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Dependence of T_c on Debye temperature Θ_D for various cuprates

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I extend the T_c-Θ_D relationship established by Ledbetter and coworkers for La-O and Y-O, and by Dominec for Bi-O, to include Tl-O and Hg-O compounds. In BCS-McMillan materials, Θ_D occurs both in the pre-exponential factor in the expression $T_c \sim \Theta_D \exp(-\lambda^{-1})$ and in McMillan's expression for the electron-phonon parameter $\lambda = C/M\langle\omega^2\rangle$, where $\langle\omega\rangle \sim \Theta_D$. In BCS materials, T_c increases with decreasing Θ_D, that is with lattice softening. In all five cuprate superconductors listed above, the opposite occurs: T_c increases with lattice stiffening. From these results, I draw two principal conclusions. First, T_c depends on phonons because it depends on Θ_D, the quintessential phonon parameter. Second, the T_c-Θ_D relationship for high-T_c oxide superconductors differs dramatically from that for conventional BCS materials.

Despite enormous study, both experimental and theoretical, two key questions remain unresolved. In high-T_c oxide superconductors, do phonons affect T_c? If yes, then how? Similar to BCS-McMillan, or otherwise?

To determine whether phonons enter the problem, we can focus on the Debye characteristic temperature Θ_D, which relates to phonon frequencies through $k\Theta_D = \hbar\omega_D$, where ω_D denotes the maximum phonon frequency and k and $\hbar$ take their usual meanings. Similarly, we could focus on the Einstein temperature $\Theta_E = (3/4)\Theta_D$.

In previous studies, Ledbetter and coworkers [1-2] showed for La and Y cuprates that T_c depends on Θ_D, increasing approximately linearly with increasing Θ_D. Thus, contrary to conventional superconductors, T_c increases with lattice stiffening, not lattice softening. Dominec [3] found a similar relationship for Bi cuprates, although results for these compounds show considerable scatter.

Here, as shown in fig. 1, I extend this analysis to include Tl and Hg cuprates. Two Tl-O lines appear because there are two crystal structures. The point corresponding to 1201 Tl-O is conspicuously low, suggesting that its slight modification (by composition or pressure) might raise T_c enormously.

In all cases, we determined Θ_D from elastic constants measured by high-pressure diffraction [4],

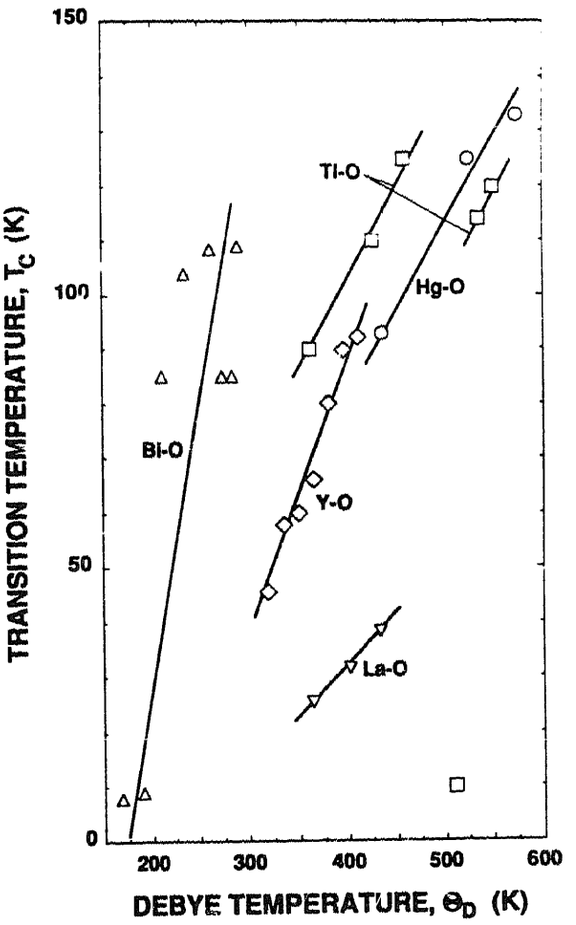

Figure 1. T_c variation with Debye temperature for five cuprate classes. Against BCS-McMillan behavior, T_c increases with lattice stiffening.

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calculated from lattice-dynamics models [5], or measured acoustically [1-2]. We avoided using specific-heat Θ_D values because they show such wide variations, as reviewed by Junod [6].

Excluding the La cuprates, the results in fig. 1 show a monotonic increase of T_c with increasing Θ_D and a possible convexity or bending-over at higher T_c values. Thus, the general trend agrees with the within-group trend. That the La cuprates fall below the general curve is not too surprising. These cuprates show different thermodynamic properties than the rest. For example, they show much higher pressure derivatives dT_c/dP [7]. In terms of the usual BCS expression for T_c (see abstract), these materials behave as though the $\exp(-\lambda^{-1})$ term has little importance.

If we accept that $T_c \sim \Theta_D$, then certain other relationships must follow. For example, invoking the Grüneisen-parameter definition: $\gamma = -d\ln\Theta_D/d\ln V$, then T_c must vary with volume according to $T_c \sim V^{-\gamma}$, similar to a relationship found experimentally by Schilling and coworkers [8] that $T_c \sim V^{-1.2}$.

In sum, for high-T_c oxide superconductors, I reach two principal conclusions: (1) T_c depends on Θ_D, thus on phonons. (2) The T_c-Θ_D relationship differs strongly from that for conventional BCS-McMillan superconductors. The similar behavior of five cuprate groups provides useful information for developing higher-T_c materials and for testing proposed models.

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