Synthetic Metals, 29 (1989) F723–F728

ELECTRON-PHONON INTERACTIONS IN HIGH-TEMPERATURE OXIDE SUPERCONDUCTORS: ISOTOPE EFFECTS AND ELASTICITY STUDIES

A. ZETTL, L.C. BOURNE, W.N. CREAGER, M.F. CROMMIE, S. HOEN
Department of Physics, University of California at Berkeley, Berkeley, California 94720 (U.S.A.)

ABSTRACT

The substitution of different oxygen isotopes into the high-T_c oxide superconductors $La_{1.85}Sr_{0.15}CuO_4$ and $YBa_2Cu_3O_7$ is investigated by transport and magnetic measurements. For both materials, replacement of ^{16}O with ^{18}O depresses T_c slightly. The observed shifts are much smaller than those expected from conventional electron-phonon pairing superconductivity. We also explore the elastic properties of La-, Y-, and Bi-based high-T_c superconductors, including single crystals. Only $La_{1.85}Sr_{0.15}CuO_4$ shows a dramatic soft phonon mode above T_c.

INTRODUCTION

Electron-phonon coupling plays an important role in the conventional mechanism of superconductivity, as well as in other collective-mode states (such as charge density waves). In conventional (BCS phonon) superconductors, phonons mediate the attractive interaction between paired electrons. In general the superconducting transition temperature T_c is then a sensitive function of the electron-phonon coupling constant and the phonon frequency (and hence the ion mass). A suggestive test for phonon-mediated electron pairing is thus the isotope effect, where $T_c \sim M^{-\alpha}$ with M the ion mass and $\alpha = 0.5$ for BCS phonons. Another indirect test of electron-phonon coupling is a determination of the crystal elastic properties. Both the Young's modulus and internal friction δ may be influenced by thermodynamic transitions affecting the electrons. In conventional superconductors such as the A-15s, the highest T_c is obtained in conjunction with soft phonon modes (observed above T_c).

0379-6779/89/$3.50

We have performed extensive oxygen isotope measurements on samples of $La_{1.85}Sr_{0.15}CuO_4$ (T_c~37K) and $YBa_2Cu_3O_7$ (T_c~90K). For both materials, statistically relevant finite oxygen isotope shifts are observed, with values of α much smaller than 0.5. Elasticity studies have been performed on various polycrystalline and single crystal samples based on La, Y, and Bi. In La and Y materials, the expected anomalies at T_c in the Young's modulus are observed and are found to be consistent with pressure dependences of T_c and specific heat anomalies. $La_{1.85}Sr_{0.15}CuO_4$ is unique in that it shows a dramatic soft phonon mode above T_c.

OXYGEN ISOTOPE SUBSTITUTIONS

In high-T_c oxide superconductors, oxygen isotopes may be substituted in a given sample by diffusion at elevated temperatures. Early oxygen isotope measurements revealed no observable T_c shift for $YBa_2Cu_3O_7$ (α=0±0.03)[1,2] and small but finite shifts for $La_{1.85}Sr_{0.15}CuO_4$ (α=0.1-0.2)[3,4]. We have refined the experimental exchange method and magnetic and resistive measurement techniques, resulting in substantial improvements in the precision of α determined for both materials.

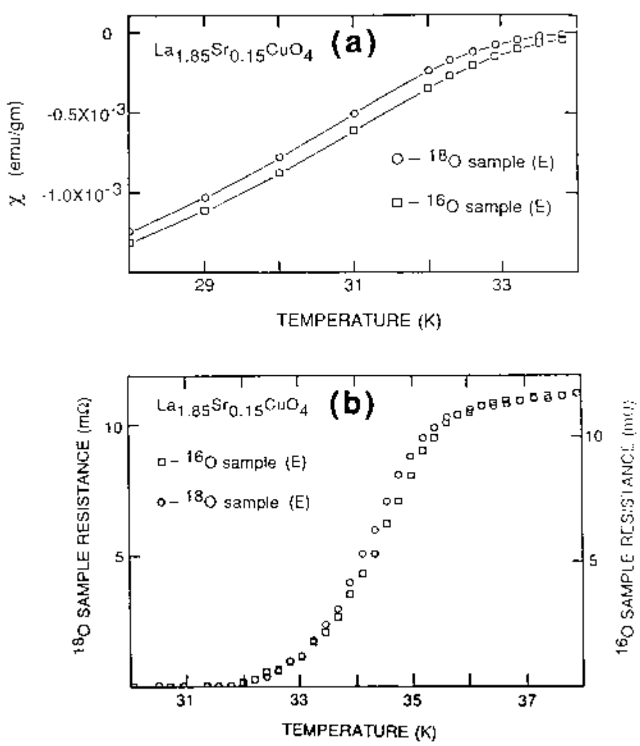

Fig. 1. (a) Magnetic Susceptibility versus Temperature for ^{16}O and ^{18}O enriched $La_{1.85}Sr_{.15}CuO_4$. (b) Resistance versus Temperature for the same samples.

