Magnetoresistance measurements on polycrystalline $YBa_2Cu_3O_{7-\delta}$

M. Andersson and Ö. Rapp
Solid State Physics, The Royal Institute of Technology, S-100 44 Stockholm, Sweden
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The magnetoresistance of a polycrystalline sample of $YBa_2Cu_3O_{7-\delta}$ has been measured by an ordinary resistive method at temperatures from about 1 to 15 K above T_c and in magnetic fields up to 12 T. From our experimental results and the theory of Hikami and Larkin, we obtain values of the coherence lengths $\xi_{ab}=15.6$ Å and $\xi_c=3.6$ Å and of the phase-breaking time $\tau_\phi=1.8\times10^{-13}$ s.

I. INTRODUCTION

By studying the paraconductivity due to superconducting fluctuations just above the superconducting transition temperature T_c, it is possible to obtain information about important microscopic quantities such as the coherence length and the phase-breaking time. These studies can be made either by ordinary resistivity measurements or by magnetoresistivity measurements. In the first type of measurement, one is forced to make an assumption about the normal-state resistivity without fluctuations before analyzing the experimental data. This is normally achieved by extrapolating the temperature dependence of the resistivity linearly from temperatures much above T_c. In magnetoresistivity measurements, on the other hand, one does not have to rely on the assumption of a linear normal-state resistivity, since one then measures a difference between the resistivity in magnetic field and in zero magnetic field.

The paraconductivity due to superconducting fluctuations is normally analyzed in terms of the Aslamazov-Larkin (AL) contribution[1] $\Delta\sigma_{\rm AL}$, and the Maki-Thompson (MT) contribution[2,3] $\Delta\sigma_{\rm MT}$. In $YBa_2Cu_3O_{7-\delta}$, the MT contribution is rather small due to strong pair breaking and has therefore been neglected in the analysis of paraconductivity from ordinary resistivity measurements.[4,5] Nevertheless, at temperatures about 10 K above T_c, the MT and the AL terms become comparable to each other, as shown from magnetoresistivity data.[6]

High-temperature superconductors are layered materials with a coherence length perpendicular to the superconducting CuO planes, $\xi_c(0)$, which is of the order of the layer spacing between the superconducting Cu-O planes. Because of the temperature dependence of the coherence length, $\xi_c(T)=\xi_c(0)/\sqrt{\epsilon}$, where $\epsilon=(T-T_c)/T_c$ is the reduced temperature, there should therefore be a crossover from a three-dimensional behavior of the fluctuations close to T_c to a two-dimensional one at higher temperatures (the Lawrence-Doniach theory).[7]

Recently, results have been calculated for the magnetoconductivity $\Delta\sigma'(B,T)=\Delta\sigma(B,T)-\Delta\sigma(0,T)$, in an applied magnetic field B, of such a quasi-two-dimensional system.[8] In a subsequent paper, Aronov, Hikami, and Larkin showed that the Zeeman effect in the magnetoconductivity gave a measurable contribution.[9] The total magnetoconductivity is thus a sum of four different contributions:

$$\Delta\sigma'=\Delta\sigma'_{{\rm AL}O}+\Delta\sigma'_{{\rm MT}O}+\Delta\sigma'_{\rm ALZ}+\Delta\sigma'_{\rm MTZ}\ ,$$

where O stands for the orbital (ordinary) contribution and Z for the Zeeman contribution.

In this study, we have measured the magnetoconductivity of a polycrystalline sample of $YBa_2Cu_3O_{7-\delta}$ and analyzed our data in terms of the Hikami-Larkin theory. The measurements are made in magnetic fields up to 12 T and in a temperature range from 1 K above T_c to about 15 K above T_c. Previously, other authors have measured the magnetoresistivity in $YBa_2Cu_3O_{7-\delta}$ at small magnetic fields in a large temperature range from T_c to about 200 K using a field-modulation technique[6,10] and at high magnetic fields with temperatures close to T_c using an ordinary resistive method.[11,12] The present study extends the magnetoresistivity measurements of $YBa_2Cu_3O_{7-\delta}$ to high magnetic fields in a region further away from T_c than explored before.

