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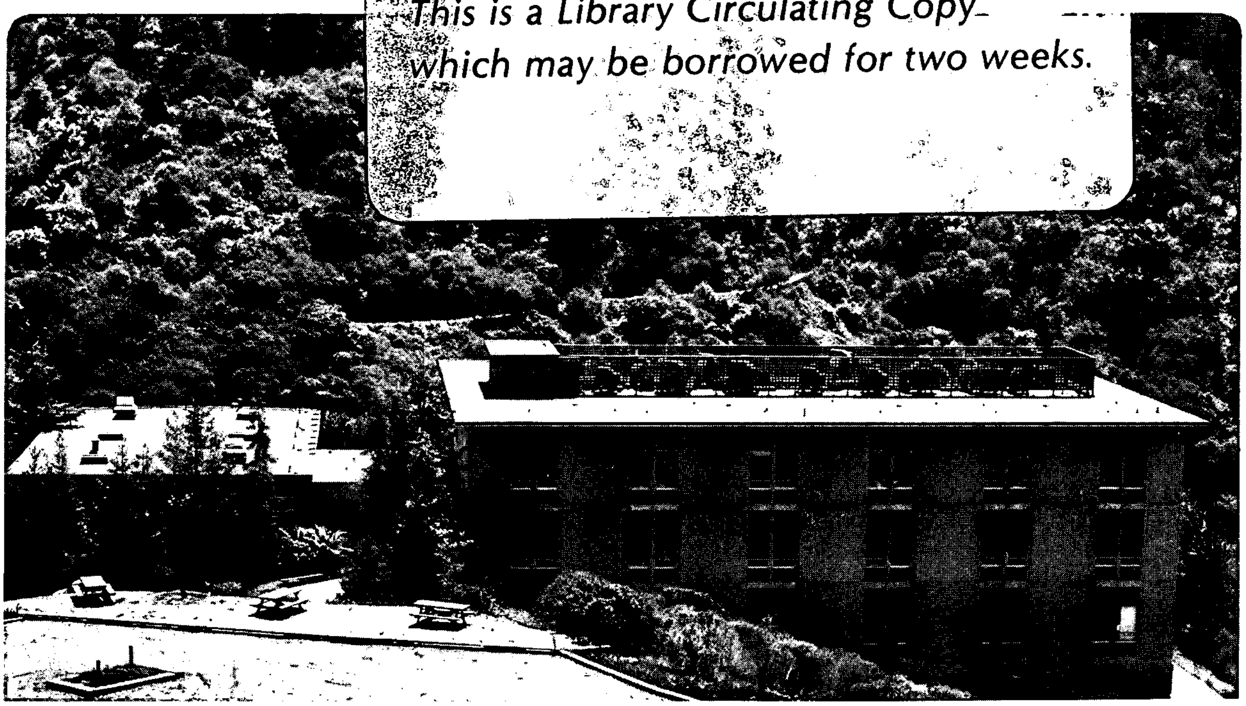



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# MAGNETIC FIELD DEPENDENCE OF THE SPECIFIC HEAT OF SOME HIGH-$T_c$ SUPERCONDUCTORS*

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Measurements of specific heat, C, were made on samples of $La_2CuO_{4-y}$ (La1), $La_{1.85}M_{0.15}CuO_{4-y}$ (Ca1, Sr1, Sr2, Ba1 and Ba2) and $YBa_2Cu_3O_{9-y}$ (Y1). Meissner effect measurements were made in 12.5G. The high-temperature onset of a change in magnetic susceptibility, $\chi$, was taken as $T_c$, and the transition width, $\Delta T_c$, as the temperature interval of the 10-90% change in $\chi$. Calculation of the fractional Meissner effect, $-4\pi\chi_V$, was based on the total sample volume, with $\chi_V$ corrected for demagnetizing effects. Figure 1 is a plot of $-4\pi\chi_V$ vs T. Two germanium thermometers were used for the specific heat