Fig. 1a shows the magnetic susceptibility for $La_{1.85}Sr_{0.15}CuO_4$. The oxygen content of one sample is roughly 80% ^{18}O[5]; for the other sample it is roughly 99% ^{16}O. There is a shift in T_c between the two samples of 0.2K. Fig. 1b shows resistance data for the same sample set. Although there is a definite shift between the different samples (near the transition midpoint the shift is approximately .25 K), the magnitude of the shift varies across the transition width. Interestingly, T_c determined resistively exceeds T_c determined magnetically by one or two degrees. This substantial difference is evidence for filamentary superconductivity above T_c(bulk=magnetic). Both the bulk and filamentary superconductivity show comparable isotope shifts. Combining the data of Fig. 1 with similar data from other samples, we find (extrapolating to 100% ^{18}O) that $\alpha=0.14\pm0.008$ for oxygen in $La_{1.85}Sr_{0.15}CuO_4$.

Oxygen isotope measurements in $YBa_2Cu_3O_7$ suffer from greater sample variability and the smaller magnitude of a possible isotope shift. To eliminate

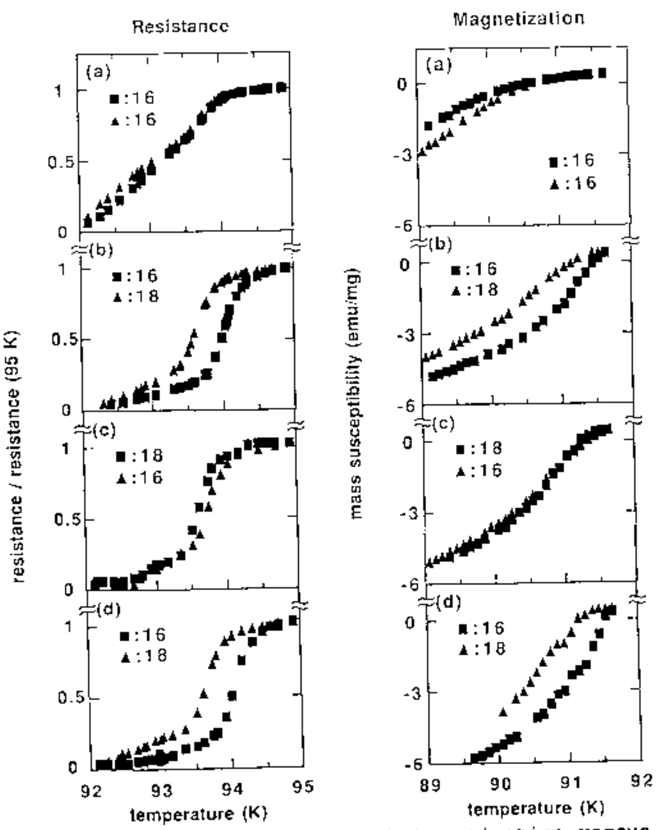

Fig. 2. Resistance versus Temperature and Magnetization versus Temperature of samples (triangles) and controls (squares) of $Y_1Ba_2Cu_3O_7$ (a) after identical preparation procedures, (b) after first isotope exchange, (c) after second isotope exchange, and (d) after third isotope exchange.

experimental errors, a series of cross-exchanges was performed on two sets of $YBa_2Cu_3O_7$ samples all originally containing 99% ^{16}O. One sample set was used for resistance measurements, the other was used for magnetic measurements. The sets were simultaneously processed always under identical conditions. In this way, magnetic depolarization factors could be more carefully controlled in the magnetic measurements. In general, the process sequence for a resistance or magnetic set (sample and its "control" partner) was as follows (mT_c means measurement of T_c):

sample $mT_c, O^{16}\rightarrow{}^{18}O, mT_c, O^{18}\rightarrow{}^{16}O, mT_c, O^{16}\rightarrow{}^{18}O, mT_c, O^{18}\rightarrow{}^{18}O, mT_c$
control $mT_c, O^{16}\rightarrow{}^{16}O, mT_c, O^{16}\rightarrow{}^{18}O, mT_c, O^{18}\rightarrow{}^{16}O, mT_c, O^{16}\rightarrow{}^{16}O, mT_c$

