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MAGNETIC AND THERMAL MEASUREMENTS ON HIGH- T_c $(La_{0.9}Ba_{0.1})_2CuO_{4-y}$

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We have measured the magnetic moment of $(La_{0.9}Ba_{0.1})_2CuO_{4-y}$ as a function of temperature and magnetic field and have found the onset of superconductivity at a temperature $T \approx 35$ 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 ~ 6 mJ/mole-K² 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.¹⁻⁵ Bednorz and Muller¹ have measured the temperature dependence of the resistivity of $Ba_{0.76}La_{4.26}Cu_5O_{15}(3-y)$ and have found a superconducting onset temperature $T_{CO} \approx 35$ K followed by the disappearance of resistivity below $T_0 \approx 12$ K. Chu et al.⁴ have obtained $T_{CO} \approx 35$ K and $T_0 \approx 14$ K for their $La_{1-x}Ba_xCuO_{3-y}$ with $x = 0.15$ and 0.20 , and at a pressure of 12 kbar, T_{CO} increases to 52.3 K and T_0 to 25 K. Very recently, they have improved the quality of their sample and have obtained an excellent sample $(La_{0.9}Ba_{0.1})_2CuO_{4-y}$, which has the K_2NiF_2 crystal structure with $T_{CO} = 44$ K and $T_0 = 28$ K, but, at 10 kbar, $T_{CO} = 45$ and $T_0 = 40$ K. This value of T_0 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 $\chi = dM/dH_{H=0}$. Figure 1 shows our results as a function of temperature. The susceptibility becomes negative below $T_0 = 31$ K. However, it starts to decrease at $T_{CO} \approx 35$ K (not shown). At 2 K, $\chi = 3.3 \times 10^{-2}$ emu/cm³, 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 χ of $La_{1.8}Ba_{0.2}CuO_{4-y}$ defined from dM/dH ($H = 0$), where M is the magnetization.

field, H_{COOL} . 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_{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_{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_{c1} . 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 1.2×10^{-4} emu/mole and nearly independent of temperature. We thus identify this as the Pauli susceptibility χ_p . Using the free-electron model, $\chi_p = 3\mu_B^2\gamma/(\pi k_B)^2$, we obtain the electronic specific heat coefficient $\gamma = 8.5$ mJ/mole- K^2 . Another $(\text{La}_{0.9}\text{Ba}_{0.1})_2\text{CuO}_{4-y}$ sample (J-6-3) with 10% diamagnetic signal gives $\chi_p = 3.06 \times 10^{-5}$ emu/mole (see Fig. 6), yielding $\gamma = 2.23$ mJ/mole- K^2 . For another sample, $(\text{La}_{0.9}\text{Sr}_{0.1})_2\text{CuO}_{4-y}$ (SL-6), with 83% of perfect diamagnetism and $\chi_p = 5.11 \times 10^{-5}$ emu/mole, we have $\gamma = 3.7$ mJ/mole- K^2 . In comparison, we find our present sample has the highest γ value. Because of our use of the free-electron model, we only expect the γ values to be moderately accurate.

Fig. 6. Paramagnetic susceptibility of $\text{La}_{1.8}\text{Ba}_{0.2}\text{CuO}_{4-y}$ and $\text{La}_{1.8}\text{Sr}_{0.2}\text{CuO}_{4-y}$ samples in the normal state as a function of temperature.

For comparison, we have made specific heat measurements. For this purpose, approximately 55 mg of the $(\text{La}_{0.9}\text{Ba}_{0.1})_2\text{CuO}_{4-y}$ 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 method⁶ between 4 and 36 K. The experimental precision was about $\pm 3\%$, 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 β is related to the Debye temperature θ_D and is proportional to θ_D^{-3} . From these data, one can

Fig. 7. Specific heat C of $\text{La}_{1.8}\text{Ba}_{0.2}\text{CuO}_{4-y}$ plotted as C/T vs. T^2 . The inset shows details of the low temperature region.

extract a γ value of 6 ± 0.6 mJ/mole- K^2 and a θ_D of 330 ± 10 K. The finite value of γ suggests that not all of the sample is superconducting even though an x-ray study showed the sample to have only the K_2NiF_2 crystal structure. Evidence of a gap from infrared transmission experiments⁸ would seem to preclude the possibility of $(\text{La}_{0.9}\text{Ba}_{0.1})_2\text{CuO}_{4-y}$ being a gapless superconductor. Based on specific heat measurements on a sample of $(\text{La}_{0.91}\text{Sr}_{0.09})_2\text{CuO}_4$ that showed a 55% Meissner effect, a θ_D of 360 K, and a γ value of 2.8 mJ/mole- K^2 , it seems likely that the observed γ 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 γ value observed, and the true value of γ must be at least 10% higher, approximately 6.6 to 7 mJ/mole- K^2 . This γ value is in reasonable accord with that estimated from the Pauli susceptibility ($\gamma = 2.2$ 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 $T_{CO} \approx 35$ K and $\kappa = 11$. The γ value obtained from specific heat is not very high relative to a typical A-15 superconductor (such as Nb_3Sn with $\gamma = 52$ mJ/mole- K^2).⁷ We conclude that a strong electron-phonon interaction may be responsible for the high T_c .

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