LBL-23808
Preprint

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Materials & Chemical Sciences Division

RECEIVED
LAWRENCE
BERKELEY LABORATORY

SEP 1 8 1987

LIBRARY AND
DOCUMENTS SECTION

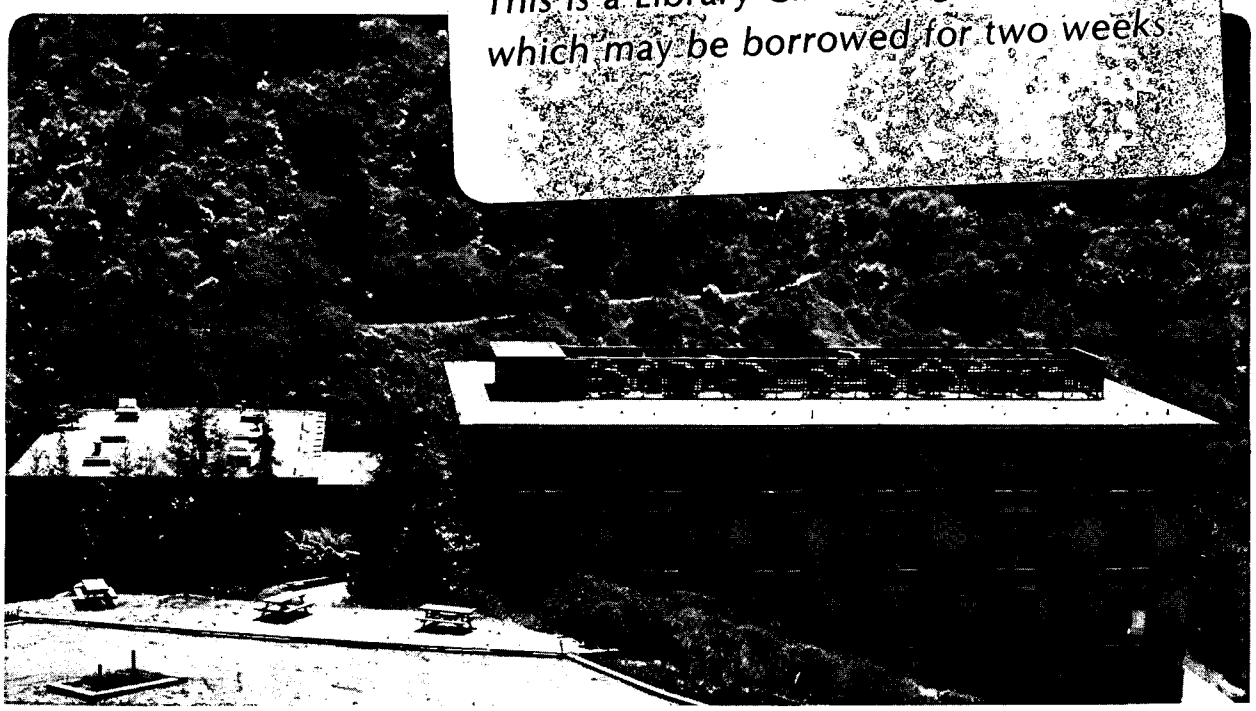
Submitted to Journal of Materials Research

Pressure Dependence of the Superconducting Transition Temperatures in $La_{1.85}Sr_{0.15}CuO_4$ to 8 GPa

D. Erskine, E. Hess, P.Y. Yu, and A.M. Stacy

July 1987

TWO-WEEK LOAN COPY
This is a Library Circulating Copy
which may be borrowed for two weeks.



LBL-23808 c.2

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

Pressure Dependence of the Superconducting Transition Temperatures in $La_{1.85}Sr_{0.15}CuO_4$ to 8 GPa

D. Erskine[(a)], E. Hess, and P. Y. Yu

Department of Physics, University of California

and

Materials and Chemical Sciences Division,

Lawrence Berkeley Laboratory, Berkeley, Ca. 94720

and A. M. Stacy

Department of Chemistry, University of California

and

Materials and Chemical Sciences Division,

Lawrence Berkeley Laboratory, Berkeley, Ca. 94720

PACS: 74.10.+v;81.40.Rs

ABSTRACT

Pressure dependence of the superconducting transition temperatures in $La_{1.85}Sr_{0.15}CuO_4$ has been measured to 8 GPa using a diamond anvil cell. The experimental results are discussed within the conventional electron-phonon model of superconductivity.