II. EXPERIMENT

The samples were prepared by an ordinary solid-state reaction technique. Stoichiometric amounts of Y_2O_3, $BaCO_3$, and CuO were carefully mixed, prefired at 500 °C for 5 h in air and then heat treated for 12 h in air at 930 °C. The samples were then grounded and once again heat treated for 12 h in air at 930 °C. After a final regrinding, the samples were calcined in flowing oxygen for 2 h at 930 °C and then oxygenized for 12 h at 450 °C.

The magnetoresistivity measurements were performed in a commercial flowing gas cryostat (Oxford Instruments, Inc.) equipped with a 12-T superconducting magnet. To ensure a sufficient temperature stability during the measurements, the sample holder was protected from the flowing gas by a shield, which also served as an extra vacuum chamber. The gas pressure within the shield was reduced to keep the cooling of the sample on a low and controllable level. By controlling the temperature on both the shield and the sample holder, a favorable and stable control situation was achieved during operation.[13]

Figure 1 shows the resistance of a sample of $YBa_2Cu_3O_{7-\delta}$ at zero field and at 12 T in part of the temperature region of the present measurement. Obviously a small drift in sample temperature during a magnetic field sweep to 12 T could be detrimental to the measurements. Most of the commonly used temperature sensors have a

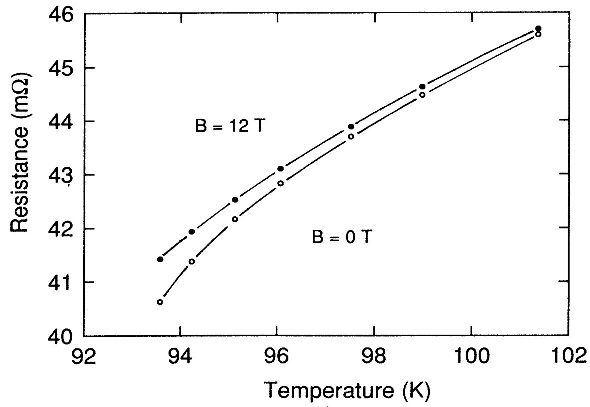

FIG. 1. Sample resistance vs temperature at zero magnetic field and at a magnetic field of 12 T for temperatures above the superconducting transition temperature, $T_c = 92.16$ K.

magnetic field dependence which at a magnetic field of 12 T and at temperatures of about 100 K give a temperature error of 0.1–1 K or larger, dependent of sensor type.[14] To achieve the necessary temperature accuracy, it is therefore convenient to use a magnetic-field-independent thermometer as control sensor.

In our measurements, the absolute temperature in zero magnetic field was measured by a calibrated Pt resistance thermometer to within better than 50 mK in absolute temperature and with a relative accuracy of 0.5 mK. The temperature during a magnetic field sweep was controlled to better than ± 10 mK by a magnetic-field-independent capacitive sensor. The sample resistance was measured by a dc comparator bridge with nV resolution.

III. RESULTS

In Fig. 2, the measured magnetoresistivity of our sintered $YBa_2Cu_3O_{7-\delta}$ sample is shown at different reduced temperatures $\epsilon = (T - T_c)/T_c$. Close to T_c, the superconducting fluctuations are strong. A large magnetoresistivity is seen due to the magnetic-field-induced pair breaking and the magnetoresistivity shows a convex magnetic field behavior. At higher temperatures ($\epsilon > 0.03$) the magnetoresistivity is essentially proportional to B^2. From the deviations in our data, we can conclude that the sensitivity of the measurement, including temperature errors, is better than 10^{-4} in $\Delta\rho/\rho$.

