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Upper critical fields of high-T_c superconducting $La_{2-x}Sr_xCuO_{4-y}$: Possibility of 140 tesla

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The upper critical fields $B_{c2}(T)$ of $La_{2-x}Sr_xCuO_4$ ($x=0.15$ and $x=0.20$) were measured near T_c in dc fields to 23 T and at 4.2 K with pulsed fields to 45 T. Resistive midpoint transitions for the $x=0.15$ sample yield $(dB_{c2}/dT)_{T=T_c}=2.2$ T/K, $T_c=38.1$ K, and $B_{c2}(0)=58$ T assuming a dirty type-II superconductor with no Pauli paramagnetic limiting. Data for the onset yield 4.5 ± 0.5 T/K, 40.1 K, and 125 ± 15 T, respectively. Pulsed-field data show that fractions of both materials are superconducting above 45 T at 4.2 K. Calculations of limits of $B_{c2}(T)$ are presented and experimental limitations of measurements in these high-field superconductors are indicated.

Since Bednorz and Müller[1] reported a high T_c in a superconducing oxygen-defect perovskite, many groups have begun investigations in this class of materials (see Refs. 2-6: These are among the papers known to us but there are many other groups actively involved). In this Rapid Communication we report measurements of the upper critical fields, $B_{c2}(T)$, with applied dc fields B_0 up to 23 T (near T_c) and with pulsed fields at 4.2 K up to 45 T in $La_{2-x}Sr_xCuO_4$ for $x=0.15$ and 0.20. We observe that extremely high upper critical fields can be achieved. $B_{c2}(T)$ is a sensitive function of composition and the resistive transition becomes very broad so that very large fields are necessary to define $B_{c2}(T)$. Calculations of $B_{c2}(T)$ are presented to show the wide range of $B_{c2}(0)$ which can be extrapolated based on which assumptions are made. The lowest estimates of $B_{c2}(0)$ are well within our pulsed-field capabilities, whereas the more optimistic projections suggest $B_{c2}(0)=140$ T. The present results are consistent with the assumptions that these new high-T_c materials are conventional superconductors with correspondingly high values of $B_{c2}(T)$.

The materials were prepared at Bell Communications Research as described in Ref. 2 which also discussed structural, magnetic, and electronic properties over the range of $0.05\leq x\leq 1.1$. The characteristics of the particular samples discussed in this Rapid Communication are given in Table I of Ref. 2 as 2S14 and 4S14 for $x=0.15$ and $x=0.20$, respectively.

The upper critical field $B_{c2}(T)$ was measured resistively with a standard four-probe method in transverse dc magnetic fields up to 23 T furnished by water-cooled magnets at the Francis Bitter National Magnet Laboratory facility. Leads were attached with Ag paint and current densities ≤ 0.5 A/cm^2 were used. Tests were made to ensure that $B_{c2}(T)$ was not sensitive to the applied dc current. The samples were small rectangular polycrystalline slabs with good mechanical integrity. The resistive measurements were made in a small cryostat having variable temperature control. The samples were in contact with He gas in the cryostat and the temperature was monitored with capacitance and carbon-glass thermometers. Most of the data were taken at fixed values of T and swept B_0 and selected points were taken at fixed B_0 while varying T. The results of these $B_{c2}(T)$ measurements near T_c are shown in Fig. 1. Detailed data are given for the $x=0.15$ sample because