[(a)]Present address: Lawrence Livermore Laboratory, University of California, Livermore, Ca. 94550.

Pressure has played a role in the recent developments of high transition temperature (T_c) superconductors. After verifying the results of Bednorz and Muller[1] in LaBaCuO compounds, Chu[2,3] and coworkers measured the pressure dependence of T_c in these compounds and found that the onset temperature for superconductivity (T_{co}) increased with pressure with a rather large coefficient of dT_{co}/dP~9 K/GPa. These results led Chu[2] and possibly others[4,5] to substitute Ba with Sr and discover that T_{co} increased to 40 K in the Sr compounds. Subsequently the pressure dependence of T_c in this family of new superconductors has been studied by several groups to 2 GPa.[6-8] In general T_c increased with pressure with an average pressure coefficient of between 2 to 4 K/GPa.

Based on experimental results in other superconductors, there are two possibilities for what will happen at higher pressures. One possibility is that T_c will increase to a maximum value at some pressure and then decrease with pressure. This has been observed, for example, in La chalcogenides by Eiling et al.[9] Another possibility is that the lattice will transform into a new phase with a different T_c and pressure dependence. The latter possibility is suggested by the existence of soft phonon modes in these materials.[10] In this paper we report the pressure dependence of T_c in $La_{1.85}Sr_{0.15}CuO_4$ to 8 GPa. We found that T_c reached a broad maximum around 5 GPa and then decreased with pressure beyond 7 GPa. A discussion of our results based on the conventional model of superconductivity is also presented.

Our measurements have been performed on polycrystalline samples of LaSrCuO. The methods of preparation have been described elsewhere.[11] These samples have been characterized by resistivity and magnetic measurements at ambient pressure.[11,12] The dc magnetic susceptibility results suggested a T_c of 36 K and a transition width of about 10 K. The resistance versus temperature curve typically showed a sudden drop at a higher temperature of 40 K and also a narrower transition width of about 1 K. The starting material in the form of a pellet was crushed and a small fragment of about 200 micron across was loaded into a diamond anvil high pressure cell. The technique for loading the cell for electrical measurements has been described by Erskine et al.[13] The sample was surrounded by $CaSO_4$ powder as the pressure medium. This produced a quasi-hydrostatic environment with a pressure inhomogeneity of typically less than 10 %. Previous studies of the pressure dependence of T_c in a number of single crystalline materials have shown the reliability of this technique.[13]

Measurements performed on the LaSrCuO samples in two different runs showed good reproducibility and no sign of pressure induced broadening of the transition up to 5 GPa. The resistance of the sample inside the high pressure cell was determined by a quasi-four-probe technique using two loops of copper wire.[13] When measured inside the cell the sample resistance did not vanish below the superconducting transition temperature. However, a larger sample from the same source measured with a true four-probe technique

outside the cell showed no residual resistance.[12] We assumed that this residual resistance resulted from poor contact between the sample and the copper leads inside the cell. Since this residual resistance was independent of pressure it did not affect our accuracy in determining the transition temperatures. To estimate the pressure dependence of the transition temperature we have defined two temperatures T_{co} and T_{c1} following Chu et al.[2] T_{co} is defined to be the temperature where the resistance drops by 10% of the total decrease in resistance due to the superconducting transition, while T_{c1} is the temperature where the resistance drops by 50% (see inset of Fig.1).