Fig. 2 shows the resistance and magnetization determinations of T_c for the first four measuring steps for the sample and its control. This method allows non-isotope related shifts to be statistically eliminated. An analysis of the results indicates that for both resistive and magnetic measurements, replacing approximately 95% of the ^{16}O content with ^{18}O in $YBa_2Cu_3O_7$ results in a T_c shift of .24 K. Again extrapolating to 100% isotope substitution, this gives α=.023±.005 for the oxygen isotope effect in $YBa_2Cu_3O_7$. This value is within the error limits set by the original oxygen isotope measurements[1,2] on $YBa_2Cu_3O_7$.

ELASTICITY MEASUREMENTS

Using a modified vibrating reed technique, we have measured Young's modulus (Y) of La-Sr-Cu-O polycrystalline materials and of single crystal specimens of $YBa_2Cu_3O_7$ and $Bi_2Sr_2CaCu_2O_8$. In general small anomalies are observed in Y near T_c. One material ($La_{1.85}Sr_{0.15}CuO_4$) shows a dramatic soft phonon mode well above T_c.

Fig. 3a shows Y for $La_{2-x}Sr_xCuO_4$ with x=0.15 as a function of temperature. Below approximately 200K, there is an enormous drop in Y, signaling a soft phonon mode[6]. A higher resolution trace of Y reveals a small additional softening in Y at T_c of magnitude $\Delta Y/Y = -1\times10^{-4}$. The anomaly at the transition is expected from thermodynamic considerations of the superconducting phase transition (see Eq. (1) below). Surprisingly, the enormous drop in Y above T_c in Fig. 3a does not occur for Sr concentrations which differ significantly from 0.15. This is demonstrated in Fig. 3b, which shows Y for a Sr concentration x=0.3. This material is still superconducting, with a lower T_c than that for x=0.15. Apparently, in the La-Sr-Cu-O system, the soft phonon mode occurs for the stoichiometry which maximizes T_c. A similar correspondence has been observed in A-15 superconductors[7].

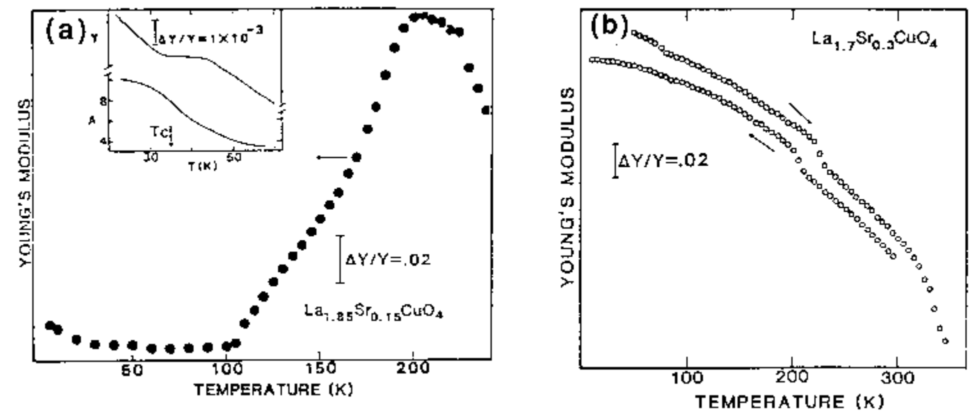

Fig. 3. (a) Young's Modulus versus Temperature for polycrystalline $La_{1.85}Sr_{.15}CuO_4$ and (b) Young's Modulus versus Temperature for polycrastalline $La_{1.7}Sr_{.3}CuO_4$

Figs. 4a and 4b show single crystal elastic data for $YBa_2Cu_3O_7$ and $Bi_2Sr_2CaCu_2O_8$, respectively. For both crystals, Y is relatively featureless over a wide temperature range. Near T_c in the Y-based material we observe an

