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Paraconductivity and magnetoconductivity in single-crystal $YBa_2Cu_3O_{7-\delta}$

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Abstract. We present results for the fluctuation paraconductivity and magnetoconductivity for a single-crystal sample of $YBa_2Cu_3O_{7-\delta}$. Both the paraconductivity and magnetoconductivity data are fitted to existing theories of the Aslamazov–Larkin and Maki–Thompson contributions to the fluctuation conductivity. The presence of a Maki–Thompson contribution in the paraconductivity and magnetoconductivity would suggest that the pairing mechanism is conventional s-wave pairing.

1. Introduction

Above the superconducting transition temperature $YBa_2Cu_3O_{7-\delta}$ exhibits as strong temperature and magnetic field dependence of the conductivity due to superconducting fluctuations. Fluctuation effects are enhanced due to a high T_c and short coherence lengths, and from measurements of the conductivity the coherence lengths can be determined. In these studies it is important to use single-crystal samples of high quality in order to eliminate effects due to inhomogeneities and grain boundaries and also to eliminate the C-factor introduced by Oh *et al* [1] to take account of these geometrical effects. In our work on single crystals there is no need for such a C-factor. Previous work on this subject has been performed on polycrystalline, [2–4] thin film [5, 6] and single crystal [7–11] samples of $YBa_2Cu_3O_{7-\delta}$. Many studies of single crystals were performed on crystals of inferior quality due to the availability of samples at that time. We report measurements on a high-quality single crystal with a smooth, sharp superconducting transition with a resistance that is zero at 92.5 K and with a transition width of ~0.3 K. Due to the small size of the crystal ($0.5\times0.5\times0.025$ mm^3) it has a small resistance, therefore with the DC technique used, the magnetoconductivity can only be measured up to $\epsilon = 0.2$ ($\epsilon = \ln(T/T_c)$). Above this temperature the change in the conductivity with applied magnetic field is below the experimental resolution. However we have been able to fit the temperature dependence of the paraconductivity, the temperature dependence of the fluctuation magnetoconductivity and the magnetic field dependence of the magnetoconductivity over a wide range. All three fitting methods produce a consistent picture of the fluctuation contributions to the electrical conductivity.

2. Experimental details

The crystal was grown using a self flux method [12] using 99.999% $BaCo_3$, CuO and Y_2O_3 mixed in the cation ratio 1:4:10 (Y:Ba:Cu). The mixture was heated to 980 °C

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in a zirconia crucible and slow-cooled to allow crystal growth. The crystals were then removed mechanically. The crystal was annealed at 500 °C in flowing oxygen for 200 h.

The measurements were performed in a cryostat equipped with a 4 T split-pair superconducting magnet. Good temperature stability during a magnetic-field sweep was essential because of the small magnetoconductivity, and so special attention has been given to thermometry. A platinum resistance thermometer was used throughout the experiment to control and measure the temperature of the samples. To take account of the effect of the magnetic field on the thermometer, the field dependence of the resistance of the platinum thermometer was measured using a capacitance thermometer to monitor the temperature in the magnetic field. This method was chosen because even though capacitance thermometers are not affected by the field the capacitance at constant temperature will drift over time due to aging effects within the dielectric. This drift can be as large as 0.1 K h^{-1} at 100 K which produces a change in the conductivity larger than the magnetoconductivity; thus the capacitance thermometer cannot be used on its own to determine the temperature accurately. In contrast the platinum thermometer is stable over time but field dependent. However, once account has been taken of its measured field dependence, the platinum thermometer allows stability in temperature control of ±5 mK during a field sweep. The samples were mounted on a rotating sample holder so the field could be aligned perpendicular or parallel to the a–b plane of the crystal. The current was in the a–b plane and was always perpendicular to the magnetic field. The resistivity was measured by a four-probe DC technique. The accuracy of the absolute value of the resistivity was about 20% and was limited by the accuracy of the thickness measurement, which was made using an optical microscope with the crystal mounted on its side. The accuracy of the magnetoconductivity measurement is limited by the small resistance of the sample and the need to use small enough currents to avoid self heating. This limit was about 10^{-4} T^{-1} in $\Delta\sigma/\sigma$.