The measured magnetoresistivity was analyzed in terms of the Hikami-Larkin theory.[8,9] In our analysis, the maximum applied magnetic field of 12 T is low enough for using the weak-field approximation for the Zeeman terms, but not low for the orbital terms.[12] Thus, the following expressions for the magnetoconductivity were used in the data analysis:

$$\Delta\sigma'_{\mathrm{ALO}} = \frac{e^2}{8\hbar}\int_0^{2\pi/d} \frac{1}{\varepsilon_k}\left[\frac{\varepsilon_k}{b}\right]^2 \left[\Psi\left[\frac{1}{2}+\frac{\varepsilon_k}{2b}\right] - \Psi\left[1+\frac{\varepsilon_k}{2b}\right] + \frac{b}{\varepsilon_k}\right]\frac{dk}{2\pi} - \frac{e^2}{16\hbar d}\frac{1}{\varepsilon\sqrt{1+2\alpha}}$$

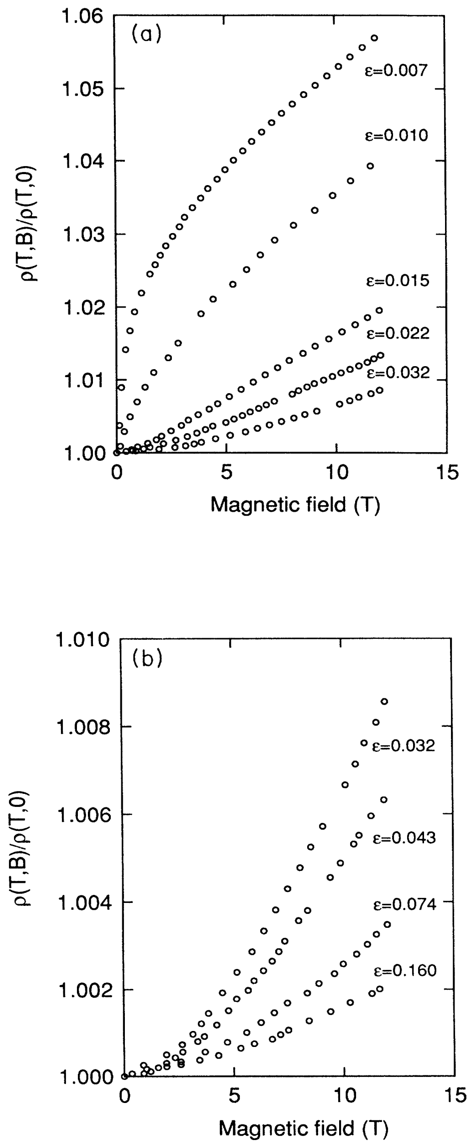

FIG. 2. Relative magnetoresistivity for $YBa_2Cu_3O_{7-\delta}$ in magnetic fields up to 12 T and temperatures ranging from 92.79 K [$\epsilon = (T - T_c)/T_c = 0.07$] to 106.88 K ($\epsilon = 0.160$). Note the different scales for $\Delta\rho/\rho$. For clarity, all curves used in the analysis are not shown in the figure.

where

$$\varepsilon_k = \varepsilon\{1+\alpha[1-\cos(kd)]\}, \quad \varepsilon = \frac{T - T_c}{T_c},$$

$$\alpha = \frac{2\xi_c^2}{d^2\varepsilon}, \quad b = \frac{2e\xi_{ab}^2}{\hbar}B,$$

d is the layer spacing, ξ_{ab} and ξ_c are the coherence lengths in the plane and perpendicular to the plane respectively, and Ψ is the digamma function.

$$\Delta\sigma'_{MTO}=\frac{e^2}{8\hbar}\frac{1}{d\varepsilon(\alpha/\delta-1)}\left\{\int_0^{2\pi}\left[\Psi\left[\frac{1}{2}+U\right]-\Psi\left[\frac{1}{2}+V\right]\right]\frac{dx}{2\pi}-\ln\left[\frac{\delta}{\alpha}\frac{1+\alpha+\sqrt{1+2\alpha}}{1+\delta+\sqrt{1+2\delta}}\right]\right\},$$

where

$$U=\frac{\epsilon}{2b}[1+\alpha(1-\cos x)],\quad V=\frac{\alpha\epsilon}{2b}\left[\frac{1}{\delta}+1-\cos x\right],$$

$$\delta=\frac{16\xi_c^2 k_B T\tau_\phi}{\pi d^2\hbar},$$

and τ_ϕ is the phase breaking time.