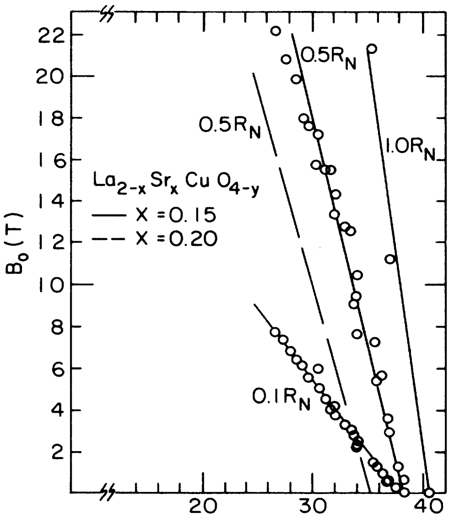

FIG. 1. Upper critical field B_{c2} vs temperature T for $x=0.15$ and 0.20 in $La_{2-x}Sr_xCuO_4$. The data are corrected for the temperature dependence of the normal resistance. The values of $B_{c2}(T)$ for midpoint resistivity ($0.5R_N$), at 10% ($0.1R_N$), and the onset ($1.0R_N$) are shown for the $x=0.15$, and for midpoint for the $x=0.20$ sample (broken line).

this specimen had the higher T_c and sharper resistive transition at $B_0=0$. The data for the $x=0.20$ sample illustrate the effect of small changes in composition.

There is a rapid increase in the resistive transition width as T is decreased below T_c and this makes it difficult to define the resistive transitions accurately over a large range of temperature unless fields in the range of 20 T or more are available. To illustrate this point we show the data for the resistive midpoint ($0.5R_N$), the bottom of the transition ($0.1R_N$), and the onset which we designate as ($1.0R_N$). In contrast with conventional superconductors, these high-T_c materials show a relatively large linear decrease of R_N near T_c. The data plotted here are corrected for this assumed change in R_N vs T below T_c [which *reduces* $|(dB_{c2}/dT)_{T=T_c}|$ by about 10% for the $x=0.15$ sample]. A much smaller effect is the magnetoresistance of the material near T_c, which is about 3% at 23 T and nearly T independent in the range we could investigate near T_c. The data taken at fixed B_0 while varying T were consistent with the field-swept data (as expected), and were more convenient for defining the onset of superconductivity.

For the $x=0.15$ sample the midpoint yields $(dB_{c2}/dT)_{T=T_c}=2.2$ T/K and $T_c=38.1$ K; for the onset $(dB_{c2}/dT)_{T=T_c}=4.5\pm0.5$ T/K and $T_c=40.1$ K. For the $x=0.20$ sample the data give for the midpoint 1.9 T/K and 34.8 K, respectively. The values of T_c are obtained from extrapolation of the respective $0.5R_N$ and $1.0R_N$ high-field data to $B_0=0$. We also took data (not shown) using a noncontacting rf-loss technique on the $x=0.15$ sample. This measurement yields a measure of $B_{c2}(T)$ near the onset of superconductivity.[7] Pulsed-field measurements were made in the pulsed-field facility at the laboratory up to 45 T at 4.2 K using the rf technique. For both the $x=0.20$ and $x=0.15$ sample, it was clear that a fraction of each sample was superconducting at 45 T. These data are indicated by the arrow in Fig. 2.

Comparison of the results for the two samples shows the following: (1) the higher-T_c material ($x=0.15$) has a higher $B_{c2}(T)$ and higher midpoint resistive slope $(dB_{c2}/dT)_{T=T_c}$ than the $x=0.20$ sample, (2) even in the $x=0.15$ sample, with a $B_0=0$ resistive transition width of 2 K, there is a large increase in the width of the resistive transition as T decreases. If $0.1R_N$ to $0.5R_N$ data are used as a measure of the half-width of the entire transition ($0.1R_N$ to $1.0R_N$) then this width is about 24 T at 30 K, (3) the values for $B_{c2}(T)$ at $0.5R_N$ are conservative estimates for the upper limits of $B_{c2}(T)$, and (4) values of $B_{c2}(T)$ far above those reported for any superconductor to date are obtained for the highest-T_c fractions. Whether the breadth of these transitions is largely due to inhomogeneity in the materials, or anisotropy in $B_{c2}(T)$, or both is not clear. Single-crystal measurements would be very useful to clarify this aspect.