3. Theory

Above the transition temperature the total conductivity $\sigma(T)$ in zero magnetic field is given by

$$\sigma(T) = \sigma_n(T) + \Delta\sigma(T) \tag{1}$$

where $\sigma_n(T)$ is the normal-state conductivity and $\Delta\sigma(T)$ is the fluctuation contribution to the conductivity—often referred to as paraconductivity. Because of the linear behaviour of the resistivity above 200 K, the normal-state resistivity is assumed to be a linear function of temperature, therefore the normal-state conductivity is assumed to have the form [2, 6, 7]

$$\sigma_n(T) = 1/(aT + b). \tag{2}$$

In fitting the data we tried two methods of determining the normal-state parameters a and b. First we assumed the paraconductivity to be negligible above 200 K and fitted the data above 200 K using only equation (2). The two parameters so determined where a_n and b_n and are shown in table 1. We also tried including a and b as free

Table 1. Coefficients for the fit to the normal-state resistivity.

a_n ($\mu\Omega$ cm K^{-1})	b_n ($\mu\Omega$ cm)	a_f ($\mu\Omega$ cm K^{-1})	b_f ($\mu\Omega$ cm)
0.86	20.5	0.86	37.8

parameters along with the other fluctuation parameter and these are shown in table 1 as a_f and b_f. The best fits to the paraconductivity data were obtained using the latter method.

The paraconductivity is the sum of two contributions, the Aslamazov–Larkin (AL) contribution and the Maki–Thompson contribution (MT). The AL term ($\Delta\sigma_{AL}(T)$) arises from the direct acceleration of superconducting pairs during their lifetime whilst the MT term ($\Delta\sigma_{MT}(T)$) arises from a detailed consideration of the decay of the pairs. From the theory of layered superconductors [13] the two contributions are given by

$$\Delta\sigma_{AL}(T) = (e^2/16\hbar d\epsilon)/(1+2\alpha)^{1/2} \tag{3}$$

$$\Delta\sigma_{MT}(T) = [e^2/\delta\hbar d(1-\alpha/\delta)\epsilon] \ln\Big((\delta/\alpha)[1+\alpha+(1+2\alpha)^{1/2}] \times [1+\delta+(1+2\delta)^{1/2}]\Big) \tag{4}$$

where $\alpha = 2\xi_c^2(0)/d^2\epsilon$ and $\delta = 16kT\tau_\phi/\pi\hbar$. d is taken to be the size of the YBCO unit cell (1.17 nm), ϵ is the reduced temperature $\ln(T/T_c)$, $\xi_c(0)$ is the zero-temperature coherence length in the c-direction and τ_ϕ is the phase relaxation time. In $YBa_2Cu_3O_{7-\delta}$ the phase relaxation time τ_ϕ has been assumed to be inversely proportional to the temperature ($T\tau_\phi$ = constant), by a number of workers [5, 8, 11] because of the linear increase of resistance with temperature above 200 K, and we do the same. The total fluctuation contribution to the conductivity is then

$$\Delta\sigma(T) = \Delta\sigma_{AL}(T) + \Delta\sigma_{MT}(T). \tag{5}$$

Because the analysis of the zero-field fluctuation conductivity requires a knowledge of the normal-state conductivity, a large uncertainty is introduced into the data analysis. The measurement of the magnetoconductivity does not have this problem. The magnetoconductivity $\Delta\sigma(B,T)$ at constant temperature is defined as

$$\Delta\sigma(B,T) = \sigma(B,T) - \sigma(0,T) \tag{6}$$

and therefore the fluctuation magnetoconductivity can be determined by experiment without any knowledge of the normal-state conductivity. $\Delta\sigma(B,T)$ comprises four contributions [13–15] the AL-orbital (ALO), MT-orbital (MTO), AL-Zeeman (ALZ) and MT-Zeeman (MTZ). The orbital terms arise from usual extended orbits of electrons in a magnetic field, and the Zeeman terms arise from the Zeeman energy splitting of the paired electrons. The total magnetoconductivity is the sum of the four contributions. For 2D superconductors the orbital contributions, MTO and ATO, are zero when the field is parallel to the a–b plane. The Zeeman terms should still be present but these are at least an order or magnitude smaller than the orbital terms. Within our experimental resolution the Zeeman terms are negligible compared to the orbital

Table 2. Fitting parameters for the paraconductivity and the magnetoconductivity. The values of τ_ϕ are for $T = 100$ K.