Figure 1 shows the pressure dependence of T_{co} and T_{c1} for two different runs on samples from the same pellet. The two sets of data (solid and open points) agree with each other within experimental uncertainties. The difference between T_{co} and T_{c1} of about 4 K remained constant up to 5 GPa. Above 5 GPa this difference increased slightly to 5 K. Above 8 GPa the room temperature resistance decreased abruptly by about an order of magnitude while the resistance drop at the superconducting transition also decreased quickly with pressure and disappeared completely around 9 GPa. On releasing the pressure the sample remained intact but has a higher conductivity. The sample also showed no resistance drop associated with superconducting transition down to 4.2 K. The disappearance of the superconducting transition above 8 GPa did not appear to be caused by disintegration of the sample. Whether it was caused by a phase transition or other irreversible changes induced by

pressure required further investigation. Although X-ray diffraction studies in these compounds showed no sign of any structural phase transition up to 20 GPa,[14] the existence of other types of more subtle phase transitions cannot be ruled out. We also note that the pressure dependence of T_{c1} is very nonlinear. Below 2 GPa T_{c1} increased with pressure at an average rate of about 2.5 K/GPa. Between 2 and 4 GPa the rate decreased to less than 1 K/GPa. Between 4 and 6 GPa T_{c1} was almost constant at the maximum value of ~46.3 K.

Usually the starting point for discussing the pressure dependence of T_c in conventional superconductors is the following equation:[15]

$$T_c = T_D \exp-[1/N(0)(\lambda-\mu^*)] \qquad (1)$$

where T_D is typically taken to be the Debye frequency, N(0) is the density-of-states of electrons at the Fermi energy, λ is the electron-phonon interaction, and μ^* is the screened Coulomb repulsion between the electrons. In most materials T_D increases with pressure since pressure tends to harden the lattice. N(0) usually do not change much with pressure. The electron-phonon interaction tends to decrease as the lattice is hardened by pressure. The pressure dependence of μ^* has not been investigated and is assumed to be negligible. Thus in most materials the net effect of pressure is to decrease T_c by decreasing λ. However, some materials do not follow this simple pattern. For example, in hexagonal Si, pressure enhanced T_c by inducing a soft mode whose coupling to the electrons was increased by pressure.[16] In La_3S_4 and La_3Se_4, Eiling et al.[9] found that T_c first increased with pressure,

reached a maximum and then decreased with pressure. They showed that although pressure suppressed the electron-phonon interaction, this decrease in λ was offset by an increase in N(0) with pressure. The pressure dependence of N(0) showed a maximum so the overall pressure dependence of T_c can be explained only by including the effect of pressure on N(0).

Qualitatively the pressure dependence of T_{co} in $La_{1.85}Sr_{0.15}CuO_4$ is very similar to that of La_3S_4 so it is tempting to explain our results in the same way. However, according to recent electronic band structure calculations[17,18] the density-of-states is relatively flat near the Fermi level in La_2CuO_4 so N(0) should not depend strongly on pressure. This has been verified by Allgeier et al. from the pressure dependence of the magnetic sucseptibility of $La_{1.85}Sr_{0.15}CuO_4$.[19]

At this point one can try to explain the present results either within the conventional electron-phonon theory of superconductivity or by using the many other mechanisms of superconductivity which have been proposed recently.[20] Unfortunately the effect of pressure on T_c in the other models have not been investigated. On the other hand recent reports of the isotope effect in LaSrCuO compounds seems to support the electron-phonon mechanism for superconductivity in this family of materials.[21]

Weber[10] has proposed a soft-phonon model to explain the T_c in $La_{1-x}Sr_xCuO$ compounds. In his model the strong pressure dependence of T_c in these superconductors was explained by the

fact that the samples were always inhomogeneous so that there was a range of values for x. In Weber's model the smaller the fraction x of Sr the higher T_c became in the metallic tetragonal phase. Since pressure would harden the Cu-O bond and hence stablize the tetragonal phase, it would allow the small fraction of the sample with smaller values of x to remain in the metallic phase and therefore caused the entire sample to appear superconducting at a higher temperature. Since we do not know the variation in the concentration of Sr across our sample, it is not possible to rule out this explanation. Otherwise this model seems to be consistent with some of our experimental observations. For example this model can explain the very large and nonlinear pressure dependence of T_c observed by the dependence of T_c on x. The saturation in T_c with pressure can be explained by the fact that there is a minimum value in x such that parts of the sample with x below this minimum value are not continuous across the sample. These parts increase the onset temperature T_{co} only. Thus when T_c reaches a maximum value an increase in pressure will broaden the transition by increasing T_{co} but not T_{c1}. Although the electron-phonon model of Weber is consistent with our result, without further experiments it is not possible to exclude other possible explanations of our result.

