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ESTIMATION OF MATERIAL PARAMETERS FROM THE OBSERVATION OF PARACONDUCTIVITY IN Y-Ba-Cu-O

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We report observations of paraconductivity in a polycrystalline high-temperature superconductor, $YBa_2Cu_3O_{7-\delta}$, which are consistent with the predictions of Aslamazov and Larkin for three dimensional fluctuations. We thus obtain an estimate of the coherence length, $\xi_0 = 13.4 \pm 4.8$ Å, which is consistent with an earlier estimate, based in part on heat capacity measurements. We use the Ginzburg criterion to estimate $H_{c2}(0) \approx 500$kG.

Measurements of the resistivity near the superconducting transition in $YBa_2Cu_3 O_{7-\delta}$ consistently reveal a rounded rather than a sharp transition. Sample inhomogeneity is one possible source of this phenomenon, but another more fundamental explanation is that thermodynamic fluctuations can produce short-lived Cooper pairs above the bulk transition temperature. During their lifetime, such pairs can be accelerated by an applied electric field, leading to an apparent decrease in the resistivity of the sample. This phenomenon is known as paraconductivity.

In this note, we report observations of paraconductivity in polycrystalline $YBa_2Cu_3O_{7-\delta}$, where $\delta \sim 0.1-0.2$. From these observations, we have estimated the Ginzburg-Landau length ξ_{GL} from the Aslamazov-Larkin formula for the paraconductivity[1] σ':

$$\sigma' = \frac{e^2}{32\hbar\xi_{GL}} t^{-1} \qquad (1)$$

where the reduced temperature $t = T/T_c - 1$, T is the temperature, T_c is the mean field transition temperature, and e is the electronic charge. Equation 1 is valid for three dimensions. The Ginzburg-Landau length is related to the BCS coherence length ξ_0 and the mean free path ℓ by the formulae[2]

$$\xi_{GL} = 0.85(\xi_0 \ell)^{1/2} t^{-1/2} \quad \ell \ll \xi_0 \quad \text{(dirty limit)}$$
$$= 0.74 \xi_0 t^{-1/2} \quad \ell \gg \xi_0 \quad \text{(clean limit)} \qquad (2)$$

We have also used the Ginzburg criterion to estimate $H_{c2}(0)$.

The samples were prepared by thoroughly mixing and grinding $BaCO_3$, Y_2O_3 and CuO powders (all 99.999% pure) and reacting them in a platinum crucible in air at 950°C for 24 hours, with two intermediate grindings. The reacted material was ground and pressed into pellets under a pressure of 500 MPa applied for 5 minutes, producing a sample with about 75% of the ideal density. After removal from the press, the pellets were heat treated in a stream of pure oxygen at 1 atmosphere pressure. The final oxygen heat treatments varied from sample to sample. The sample, whose data are shown in Figure 1, was heated at 920°C for 4 hours, cooled to 700°C in 1/2 hour, held at 700°C for 8 hours, and finally slow cooled to room temperature at 12°C/hour.

Resistivity measurements were made using an a.c. bridge operated at ~ 100 Hz. Samples were cut from pellets into bars ~ 0.5x0.5x5 mm^3 using a diamond saw; fine copper wires were attached with silver paint, and the samples were thermally anchored to a sapphire substrate using GE 7031 varnish. Temperature was measured using a calibrated carbon-glass thermometer. Data were taken only after thermal equilibrium had been achieved, and were corrected by a numerical factor of 3/4 to take into account the porosity of the samples.

Figure 1 shows a graph of the resistivity, ρ, versus temperature for a sample of $YBa_2Cu_3O_{7-\delta}$. Inset is an enlargement of the transition region, showing a 'foot' extending into the superconducting region. We have observed this foot in all the samples of $YBa_2Cu_3O_{7-\delta}$, but it appears to be absent in samples with Gd substituted fully for Y. We presume that the foot is due to some combination of the effects of inhomogeneities, of grain boundaries, and of aver-