Paraconductivity $\Delta\sigma(0)$			Magnetoconductivity $\Delta\sigma(B)$			
ξ_c (nm)	τ_ϕ (ps)	T_c (K)	ξ_c (nm)	ξ_{ab} (nm)	τ_ϕ (ps)	T_c (K)
0.23±0.02	0.10	92.3	0.3±0.05	1.2±0.1	0.12	92.6±0.4

terms, therefore we take the total magnetoconductivity with a magnetic field applied perpendicular to the a–b plane of the crystal to be

$$\Delta\sigma(B,T) = \Delta\sigma_{\mathrm{ALO}}(B,T) + \Delta\sigma_{\mathrm{MTO}}(B,T). \tag{7}$$

In the low-field limit ($h \ll \epsilon$) we use the following expressions [13]

$$\Delta\sigma_{\mathrm{ALO}}(B,T) = -(e^2/64\hbar d\epsilon^3)\left[(2+4\alpha+3\alpha^2)/(1+2\alpha)^{5/2}\right]h^2 \tag{8}$$

$$\Delta\sigma_{\mathrm{MTO}}(B,T) = -\left[e^2/48\hbar d(1-\alpha/\delta)\epsilon^3\right]\Big((\delta^2/\alpha^2)(1+\delta)/(1+2\delta)^{3/2} - (1+\alpha)/(1+2\alpha)^{3/2}\Big)h^2 \tag{9}$$

where $h = (2e/\hbar)\xi_{ab}^2(0)B$.

Close to the transition and at large magnetic fields where $h \sim \epsilon$ these expressions are no longer valid and we use [13]

$$\Delta\sigma_{\mathrm{ALO}}(B,T) = \int_0^{2\pi/d} \frac{e^2}{8\hbar\epsilon_k}\left(\frac{\epsilon_k}{h}\right)\left[\psi\left(\frac{1}{2}+\frac{\epsilon_k}{2h}\right) - \psi\left(1+\frac{\epsilon_k}{2h}z\right) + \frac{h}{\epsilon_k}\right]\frac{\mathrm{d}k}{2\pi} \tag{10}$$

where $\epsilon_k = \epsilon(1+\alpha(1-\cos kd))$ and ψ is the digamma function. In the temperature range where $h \sim \epsilon$ $\Delta\sigma_{\mathrm{ALO}}(B,T) \gg \Delta\sigma_{\mathrm{MTO}}(B,T)$ and so we neglect the MTO term and fit the data to equation (10). The digamma function is evaluated using the appropriate NAG routines, and the values so determined were checked against standard tables.

4. Results and discussion

Figure 1 shows the resistive transition for sample 1 and the inset shows the derivative of the resistivity. The resistance is zero at 92.5 K and the half width of the single $\mathrm{d}\rho/\mathrm{d}T$ peak is 0.3 K. Figure 2 shows the fits of the paraconductivity to equation (3) and (4) and the parameters derived from the fits are given in table 2. This figure shows that the paraconductivity is well described by the theory over a large temperature range up to ~200 K. An interesting feature of the fits are the values of a_f and b_f, whilst the parameter describing the slope of the normal-state resistivity, a_f, is approximately the same as a_n, the intercept, b_f, is substantially different to b_n. If a and b are fixed to be a_n and b_n and are not used as fitting parameters then attempts to fit the data to equation (3) and (4) fail completely. This indicates that even at temperatures of ~200 K the fluctuation conductivity still contributes substantially to the measured conductivity. It also emphasizes that it is not possible to extract the paraconductivity by fitting just the normal-state behaviour at high temperatures.

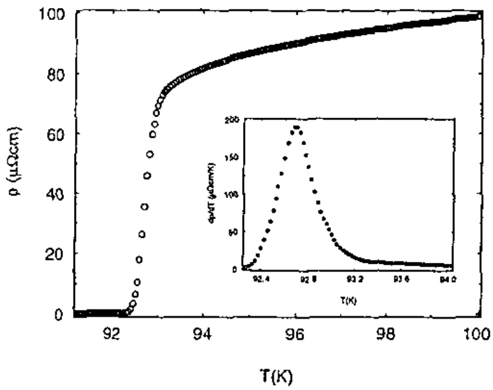

Figure 1. The resistivity versus temperature. The inset shows the derivative $d\rho/dT$ versus temperature near T_c.