Figure 2 shows the range of $B_{c2}(T)$ predicted by midpoint and onset data near T_c for $x=0.15$ using the standard $B_{c2}(T)$ theory for a three-dimensional dirty type-II superconductor.[8] $B_{c2}(0)$ ranges from 50 to 140 T. [For convenience we chose the upper limit for the onset data as $(dB_{c2}/dT)_{T=T_c}=5.0$ T/K.] The upper bound assumes that the spin-orbit scattering parameter $\lambda_{SO}=\infty$, so that the superconducting pairs are broken only by the orbital pair breaker, whereas the lower bound assumes $\lambda_{SO}=0$, so that these pairs are broken by both the orbital and Pauli-spin pair breakers. The dashed curves give the range of $B_{c2}(T)$ for the midpoint $B_{c2}(T)$ data and the solid curves are the range $B_{c2}(T)$ for the onset $B_{c2}(T)$ data. An increased $B_{c2}(T)$ from the lower bound is calculated for increased λ_{SO} or by an increased Pauli pair breaker H_P (which includes many-body renormalization by the antisymmetric Fermi-liquid parameter,[9,10] and here is estimated as the electron-phonon coupling constant $\lambda_{e\text{-ph}}$). Table I lists values of $B_{c2}(T)$ at $T=0$, 4.2, and 27 K (liquid Ne) for various $\lambda_{e\text{-ph}}$'s. (The upper bound $\lambda_{SO}=\infty$ is not affected by choice of $\lambda_{e\text{-ph}}$.) These values can be used to make projections for possible high-field tests. Based on our experience with conventional superconductors, we believe that the onset data reflect the upper limit expected for homogeneous material, whereas the midpoint data give a conservative limit.

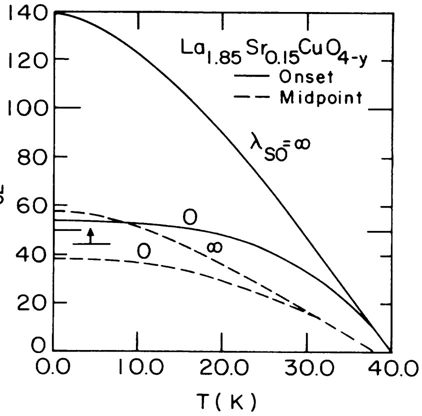

FIG. 2. Calculated upper ($\lambda_{SO}=\infty$) and lower ($\lambda_{SO}=0$) bounds for $B_{c2}(T)$ using $B_{c2}(T)$ for $0.5R_N$ (dashed curves) and $1.0R_N$ (solid curves) data of Fig. 1 for $\lambda_{e\text{-ph}}=0$. Points at 0, 4.2, and 27 K are listed in Table I for reasonable values of $\lambda_{e\text{-ph}}$. The arrow indicates that there is a fraction of the material which is superconducting above 45 T as measured with pulsed fields at 4.2 K.

Both Figs. 1 and 2 point out several difficulties for extending experiments to higher fields in these high-T_c materials. With the present relatively narrow $B_0=0$ resistive transition materials, calculations show that dc fields of 30 T may be sufficient to narrow the range of estimated $B_{c2}(0)$ somewhat.

The temperature dependence of the resistance $\rho(T)$ in the normal state (which is large here[2]) also affects the estimate of $B_{c2}(T)$. In the dirty limit we assume that we can multiply the orbital pair breaker by $\rho(T_c)/\rho(T)$. Inclusion of $\rho(T)$ shows that $B_{c2}(27\text{ K})$ is hardly affected, but $B_{c2}(0\text{ K})$ and $B_{c2}(4.2\text{ K})$ can be reduced by as much as $\rho(0)/\rho(T_c)$. If $\rho(T)$ decreases linearly to 20 K and then remains constant, $\rho(20)/\rho(T_c)=0.65$ for $x=0.15$.[2] Further reduction in $\rho(T)$ can lead to a sufficient reduction in $B_{c2}(T)$ to show a reentrantlike shape at low T. The above discussion suggests that extrapolations of $B_{c2}(T)$ to low temperatures may be open to a wide variation; direct

TABLE I. Estimates of $B_{c2}(T)$ based on high-field data near T_c.