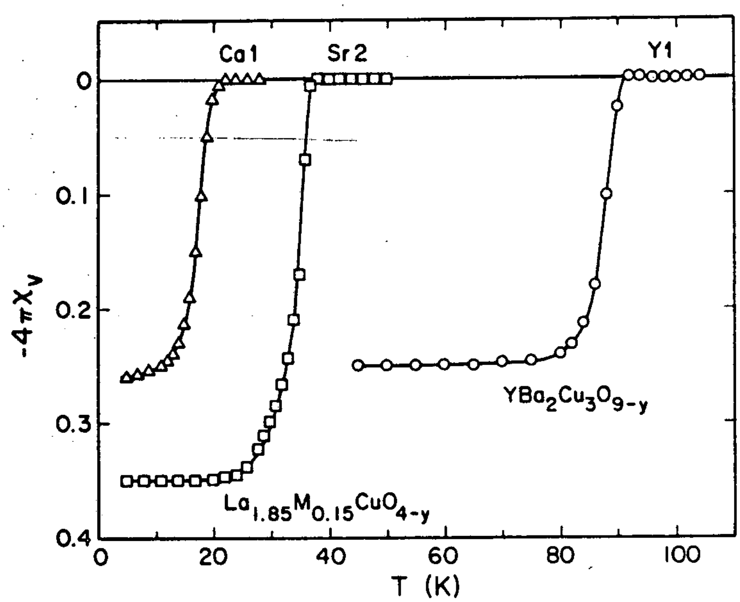


Fig. 1. Fractional Meissner effect, $-4\pi\chi_V$ vs T.

Table 1. Parameters characterizing the high-$T_c$ superconductors $La_{1.85}M_{0.15}CuO_{4-y}$ and $YBa_2Cu_3O_{9-y}$. (All units are in mJ, mole, K and T. ND = not determined.)

| | $-4\pi\chi_V$ | $T_c$ | $\Delta T_c$ | A(0) | $\gamma(0)$ | $\partial\gamma(H)/\partial H$ | $B_3(0)$ | $\partial B_3'(H)/\partial H$ | $B_5$ | $\Theta_D$ |
|---|---|---|---|---|---|---|---|---|---|---|
| La1 | - | - | - | 0.16 | 1.10 | -0.096 | 0.137 | 0 | 0.0019 | 460 |
| Ca1 | 0.26 | 22 | 6 | <0.02 | 3.05 | 0.035 | 0.145 | 0.0019 | 0.0013 | 450 |
| Sr1 | 0.20 | 37 | 18 | ~0 | 3.9 | ~0 | 0.15 | ~0 | ND | 450 |
| Sr2 | 0.35 | 37 | 8 | 0.16 | 1.54 | 0.109 | 0.168 | 0.0011 | 0.00085 | 430 |
| Ba1 | 0.24 | 33 | 11 | 0.34 | 3.6 | ~0 | 0.16 | ~0 | ND | 440 |
| Ba2 | ~0.02 | 34 | >30 | 0.36 | 3.6 | ~0 | 0.16 | ~0 | 0.0013 | 440 |
| Y1 | 0.25 | 91 | 9 | ~4400 | 20 | 0.6 | 0.47 | ND | 0.0006 | 380 |

measurements, a standard $0.3<T<40$K thermometer and a high-resolution one for $2.5<T<40$K which was used only for Ca1 and Sr2. The precision of the total measured C was 0.1% or 0.01% depending on the thermometer. Samples La1, Ca1, Sr2, Ba2 and Y1 were about 25g, and Ba1 and Sr1 only 5g. For the former samples, C ranged from 30 to 60% of the total measured. Parameters characterizing the samples are given in Table 1.