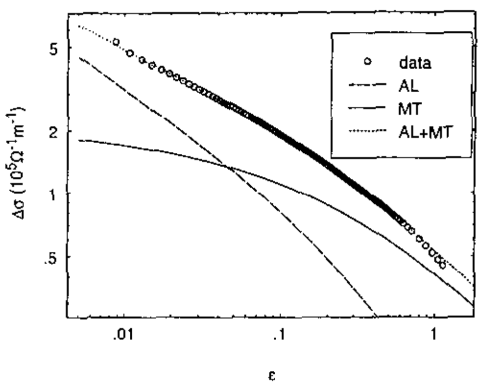

Figure 2. The temperature dependence of the fluctuation conductivity (paraconductivity).

The enormous drawback of fitting the paraconductivity is the need to know the normal-state conductivity. However, the analysis of the magnetoconductivity needs no information or assumptions about the normal-state conductivity and is free from the problems associated with the determination of a and b. The magnetoconductivity close to T_c is shown in figure 3, with the solid lines being theoretical fits to the data. Close to the transition, the measured magnetoconductivity is found to be well fitted by equation (10) and from these fits values of ξ_{ab}, ξ_c and T_c are found at each temperature. At higher temperatures the magnetoconductivity is found to be proportional to B^2 as expected from equations (8) and (9). Since the coefficient of this B^2 depends on all the above three parameters, and on τ_ϕ, one can only extract a single number which depends on all three parameters. However we can examine the temperature dependence of the magnetoconductivity by plotting the value of the magnetoconductivity at 1 T. This is shown in figure 4. Each data point in the figure is determined from the magnetoconductivity at each temperature. The lines are fits using equations (8) and (9) with the fitting parameters ξ_{ab}, ξ_c, T_c and τ_ϕ. The fits from the temperature dependence of the magnetoconductivity (equations (8) and (9)) and from the field dependence (equation (10)) at a number of temperatures close to T_c all give similar values for ξ_{ab}, ξ_c, T_c and τ_ϕ. Table 2 shows the value of τ_ϕ at 100 K (with τ_ϕ assumed to be proportional to T^{-1} along with the average value of ξ_{ab}, ξ_c and T_c determined from the fits using equation (10) at different temperatures and equations (8) and (9) for the temperature dependence of the magnetoconductivity. The error bars give an indication of the spread of values from the fits.

The theory, which includes the MTO and ALO terms provides a good fit to the data. In both the paraconductivity and the magnetoconductivity the AL term dominates close to T_c. However the MT contribution is certainly present at higher temperatures. This is clearly seen in the paraconductivity where there is a crossover and the MT dominates above $\epsilon = 0.04$. There is also a crossover in the magnetoconductivity at about $\epsilon = 0.3$. The difference in these crossover temperatures simply reflects the difference in the temperature dependence of the AL and MT contributions to the paraconductivity and the magnetoconductivity. Yip [16] pointed out that for unconventional superconductivity the MT contribution would

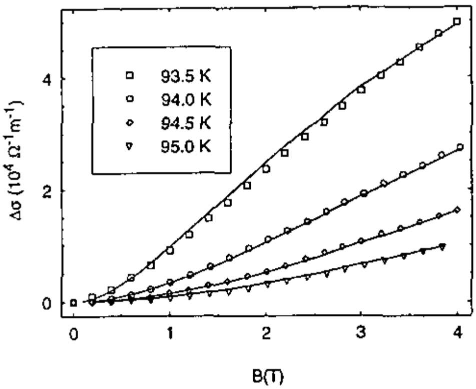

Figure 3. The magnetoconductivity at various temperatures. The lines are fits to the data using equation (10).

