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Specific Heat Evidence for Strong Coupling in $YBa_2Cu_3O_7$

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Specific heat data for $YBa_2Cu_3O_7$ are consistent with $\gamma = 15\pm3$ mJ/mole•K^2 and $2\Delta_0/kT_c = 6.8\pm0.6$. These results indicate that strong-coupling effects are present but that the coupling is unlikely to be predominantly a conventional electron-phonon interaction.

In this note an interpretation of specific heat, C, measurements on $YBa_2Cu_3O_7$ is applied to an analysis of data in the vicinity of T_c to obtain information about the strength of the coupling responsible for the superconductivity. Correlations among several sample-dependent parameters have been interpreted (Phillips et al 1990) as showing that typical samples are only 30-90% superconducting; that the volume fraction of superconductivity, f_s, can be determined from the discontinuity, $\Delta C(T_c)$, at the critical temperature, T_c; and that the Sommerfeld constant for the fully normal state, γ, is ~16 mJ/mole•K^2, a value close to that calculated (Massidda et al 1987; Krakauer et al 1988) for the bare density of states, γ_{bs}, indicating that electron-phonon enhancement effects are not significant. Thus, if electron-phonon coupling is responsible for the superconductivity, $YBa_2Cu_3O_7$ should be a weakly-coupled BCS superconductor with $\beta = \Delta C(T_c)/\gamma T_c = 1.43$. However, such a conclusion is clearly at odds with γ ~ 16 mJ/mole•K^2 and the measured values of $\Delta C(T_c)$.

Figure 1 shows C/T vs T for a $YBa_2Cu_3O_7$ sample made by the citrate pyrolysis technique. An entropy-conserving construction gives $\Delta C(T_c)/T_c$ ~ 64 mJ/mole•K^2, ~83% of the value expected for a fully superconducting sample (Phillips et al 1990; see also Junod et al 1990), i.e., $f_s = 0.83$. With $\gamma = 16$ mJ/mole•K^2 and $\beta = \Delta C(T_c)/f_s\gamma T_c = 5.5$ -- almost 4 times the BCS weak-coupling value and clearly indicative of strong-coupling. The dotted and solid curves in Fig. 1 represent, respectively, approximations to C_n and C_s, the normal- and the 83%-superconducting-state values of C. $C_n = C_1 + \gamma T$, where C_1, the lattice contribution, is assumed to consist of dilatation and harmonic terms. C_n was obtained by interpolation between the data above 96K and the data in the region 62-65K, the region expected to include the temperature, T_x, at which $C_s = C_n$. Over this interpolation interval the