In the following discussion and analysis of the data, subscripts are used to distinguish the various components of C: e for electronic, l for lattice, h for hyperfine, and i for impurity; additional subscripts n, s and m are used to distinguish the normal, superconducting and mixed states; and a quantity in parentheses following the symbol for a component of C or for the coefficient of one of its terms specifies the value of H. Even for H=0, all samples show a linear term in C, $\gamma(0)T$, which is taken to be $C_e$ for a fraction of the sample, $1-f_s$, that is not superconducting. One expects $C_l$ to be independent of H, and $C_l=B_3T^3+B_5T^5$ in the low-temperature limit. ($\Theta_D$ was derived from $B_3$ for one formula weight.) In the mixed state there are field-dependent terms in T and $T^3$ for $C_e$: $C_{em}=\gamma(H)T+B_3'(H)T^3$ [1]. For H≠0 a hyperfine specific heat, $C_h=A(H)/T^2$ is expected. However, for H=0 most samples show deviations from the expected low-temperature limiting be-

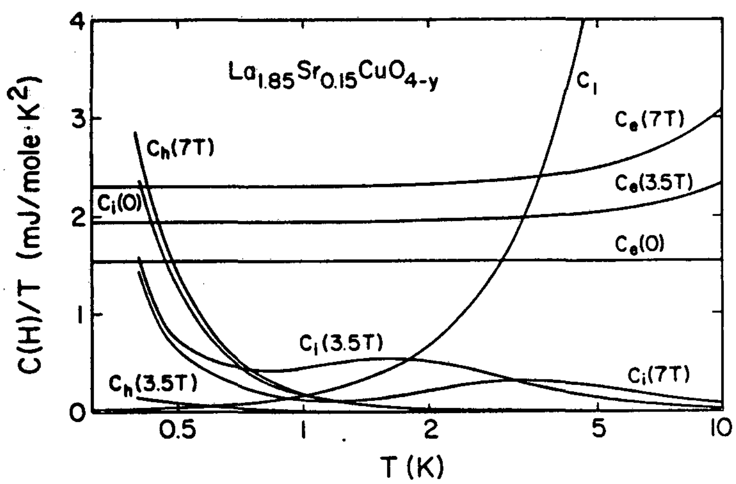


Fig. 2. Components of C for $La_{1.85}Sr_{0.15}CuO_{4-y}$.

havior, $C = C_e + C_1$, of the form $A(0)/T^2$. These deviations are apparently associated with a magnetic "impurity" that becomes partially ordered for $0.4<T<1K$. The evidence for this is clearest for the sample Sr2 for which Schottky anomalies with characteristic temperatures proportional to H are apparent for H=7T and particularly for H=3.5T. The results for all other samples of the La-based compounds are consistent with amounts of the same impurity that vary from sample to sample in proportion to the observed value of A(0). The experimental values of A(H) are then accounted for by the sum of the impurity contributions, $A(0)/T^2$, for that fraction of the sample not penetrated by flux and the hyperfine contribution, $A(H)/T^2$, calculated for the interaction of H with the nuclear moments for that part of the sample penetrated by flux, the penetration being measured by $\gamma(H)$.

For sample Sr2, the analysis of C into its components for T<10K is represented in Fig. 2. For Ca2, Sr2 and La1, the only samples that show a measurable dependence of $C_e$ on H, the field dependence is illustrated in Fig. 3. Within the precision of the data, $C_1$ is nearly the same for all the La-based compounds. It is shown as $C_1/T^3$ for sample Ca1 in Fig. 4. Parameters derived from these analyses are listed in Table 1 for all the La-based samples. Fig. 5 shows $[C_e(0)-C_e(7T)]/T$ for Ca1 and Sr2. The