We wish to thank Profs. M. L. Cohen and A. Zettl for their interest and encouragement during the course of this work. This research was supported by the Director, Office of Energy Research, Office of Basic Sciences, Materials Sciences Division of the US Department of Energy, under contract DE-AC03-76SF00098.

REFERENCES

1. J. G. Bednorz and K. A. Muller, Z. Phys. B 64, 18 (1986).
2. C. W. Chu, P. H. Hor, R. L. Meng, L. Gao, Z. J. Huang, Science 235, 567 (1987).
3. C. W. Chu, P. H. Hor, R. L. Meng, L. Gao, Z. J. Huang, and Y. Q. Wang, Phys. Rev. Lett. 58, 405 (1987).
4. R. J. Cava, R. B. van Dover, B. Batlogg, and E. A. Rietman, Phys. Rev. Lett. 58, 408 (1987).
5. J. G. Bednorz, K. A. Muller, and M. Takashige, Science 236, 73 (1987).
6. J. E. Schirber, E. L. Venturini, J. F. Kwak, B. Morosin, D. S. Ginley (unpublished).
7. R. N. Sheldon, presented at the 1987 Spring Meeting of the Materials Research Society, Anaheim, Ca.
8. M. Sato, M. Onoda, S. Shamoto, S. Hosoya and Y. Maruyama (unpublished).
9. A. Eiling, J. S. Schilling and H. Bach, in Physics of Solids under High Pressure, ed. by J. S. Schilling and R. N. Sheldon (North Holland Publishing Company, 1981) p.385.
10. W. Weber, Phys. Rev. Lett. 58, 1371 (1987).
11. U. Walter, M. S. Sherwin, A. Stacy, P. L. Richards and A. Zettl (to appear in Phy. Rev. B, May 1, 1987).
12. A. Zettl (unpublished).
13. D. Erskine, P. Y. Yu and G. Martinez, Rev. Sci. Instr. 58, 406 (1987).

14. H. Wuhl, I. Apfelstedt, M. Dietrich, J. Ecke, W. H. Fietz, J. Fink, R. Flukiger, E. Gering, F. Gompf, H. Kupfer, N. Nucker, B. Obst, C. Politis, W. Reichardt, B. Renker, H. Rietschel, W. Schauer and F. Weiss, presented at the 1987 Spring Meeting of the Materials Research Society Meeting, Anaheim, Ca.

