specific heat was measured by the time constant relaxation method between 4 and 36 K. The experimental precision was about ±3%, and the addenda contribution was between 15 and 20% of the total measured specific heat. The results are shown in Fig. 7, plotted as $C/T$ vs. $T^2$. Because of the relatively large scatter in the data, it was not possible to directly observe the specific heat jump at the superconducting transition. Below about 10 K, the specific heat can be represented as $C/T = \gamma + \beta T^2$, where $\beta$ is related to the Debye temperature $\Theta_D$ and is proportional to $\Theta_D^{5/2}$. From these data, one can extract a $\gamma$ value of $6 \pm 0.6 \text{ mJ/mole-K}^2$ and a $\Theta_D$ of 330 ± 10 K. The finite value of $\gamma$ suggests that not all of the sample is superconducting even though an x-ray study showed the sample to have only the $K_2NiF_4$ crystal structure. Evidence of a gap from infrared transmission experiments would seem to preclude the possibility of (La$_{0.9}$Ba$_{0.1}$)$_2$CuO$_{4-y}$ being a gapless superconductor. Based on specific heat measurements on a sample of (La$_{0.9}$Sr$_{0.1}$)$_2$CuO$_{4-y}$ that showed a 55% Meissner effect, a $\Theta_D$ of 360 K, and a $\gamma$ value of 2.6 mJ/mole-K$^2$, it seems likely that the observed $\gamma$ results from volumes of the majority phase that are nonsuperconducting due to stoichiometry variations. If the superconducting fraction of the sample can be assumed proportional to the size of the Meissner effect (10%), then the nonsuperconducting fraction of approximately 90% must be responsible for the finite $\gamma$ value observed, and the true value of $\gamma$ must be at least 10% higher, approximately 6.6 to 7 mJ/mole-K$^2$. This $\gamma$ value is in reasonable accord with that estimated from the Pauli susceptibility ($\gamma = 2.2 \text{ mJ/mole-K}^2$). The Debye temperature is lower than expected, indicating that the high $T_c$ value in our sample may arise from strong electron-phonon interactions.

In conclusion, magnetic measurements have shown that our sample is a bulk type-II superconductor with $T_{co} \approx 35 \text{ K}$ and $\kappa = 11$. The $\gamma$ value obtained from specific heat is not very high relative to a typical A-15 superconductor (such as Nb$_3$Sn with $\gamma = 52 \text{ mJ/mole-K}^2$). We conclude that a strong electron-phonon interaction may be responsible for the high $T_c$.

References