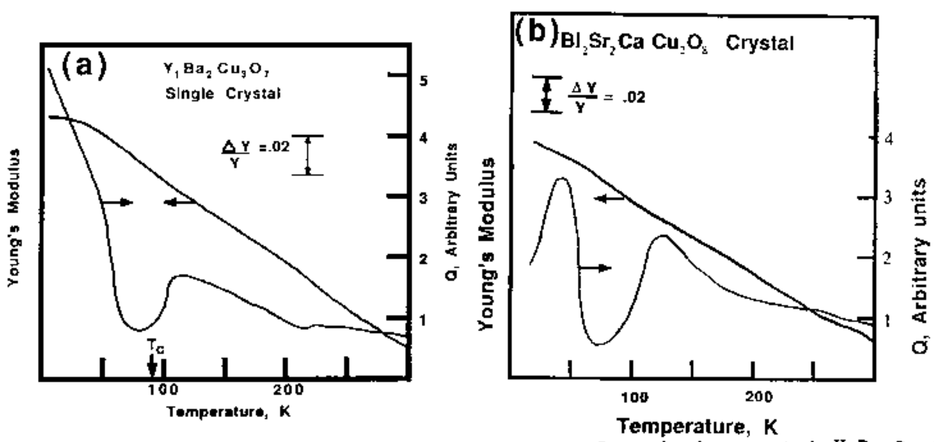

Fig. 4. (a) Young's Modulus versus Temperature for single crystal $Y_1Ba_2Cu_3O_7$ and (b) Young's Modulus versus Temperature for single crystal $Bi_2Sr_2CaCu_2O_8$.

anomaly in Y of magnitude and sign $\Delta Y/Y = -7x10^{-5}$, which can be related to other measurable quantities by the thermodynamic relation

$$\partial T_p/\partial \sigma_i = [-(\Delta Y/Y)T_p/Y\Delta C_p]^{1/2} \qquad (1)$$

where σ_i is the i^{th} component of the stress and C_p is the specific heat. Assuming a pressure dependence of T_c $\partial T_c/\partial P$ = .07 ^oK/kbar[8], the measured anomaly in Y near T_c gives ΔC_p = 11.6 J/^oK mole, in reasonable agreement with that determined experimentally, ΔC_p= 4.95 J/^oK mole [9]. For the Bi material, we see near T_c no anomaly within a resolution $\Delta Y/Y$= $5x10^{-5}$. Hence, from Eq. (1) and using the measured pressure coefficient dT_c/dP = .17 ^oK/kbar [10], we predict that ΔC_p< 1.94 J/^oK mole for this material.

ACKNOWLEDGEMENTS

We thank J. Kinney and L. Bernardez for the oxygen isotope content measurements, and D.E. Morris for providing ^{18}O for the $La_{1.85}Sr_{0.15}CuO_4$ isotope substition. This research was supported in part by NSF Grant DMR84-00041 and the DOE under contract No. DE-AC03-76SF00098. AZ received additional support from the Alfred P. Sloan Foundation. SH acknowledges support from the Fannie and John Hertz Foundation.

REFERENCES

1 L.C. Bourne, M.F. Crommie, A. Zettl, Hans-Conrad zur Loye, S.W. Keller, K.L. Leary, Angelica Stacy, K.J. Chang, Marvin Cohen, and Donald Morris, Phys. Rev. Lett 58 (1987) 2337.

2 B. Batlog et al, Phys. Rev. Lett. 58 (1987) 2333.

3 T.A. Faltens, W.K. Ham, S.W. Keller, K.J. Leary, J.N. Michaels, A.M. Stacy, H. zur Loye, D.E. Morris, T.W. Barbee III, L.C. Bourne, M.L. Cohen, S. Hoen, and A. Zettl, Phys. Rev. Lett. 59 (1987) 915.

4 B. Batlog et al, Phys. Rev. Lett. 59 (1987) 912.

5 Isotope content determined by laser-assisted ion mass analysis.

6 L.C. Bourne, A. Zettl, K.J. Chang, M.L. Cohen, A.M. Stacy, and W.K. Ham, Phys. Rev. B 35 (1987) 8785.

7 L.R. Testardi, in W.P. Watson and R.N. Thurston (editors), Physical Acoustics, Vol 10, Academic, New York, 1973, p.193.

8 J.E. Schirber et al, Phys. Rev. B 35 (1987) 8709.

9 Nevitt et al, Phys. Rev. B 36 (1987) 2398; S.E. Inderhees et al, Phys. Rev. B 36 (1987) 2401.

10 H.F. Goldstein, L.C. Bourne, P.Y. Yu, and A. Zettl, Phys. Rev. B (submitted).