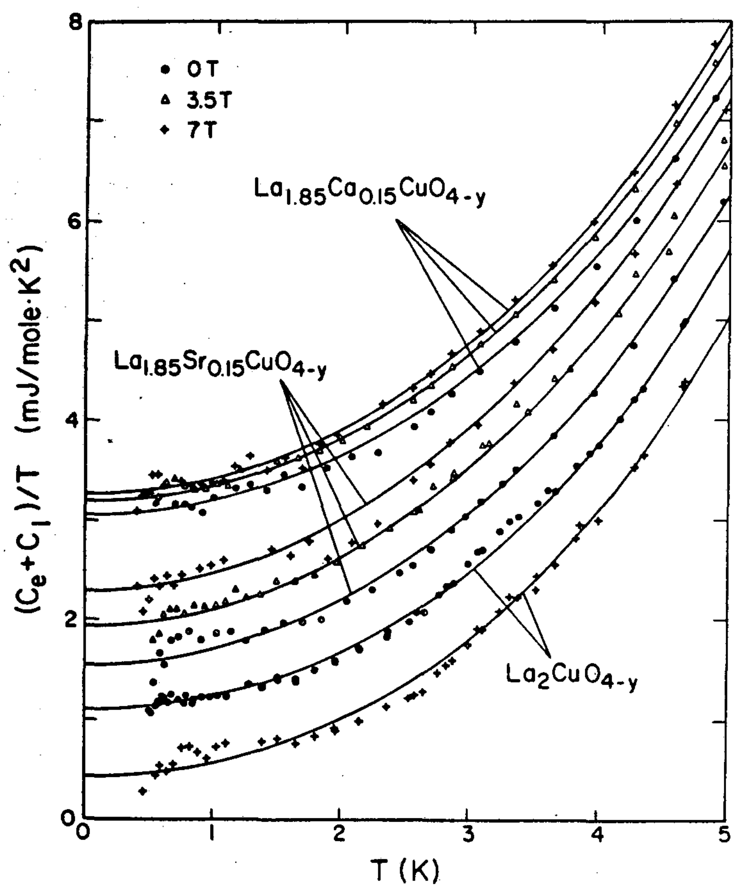


Fig. 3. $(C_e + C_1)/T$ vs T for $La_{1.85}M_{0.15}CuO_{4-y}$.

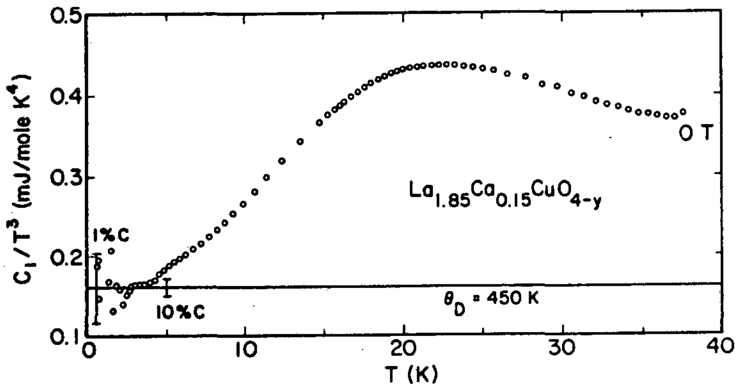


Fig. 4. $C_l$ for $La_{1.85}Ca_{0.15}CuO_{4-y}$ vs T.

low-temperature behavior is in qualitative agreement with expectation for the mixed state in H=7T; the dashed lines represent entropy conserving constructions used to estimate $\Delta C$ at $T_c$; the horizontal bars represent $\Delta T_c$.

If a fraction $f_s$ of the sample is superconducting, $\Delta C=\beta f_s \gamma T_c$ and $\gamma(0)=(1-f_s)\gamma$, where $\beta$ is a numerical coefficient equal to 1.43 in the weak coupling limit, $\gamma$ is the coefficient of $C_e$ for the whole sample and $\gamma(0)$ is the value measured in zero field. If $\beta$=1.43 is assumed, these two relations can be solved to obtain: for Ca1, $f_s$=0.31 and $\gamma$=4.4 mJ/mole·K$^2$; for Sr2, $f_s$=0.82 and $\gamma$=8.6 mJ/mole·K$^2$. Empirically, $\gamma(H)$ is approximately linear in H for $H_{c1}<H<H_{c2}$ [2]. With this approximation $H_{c2}$ at OK, extrapolated from $\gamma$(7T) is 39T for Ca1 and 65T for Sr2. These values are in quite reasonable