$\lambda_{e\text{-ph}}$	λ_{SO}	$B_{c2}(0\ \text{K})$	$B_{c2}(4.2\ \text{K})$	$B_{c2}(27\ \text{K})$
Estimate based on onset of data; $(dB_{c2}/dT)_{T=T_c}=5.0$ T/K, $T_c=40.1$ K				
$\cdots$	∞	140 T	135 T	59 T
0	0	52	50	38
1	0	84	84	51
2	0	104	104	55
Estimate based on midpoint data; $(dB_{c2}/dT)_{T=T_c}=2.2$ T/K, $T_c=38.1$ K				
$\lambda_{e\text{-ph}}$	λ_{SO}	$B_{c2}(0\ \text{K})$	$B_{c2}(4.2\ \text{K})$	$B_{c2}(27\ \text{K})$
$\cdots$	∞	58	57	23
0	0	38	38	21
1	0	50	50	23
2	0	54	53	23

measurements are necessary and these will require very high fields.

The measured $(dB_{c2}/dT)_{T=T_c}$, T_c, and $\rho(T_c)$ yield superconducting and normal-state parameters.[10] For $(dB_{c2}/dT)_{T=T_c}=5$ T/K, $\rho(T_c)=430\ \mu\Omega\,\text{cm}$ (Ref. 2), and $T_c=40$ K, the electronic specific heat $\gamma=2600$ erg cm^{-3}K^{-2}, the Ginsburg-Landau coherence length $\xi_{GL}(0)$, and penetration depth $\lambda_{GL}(0)$ are 1.3 and 210 nm, respectively. The above parameters assume that these samples are in the dirty limit with carrier densities $> 10^{22}$ cm^{-3}. Estimates based on $(dB_{c2}/dT)_{T=T_c}=2.2$ T/K give $\gamma=1100$ erg cm^{-3}K^{-2}, and comparable GL lengths. It should be noted that the value of γ, although low, is comparable to that of NbN (Ref. 11) ($\gamma=1700$ erg cm^{-3} K^{-2}). Furthermore, the quoted ρ values for the high-T_c materials are probably upper limits. The estimates above indicate that the La-Sr-Cu-O system is probably a conventional BCS superconductor as suggested.[6]

The large values of $B_{c2}(T)$ projected for these new superconductors will make measurements at low temperature very difficult. To test whether paramagnetic limiting is appreciable,[12] measurements can be extended with dc or pulsed fields at liquid Ne temperatures. An experimental magnet using a new Cu/Nb microcomposite has been tested up to 68.4 T at the Francis Bitter National Magnet Laboratory[13] and can be used for selected measurements. Such experiments are planned for the near future.

On completion of this work we received a copy of work by Capone II, Hinks, Jorgensen, and Zhang[14] which reports $B_{c2}(T)$ measurements to 6 T on $La_{1.85}Sr_{0.15}CuO_4$ with a midpoint $(dB_{c2}/dT)_{T=T_c}=2.13$ T/K, midpoint $T_c=34.7$ K, and extrapolated $B_{c2}(0)\simeq 50$ T. (Data by Tarascon *et al.*[2] taken to 5 T on our samples also indicated that these materials are high-field superconductors.) Because of the broad transitions and curvature near T_c we would expect low-field data ($\sim$5–6 T) to underestimate $B_{c2}(T)$. Our reported midpoint slope for the $x=0.15$ sample is in very good agreement with the lower-field data of these authors, but our midpoint is $T_c=38.1$ K. On the other hand, our midpoint slope for the $x=0.20$ sample is 1.9 T/K and has a midpoint $T_c=34.8$ K, very close to these authors' $x=0.15$ sample. Our high-field data thus confirm these earlier projections that these high-T_c materials will have very high upper critical fields.

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