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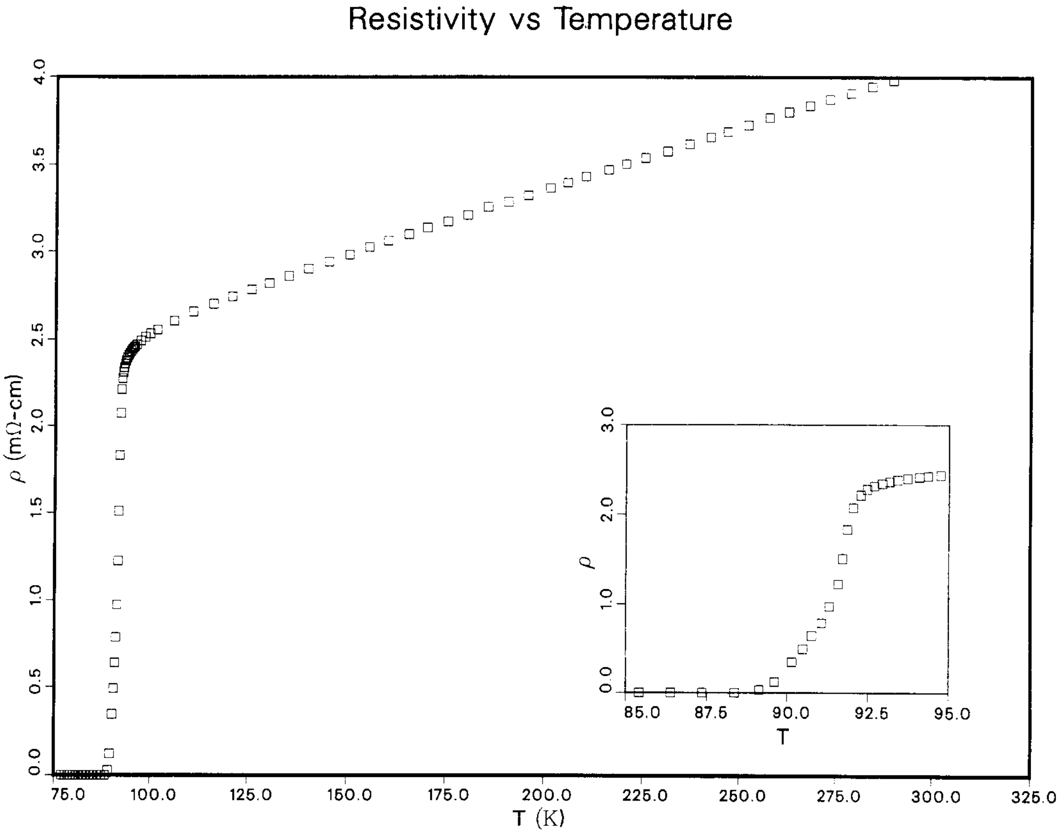


1. Graph of resistivity versus temperature for a single sample of $YBa_2Cu_3O_{7-\delta}$. Inset is a magnification of the transition region.

aging the anisotropic conductivity tensor over randomly oriented crystal grains.

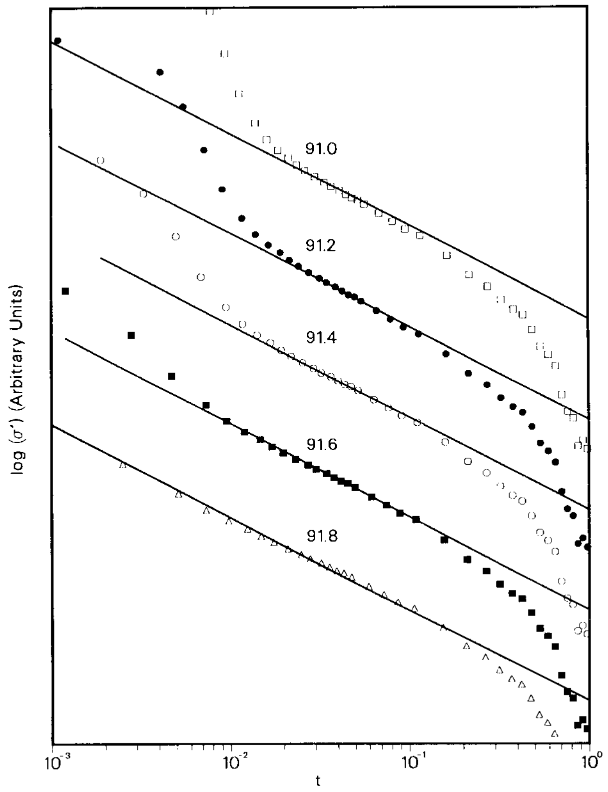
We analyzed the data to extract the fluctuation contribution or paraconductivity σ' to the conductivity σ. To do this, we modelled the high temperature form of $\rho(T)$ as $\rho(T) = a+bT$, for $T > 2T_c$. Then