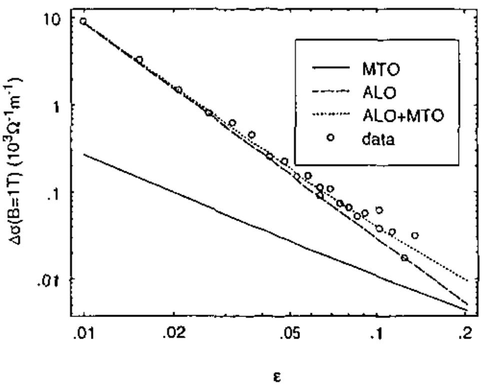

Figure 4. The temperature dependence of the magnetoconductivity.

not be present while the AL contribution would be essentially unchanged. Thus the presence of a MT contribution in the paraconductivity and magnetoconductivity may be considered evidence that YBCO is a conventional s-wave superconductor. However, the MT contribution in the magnetoconductivity is small and perhaps more detailed measurements, over a wider range, would produce more convincing evidence that the MT contribution is present and therefore YBCO is an s-wave superconductor. Matsuda *et al* [4,5] have done some very nice work on this up to 200 K using a novel AC technique which did seem to suggest the presence of the MT contribution but there were strong deviations from the fits at high temperatures.

The values of ξ_{ab} and ξ_c are similar to those found by other workers [3–5, 8–11, 17]. There have been a number of different estimates of the value of τ_ϕ in the literature and all are of the order of 10^{-13} s at about 100 K—similar to the value we observe for our sample. There are, however, significant differences between studies with τ_ϕ varying by as much as a factor of three. It is interesting to note that although most workers find ξ_{ab}, ξ_c in the region of 1.2 and 0.2 nm there are a variety of results for τ_ϕ. One of the reasons for this is that the MT contribution to the paraconductivity and magnetoconductivity is much smaller than the AL contribution and so the fits are not so sensitive to changes in τ_ϕ. The other reason is that τ_ϕ is probably more sensitive to growth and material parameters than the coherence lengths. It thus needs more detailed and systematic study of the paraconductivity as a function of growth and annealing parameters and over a wider temperature range. Indeed, if Yip [16] is correct and the MT term is only present in s-wave superconductors, this is a crucial issue, with many theories arguing for unconventional pairing mechanisms [18].

We fitted out data assuming τ_ϕ to be proportional to T^{-1}. This assumption has been used by a number of workers [3–5, 8–11, 17] and is based on the assumption that the processes destroying the phase coherence are the same processes that are involved in the scattering giving rise to the linear T dependence of the resistivity. Using the Hall coefficient to estimate the carrier density [19] ($n \approx 4 \times 10^{21}$ cm^{-1}) and assuming the effective mass to be $5m_e$ [19] we can use the resistivity to determine the transport scattering rate and find $\tau_{tr} \approx 3 \times 10^{-13}$ s at 100 K. This is similar in magnitude to the phase-coherence time, supporting the assumption of the equivalence of the phase-coherence time and the scattering time. The Fermi velocity can be estimated from the BCS coherence length and so the transport mean free path can also be estimated; we find $l_{tr} = \tau_{tr} v_F$, is approximately 130 Å.

Although the paraconductivity fit requires knowledge of the normal-state temperature dependence of the resistivity it is important to note that the parameters derived from both the paraconductivity and magnetoconductivity fits, shown in table 2, are essentially the same. This suggests that the fit to the normal-state resistivity, as determined by the parameters a_f and b_f is reliable. Indeed, we have determined the parameters ξ_{ab}, ξ_c and T_c from three different routes—from the paraconductivity, the magnetoconductivity and the temperature dependence of the magnetoconductivity—and all are very similar.

The magnetoconductivity with the field parallel to the current was too small to be measured. So this puts an upper limit of about 10^{-4} T^{-1} for $\Delta\sigma/\sigma$. It also emphasizes the two-dimensional character of the fluctuations in this temperature regime. For 2D superconductors the orbital contributions, MTO and ALO, are zero when the field is parallel to the current. The Zeeman terms should still be present but these are several orders of magnitude smaller than the orbital terms and so are below the 10^{-4} T^{-1} experimental threshold.

5. Summary

We have presented results for the paraconductivity and magnetoconductivity of a single crystal sample $YBa_2Cu_3O_{7-\delta}$. We have fitted these data to the existing theories of the Maki–Thompson and Aslamazov–Larkin contributions to the fluctuation conductivity. We find we can obtain consistent values of the coherence lengths, transition temperature and phase-coherence time from independent fits to the paraconductivity, magnetoconductivity and the temperature dependence of the magnetoconductivity. The presence of the Maki–Thompson contribution suggests that the pairing mechanism is s-wave. However we point out that the contribution is small, and fits over a wider temperature range are needed to confirm this conclusion. It is unfortunate that the small resistance of the YBCO crystals makes this a difficult experiment to do.

Acknowledgments

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