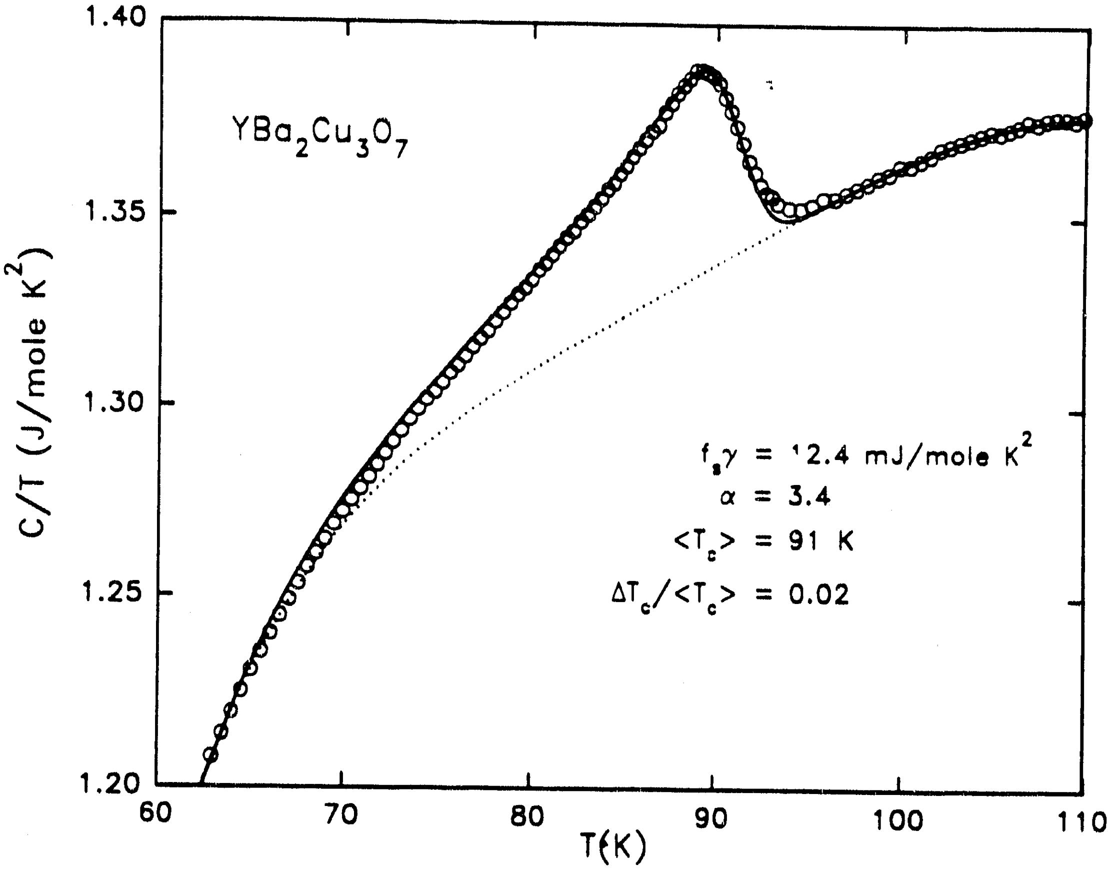

Figure 1. C/T vs T. See text for discussion.

harmonic lattice term can be adequately represented by a polynomial in T, by an expansion of the form described by Gordon et al (1989), or by a superposition of Einstein terms. The solid curve is given by $C_s = C_l + f_s C_{es} + (1-f_s)\gamma T$, where C_{es} is the fully-superconducting-state electronic C, and has been calculated by assuming a Gaussian distribution of transition temperatures centered on $<T_c>$ with a width ΔT_c. It is also assumed that the superconducting state can be described by the "α model" (Padamsee et al 1973) in which the gap in the density of states is related to the BCS gap by the factor $\alpha/1.764$. Application of this model involves two adjustable parameters: α which determines the shape of the anomaly, and $f_s\gamma$ which determines the amplitude. The solid curve corresponds to $<T_c> = 91K$, $\Delta T_c/<T_c> = 0.02$, $\alpha = 3.4$, and $f_s\gamma = 12.4$ mJ/mole$\cdot$K^2, and results in $\Delta C(T_c)/\gamma T_c = 5.3$ and $T_x = 63K$. The inclusion of a small fluctuation contribution that lowers $f_s\gamma$ to 12 mJ/mole$\cdot$K^2 would slightly improve the fit in the region near 93K, but is not essential. As required by thermodynamics, the area between the data and the dotted curve in the temperature region $63 \leq T \leq 96K$ is equal to the entropy difference between the normal and superconducting states at T_x. (For this comparison, the normal-state value was taken as γT_x and the superconducting-state value was calculated using the α model.) The results of the fitting procedure are not unique. Reasonably good fits to the data can be obtained with other choices for $f_s\gamma$ and α (but $<T_c>$ and ΔT_c remain essentially the same). We conclude that the data are consistent with the values $f_s\gamma = 12.4\pm3$ mJ/mole•K^2 and $\alpha = 3.4\pm0.3$. With $f_s = 0.83$, this range in $f_s\gamma$ corresponds to $\gamma = 15\pm3$ mJ/mole•K^2, in agreement with the value 16 mJ/mole•K^2 obtained on the basis of other considerations (Phillips et al 1990). The values of α consistent with the data are twice the weak-coupled BCS value. They correspond to a gap ratio $2\Delta_0/kT_c = 6.8\pm0.6$, in agreement with other measurements (see, eg., Batlogg 1990) and, when combined with the result $\gamma \sim \gamma_{bs}$, imply that the conventional electron-phonon interaction cannot be solely responsible for the superconductivity.

The principal uncertainty in the conclusions derives from uncertainty in C_n, the "background" C on which the analysis is based. Loram and Mirza (1988) have also used the α model to obtain similar values for γ and α. They made differential C measurements with quenched non-superconducting $YBa_2Cu_3O_7$ as the reference. In that case there are uncertainties in the correction to C_1 (comparable to those in C_n in this work), and there are also uncertainties in the interpretation of the several linear terms that occur in the data.

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