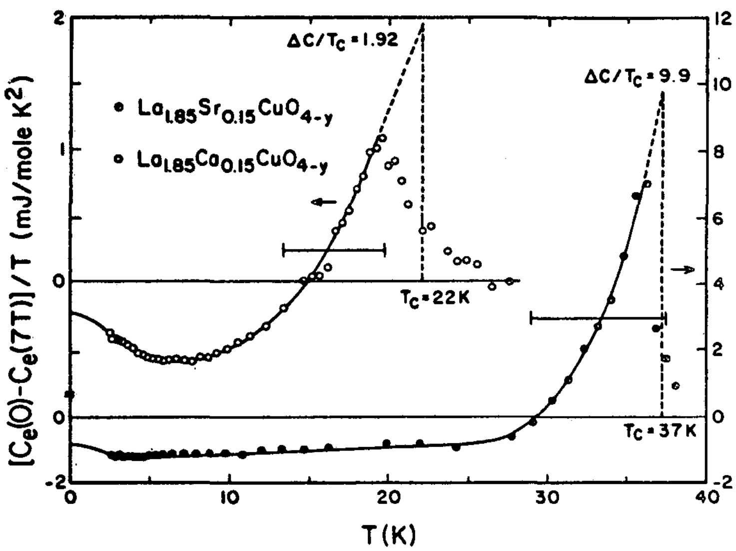


Fig. 5. $[C_e(0)-C_e(7)]/T$ vs T for $La_{1.85}M_{0.15}CuO_{4-y}$.

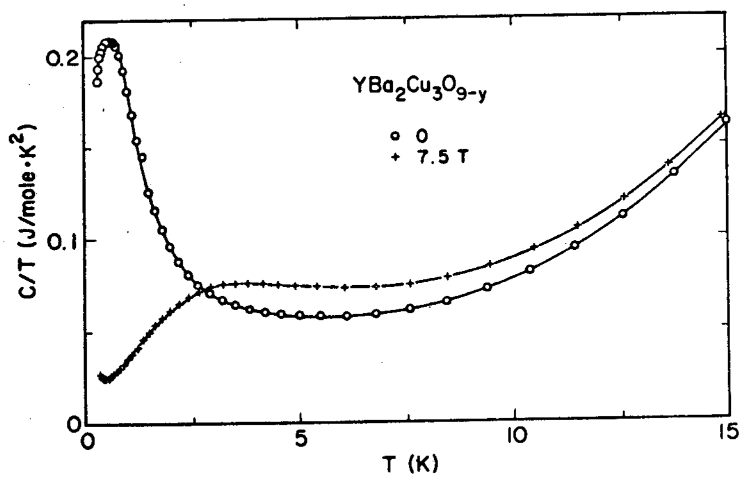


Fig. 6. C/T vs T for $YBa_2Cu_3O_{9-y}$ at 0 and 7.5T.

agreement with reported values [3] but there is enough latitude to allow $\beta$=2. Other interesting results include the poor correlation of $f_s$ obtained in this way for Ca1 and Sr2 with the Meissner effect, the obvious discrepancy between the field independent $\gamma$ values and Meissner effect data for other samples, the nonzero value of $\gamma$ for $La_2CuO_{4-y}$, which is predicted theoretically [4], and its strong field dependence. For $La_{2-x}Sr_xCuO_{4-y}$ other measurements of C(0) and $\Delta C/T_c$ have been reported [5].

For the Y-based compound, as shown in Fig. 6, analysis of the data is complicated by a large impurity effect. However, rough estimates of $\gamma(0)$, $\partial\gamma(H)/\partial H$ and $\Theta_D$ are included in Table 1.

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