$$\Delta\sigma'_{ALZ}=-0.526\frac{e^2}{\hbar d\epsilon^2}\frac{1+\alpha}{(1+2\alpha)^{3/2}}\left[\frac{g\mu_B B}{4\pi k_B T_c}\right]^2,$$

where g is the gyromagnetic ratio and μ_B is the Bohr magneton.

$$\Delta\sigma'_{MTZ}=\frac{e^2}{8d\epsilon\hbar}\frac{1}{1-\alpha/\delta}\left[\frac{g\mu_B B\tau_\phi}{\hbar}\right]^2$$
$$\times\left[-\left[\frac{\alpha}{\delta}\right]^2\frac{1}{(1-\alpha/\delta)^2}\ln\left[\frac{\delta}{\alpha}\frac{1+\alpha+\sqrt{1+2\alpha}}{1+\delta+\sqrt{1+2\delta}}\right]-\frac{1}{2}\frac{1+\delta}{(1+2\delta)^{3/2}}+\frac{1}{\sqrt{1+2\delta}}\frac{1}{1-\alpha/\delta}\frac{\alpha}{\delta}\right].$$

In a polycrystalline sample, there is a random distribution of grains. Since the orbital terms ($\Delta\sigma'_{ALO}$ and Δ'_{MTO}) are derived for a magnetic field perpendicular to the superconducting planes, one has to average over all grain directions for these two terms. We therefore introduce an effective magnetic field B_{eff}, which is parallel to the c direction of a crystallite; $B_{eff}=B\cos\theta$, where B is the applied field and θ is the angle between B and the c direction of the crystallite. We then average over all crystallites by integrating over the whole solid angle Ω and obtain the effective contribution to the magnetoconductivity from the orbital terms:

$$(\Delta\sigma'_{ALO})_{eff}=\frac{1}{4\pi}\int_\Omega\Delta\sigma'_{ALO}d\Omega$$

and

$$(\Delta\sigma'_{MTO})_{eff}=\frac{1}{4\pi}\int_\Omega\Delta\sigma'_{MTO}d\Omega\ .$$

The Zeeman terms, on the other hand, are independent of the grain direction, and thus no averaging is necessary.

Furthermore, in a polycrystalline anisotropic medium, the effective resistivity of the sample is higher than in a single crystal, because of the different grain directions.[15] Voids are also present in the sample, which results in a smaller effective cross section for the electron transport, and thus a higher apparent resistivity. These effects can be taken into account by introducing a sample dependent constant C, which can be estimated from the slope of the resistivity versus temperature curve far above T_c.[5] The observed magnetoconductivity is calculated from

$$\Delta\sigma'_{obs}=\frac{1}{C}[(\Delta\sigma'_{ALO})_{eff}+(\Delta\sigma'_{MTO})_{eff}+\Delta\sigma'_{ALZ}+\Delta\sigma'_{MTZ}]\ .$$

T_c is defined from the 50% level of the normal-state resistance. Then there are three free parameters in this expression, ξ_{ab}, ξ_c, and τ_ϕ. In addition, we allowed for a small variation of C from the estimated value. A fit of the calculated magnetoconductivity to our experimental data is shown in Fig. 3. As seen from the figure, good fits were obtained for temperatures from about 2 K above T_c to our highest temperatures and for magnetic fields up to 12 T. For temperatures within about 2 K from T_c, the choice of T_c becomes critical for the analysis. The width of the transition, of order 1 K in zero field, reflects the sample homogeneity and indicates the range over which superconducting T_c:s are distributed. Therefore, we have excluded this region in the fitting procedure. Further-