15. W. L. McMillan, Phys. Rev. 167, 331 (1968).

16. D. Erskine, P. Y. Yu, K. J. Chang and M. L. Cohen, Phys. Rev. Lett. 57, 2741 (1986).

17. L. F. Mattheiss, Phys. Rev. Lett. 58, 1028 (1987).

18. J. Yu, A. J. Freeman and J. H. Xu, Phys. Rev. Lett. 58, 1035 (1987).

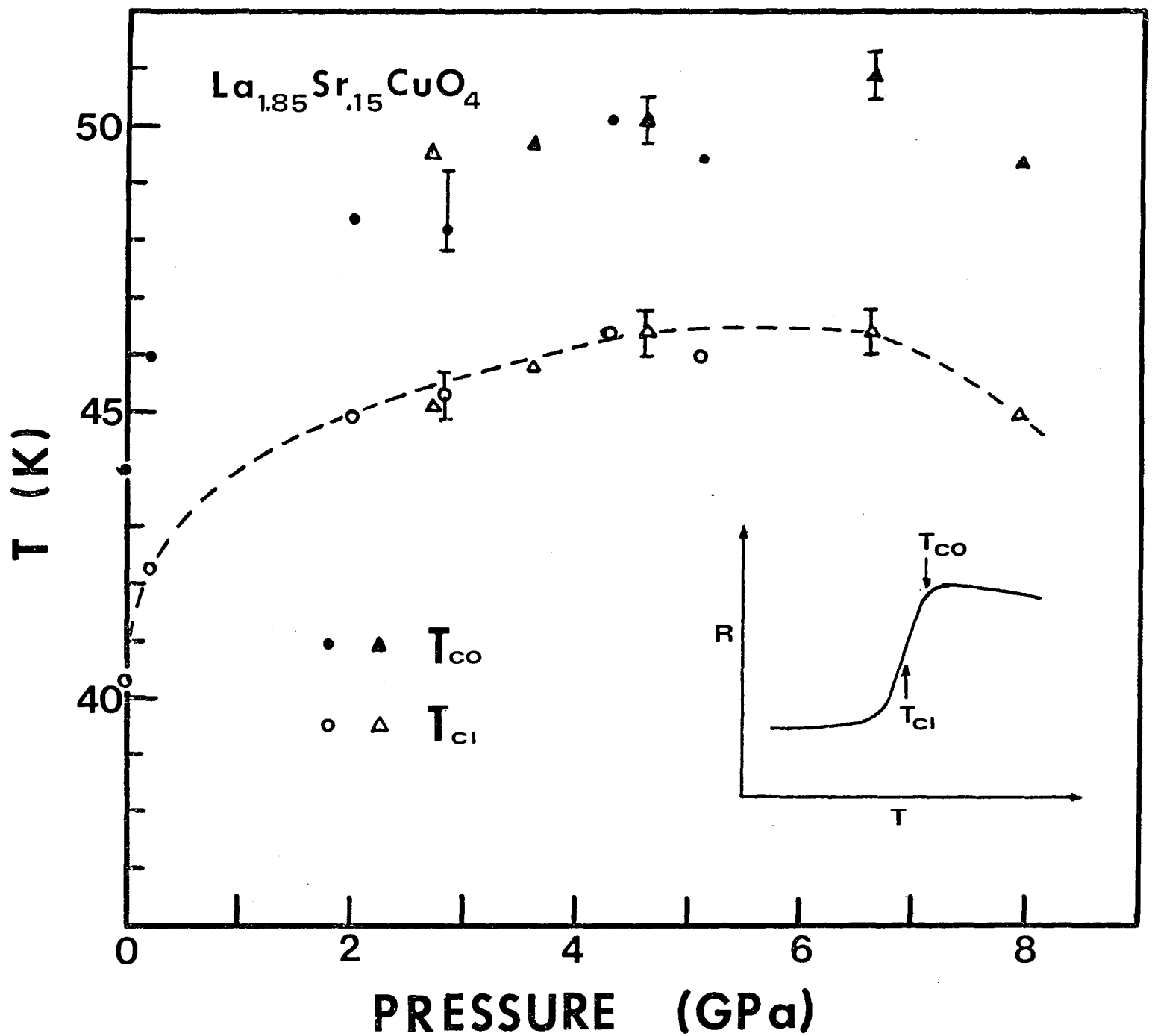
19. C. Allgeier, J. S. Schilling, H. C. Ku, P. Klavins, and R. N. Shelton, Solid State Commun. (in press).

20. See for example P. W. Anderson, Science 235,1196 (1987); and V. Z. Kresin, Phys. Rev. B (to be published).

21. T. A. Faltens, W. K Ham, S. W. Keller, K. J. Leary, J. N. Michaels, A. M. Stacy, H-C zur Loye, D. E. Morris, T. W. Barbee III, L. C. Bourne, M. L. Cohen, S. Hoen and A. Zettl, (unpublished).

FIGURE CAPTION

Fig. 1 Pressure dependence of the superconducting temperatures T_{co} and T_{c1} in $La_{1.85}Sr_{0.15}CuO_4$ measured in two different runs. The definition of T_{co} and T_{c1} are shown schematically in the inset.


La1.85Sr.15CuO4
50
45
40
T (K)
0
2
4
6
8
PRESSURE (GPa)
Tco
Tcl
R
T
Tco
Tcl

LAWRENCE BERKELEY LABORATORY
TECHNICAL INFORMATION DEPARTMENT
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720