$$\sigma' = \frac{1}{\rho} - \frac{1}{a+bT} \qquad (3)$$

where, in Figures 1 and 2, $a = 2.037\,m\Omega cm$ and $b = 6.89\times10^{-3} m\Omega cm\ K^{-1}$. We were interested in the way, if any, in which σ' scaled with t, to verify the Aslamazov-Larkin prediction. We adjusted T_c to obtain the best fit to the expected behaviour. The result, for different values of T_c, is shown in Figure 2. Evidently these graphs are quite sensitive to the choice of T_c, and we have chosen that value of T_c which minimizes the least square deviation from the Aslamazov-Larkin prediction. This procedure also gave the best 'eyeball' fit. For the data shown in Figure 2, we obtained $T_c = 91.5\pm0.1$ K.

We have analysed the results of measurements of 6 different samples to determine ξ_0 and ℓ. Figure 3 is a graph of σ' versus t for these samples. First, let us assume that the samples are in the clean limit. Then we obtain from Figure 3 the value $\xi_0 = 13.4\pm4.8$ Å. If we assume that they are in the dirty limit, then we find that $(\xi_0\ell)^{1/2} = 11.8\pm4.2$ Å. The indicated uncertainties correspond to one standard deviation. Earlier determinations of these quantities at this laboratory,[3] based on the heat capacity jump at the transition and a.c. Hall measurements,[4] which implied a value for the Fermi wavevector $k_F \approx 6.4\times10^7\ cm^{-1}$, found that $\xi_0 \approx 12$ Å and $\ell\approx16$ Å. It seems that $YBa_2Cu_3O_{7-\delta}$ is in an intermediate regime between the clean and dirty limits: $\xi_0 \sim \ell$. In principle, the complete functional form of Equation 2 should be used to analyse the results, not just the limiting forms; however, in view of the uncertainties present in these estimates from other sources, such as anisotropy, we did not feel that such a detailed analysis was warranted.

We can also use our data to estimate the width of the Ginzburg region,[5] t_G, and hence determine $H_{c2}(0)$. The Aslamazov-Larkin theory accounts for fluctuations of the order parameter at the one-loop level, so for $t<t_G$, where critical fluctuations become important,



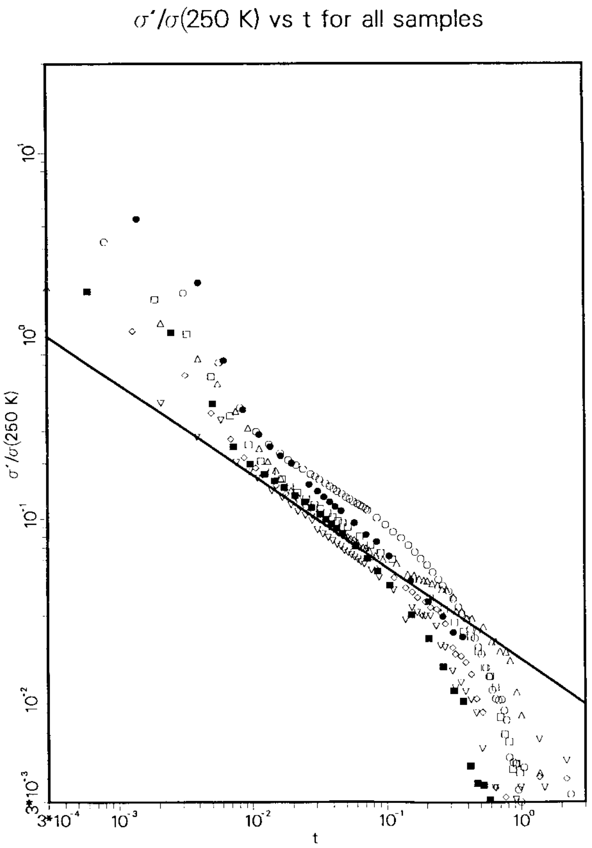
2. Graph of log σ' versus t, for different values of T_c, for the sample of Figure 1. The solid line has a slope of -1/2.

