# Pressure dependence of the superconducting transition temperatures in $La_{1.85}Sr_{0.15}CuO_4$ to 8 GPa

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Pressure dependence of the superconducting transition temperature 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.

## I. INTRODUCTION

Pressure has played a role in the recent developments of high-transition temperature ($T_c$) superconductors. After verifying the results of Bednorz and Müller[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 $dT_{co}/dP \sim 9$ 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 2–4 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 article 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.

## II. MEASUREMENTS

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 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 about 200 $\mu$ 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 quasihydrostatic 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] Here $T_{co}$ 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 tempera-

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ture where the resistance drops by 50% (see inset of Fig. 1).

## III. DISCUSSION

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 (circles and triangles) 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 reistance 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 had 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 $\sim$46.3 K.

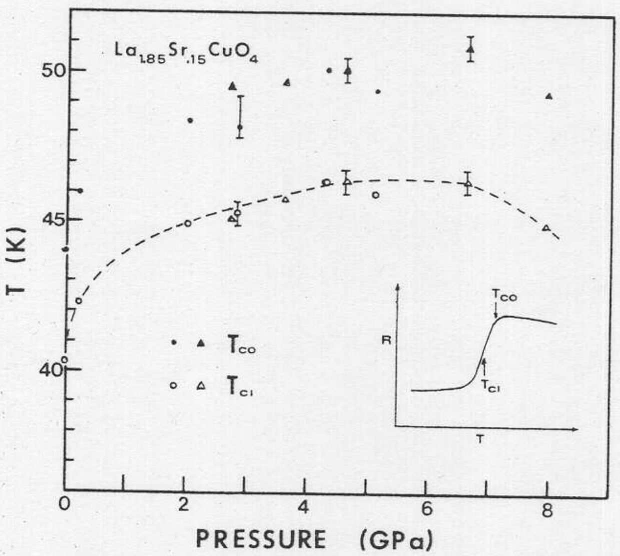


FIG. 1. Pressure dependence of the superconducting temperatures $T_{co}$ and $T_{c1}$ in $La_{1.85}Sr_{0.15}CuO_4$ measured in two different runs. The definition of $T_{co}$ and $T_{c1}$ are shown schematically in the inset.

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, $\lambda$ is the electron–phonon interaction, and $\mu^*$ is the screened Coulomb repulsion between the electrons. In most materials $T_D$ increases with pressure since pressure tends to harden the lattice. The $N(0)$ usually does not change much with pressure. The electron–phonon interaction tends to decrease as the lattice is hardened by pressure. The pressure dependence of $\mu^*$ 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 $\lambda$. 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 $\lambda$ was offset by an increase in $N(0)$ with pressure. The pressure dependence of $N(0)$ showed a maximum, so that 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 $La_3S_4$; therefore 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 susceptibility 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 that have been proposed recently.[20] Unfortunately, the effect of pressure on $T_c$ in the other models has 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 in such a way 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 stabilize 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 cause the entire sample to appear superconducting at 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.

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