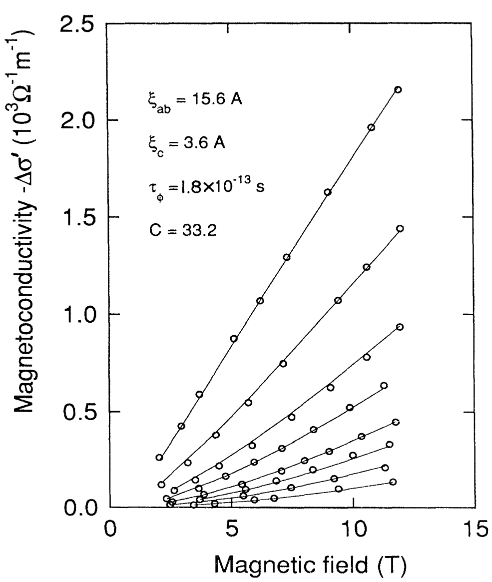

FIG. 3. A fit to our experimental data using the formula for the observed magnetoconductivity described in the text (experimental points are shown by circles). The $\epsilon=(T-T_c/T_c$ values for the curves are 0.015, 0.022, 0.032, 0.042, 0.058, 0.074, 0.100, and 0.160 from top to bottom. The parameters used in the fits are given in the figure.

TABLE I. Results from magnetoresistance measurements of $YBa_2Cu_3O_{7-\delta}$.

Sample	Field and temperature range	ξ_{ab} (Å)	ξ_c (Å)	τ_ϕ (s)
Thin film[a]	$B=1$ T, $T<2T_c$	11.5	1.5	1×10^{-13}
Polycrystalline[b]	$B=1$ T, $T<2T_c$	16.4	2.0	3×10^{-14}
Single crystal[c]	$B<12$ T, $T<T_c+5$ K	15	3	
Polycrystalline[d]	$B<12$ T, $T<T_c+15$ K	15.6	3.6	1.8×10^{-13}

[a]Reference 9.
[b]Reference 10.
[c]Reference 12.
[d]This study.

more, the lowest magnetic fields ($B<2$ T) were not used in the fitting procedure, partly because of larger relative experimental errors for these values and partly because of the fact that a low-field approximation has to be introduced in the fitting procedures to avoid computational difficulties.

From our analysis, we obtain the following values: $\xi_{ab}=15.6\pm0.3$ Å, $\xi_c=3.6\pm0.2$ Å, and $\tau_\phi=(1.8\pm0.2)\times10^{-13}$ s. The errors given in the parameter values correspond to twice the root-mean-square value when keeping the other parameters constant. For the sample-dependent constant C, we obtain a value of 33.2 ± 1.0. This value is in good agreement with the expected value for our sample, as discussed above. The seemingly high value of C comes from the rather high porosity in the sample, which was desired to allow for a full oxygenization during preparation.

IV. DISCUSSION

In Table I, some results from magnetoresistance measurements on different types of $YBa_2Cu_3O_{7-\delta}$ samples and by different experimental methods are shown. The derived coherence lengths in the ab plane only slightly deviate between the different investigations, while the coherence length along the c axis is scattered within a factor of 2 and the phase-breaking time is of the same order of magnitude. These differences also reflect the relative difficulties in determining the different parameters from magnetoresistivity measurements.

Our analysis suggests a somewhat higher value of τ_ϕ than the other analyses. Since τ_ϕ only affects the MT terms and these terms become relatively more important at higher temperatures, our value of τ_ϕ is mainly determined by the high-field data at the highest temperatures used; a region which has not been explored before. A higher value of τ_ϕ has recently been suggested when using a clean-limit theory for analyzing the magnetoresistance of a $YBa_2Cu_3O_{7-\delta}$ thin film.[16]

The present analysis has used both the temperature and the field dependence of the magnetoconductivity for the data analysis. We suggest this to be important when deriving superconducting parameters from magnetoconductivity measurements.

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