the theory is no longer valid. This is manifested in a change in the power law dependence of σ' on t. For $t<8x10^{-3}$, the magnitude of the power law exponent is greater than 1/2, but there are indications that it begins to decrease for $t<2x10^{-3}$. We tentatively identify this as the cross-over region to the critical region,[6] where $\sigma' \sim t^{-0.33}$, and estimate t_G as roughly $2x10^{-3}$. For type II superconductors

$$t_G \approx 10^{-9} \frac{\kappa^4 T_c^2}{H_{c2}(0)} \qquad (4)$$

where $H_{c2}(0)$ is the extrapolated upper critical field measured in Gauss and κ is the ratio of the penetration depth to the coherence length (in $YBa_2Cu_3O_{7-\delta}$, which should be anisotropic, these will be the geometrical means of the values along the principal directions[6]). Independent measurements of the penetration depth λ are available,[7] and yield $\lambda \sim 1400$ Å. Using $\xi_0 \approx 13.4$ Å, we thus find that $H_{c2}(0) \sim 500$kG.

We have assumed that the width of the resistive transition is determined purely by fluctuation effects. This should be determined by the method suggested originally by Aslamazov and Larkin: measure the width, ΔH, of the transition at constant temperature in a magnetic field, H_c. The relative broadening, $\Delta H/H_c$ associated with inhomogeneities should be temperature independent, whilst the fluctuations will cause this ratio to increase with temperature. Such measurements should be attempted on single crystal specimens, with fixed orientation with respect to the magnetic field, to eliminate anisotropy effects.



3. Graph of σ' versus t for six different samples of $YBa_2Cu_3O_{7-\delta}$. For each sample, T_c was determined using the procedure described in the text. The solid line has a slope of -1/2. The open squares correspond to the same sample as the data in Figures 1 and 2.

Finally, we should mention that our results rely on standard Ginzburg-Landau theory for Type II superconductors and the weak-coupling BCS theory. There is, a priori, no reason that this procedure should be valid; if superconductivity occurs through the resonant valence bond mechanism,[8] or any other mechanism which is not equivalent to the BCS mechanism, then the phenomenology might differ from that which we have assumed. We hope to report on this possibility at a future date.

During the course of this work, we received preprints[9,10] which report observations similar to ours, but which do not analyze the data to obtain H_{c2}. In Reference 9, deviations from the Aslamazov-Larkin theory are present in the data close to T_c; the deviations which they report also appear to steepen the slope, but it is not possible to tell whether or not the data flatten out close to T_c.

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REFERENCES

1. L. G. Aslamazov and A. I. Larkin, Fiz. Tverd. Tela 10, 1104 (1968). [Sov. Phys. Sol. St. 10, 875 (1968)]

2. See, for example R. E. Glover, Progress in Low Temperature Physics, C. J. Gorter, editor (North-Holland, Amsterdam), Vol. 6, p. 291 (1970).

3. M. B. Salamon and J. Bardeen, to be published.

4. C. F. Gallo and R. V. Rao, to be published.

5. V. L. Ginzburg, Fiz. Tverd. Tela 2, 2031 (1961) [Sov. Phys. Sol. St. 2, 1824 (1961)].

6. C. J. Lobb, to be published.

7. R. J. Cava, B. Batlogg, R. B. van Dover, D. W. Murphy, S. Sunshine, T. Siegrist, J. P. Remeika, E. A. Rietman, S. Zahurak, and G. P. Espinosa, , Phys. Rev. Lett. 58, 1676 (1987).

8. P. W. Anderson, Science 235, 1196 (1987).

9. P. P. Freitas, C. C. Tsuei and T. S. Plaskett, to be published.

10. M. Dubson, J. J. Calabrese, S. T. Herbert, D. C. Harris, B. R. Patton and J. C. Garland, to be published.