Possible fluctuation origin of the anomalies in the *c*-axis magnetoresistance observed in $Bi_2Sr_2CaCu_2O_{8+x}$ above the critical temperature

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(Submitted 14 April 1995)
Pis'ma Zh. Éksp. Teor. Fiz. **61**, No. 10, 814–818 (25 May 1995)

An expression for the transverse magnetoresistance above T_c has been derived from the theory of fluctuation contribution to the c-axis conductivity of layered superconductors under an external magnetic field, , which was recently developed by Dorin *et al.* The suppression of fluctuations due to the magnetic field leads to a decrease of the negative fluctuation contribution to the conductance, and therefore to a negative transverse magnetoresistance at temperatures not too close to T_c. The formula derived from the theory has been compared with the available experimental data of the magnetoresistance of BSCCO single crystals obtained by Ong *et al.* at temperatures 10–20 K above T_c. The quadratic increase of the relative magnetoresistance with the field and its temperature dependence are explained clearly. A quantitative fit to the experimental data shows a remarkable agreement of the theory with experiment, and allows to extract the values of several physical parameters. © *1995 American Institute of Physics.*

Among the most characteristic properties of high-T_c superconducting oxides (HTSC) is their layered structure, which leads to a high anisotropy of their properties due to weak coupling among superconducting Cu–O layers. This circumstance gives rise to a peculiar behavior of the resistivity of the c axis which is one of the most puzzling and interesting features of the transport properties of these compounds. In fact, the transverse resistivity, plotted as a function of temperature in zero external field, often shows a peak close to T_c, which has been studied by several authors.[1–3] It turns out that this peak is very pronounced in highly anisotropic samples [$Bi_2Sr_2CaCu_2O_{8+x}$ (BSCCO) annealed in reducing atmosphere] but almost absent in samples with low anisotropy [$YBa_2Cu_3O_\delta$ (YBCO) with $\delta \simeq 7$; BSCCO annealed in oxygen atmosphere].[4–6]

The origin of this peak has been debated for a long time, and many attempts to find a physical explanation for it or at least to reconstruct its shape using empirical formulas have been undertaken. Moreover, such a striking contrast between the temperature dependences of in-plane and out-of-plane resistivities was by some authors indicates as a critical point for the applicability of a Fermi liquid theory to these compounds.[7,8] An explanation of the origin of this peak, based on thermodynamical fluctuations, was recently given by Ioffe *et al.*[9] According to this theory, there is a competition among several fluctuation contributions to the conductivity of the c axis. The positive Aslamazov–Larkin (AL) contribution has a temperature dependence which is more singular in $T-T_c$ but is strongly depressed by its proportionality to the square of the transparency[9] above the Lawrence-Doniach crossover point. On the other hand, the fluctuation of the one-electron density of states (DOS) decreases at the Fermi level close to T_c (the opening of the fluctuation pseudogap). The negative DOS contribution is less singular in temperature but proportional to the first order of the transparency only. The competition among these contributions of different signs determines the shape of the resistivity peak close to T_c.

The quantitative agreement of this theory with experimental data was proved shortly after[6,8,10] by fitting the resistivity peaks of the BSCCO and YBCO samples which had good metallic behavior far from the transition, and therefore showed a relatively small peak. In these experiments the carrier concentration and the anistropy of the $Bi_2Sr_2CaCu_2O_{8+x}$ film grown on a misaligned substrate were changed by reducing and oxidizing the annealing treatments. Since the AL contribution is more heavily dependent on the interlayer coupling than on the DOS one, a more pronounced peak is expected for materials with higher anisotropy. the carrier density also affects the magnitude of the peak, since a higher carrier concentration means that the fluctuation contribution is lower and the normal-state conductivity is higher, which therefore strongly reduces the relative change in the conductivity. The evolution of the resistivity peak under redox treatments confirmed these predictions.

However, for strongly oxygen-deficient YBCO (δ=6.4–6.8) the increase in the resistivity of the c-axis begins far from T_c and the peak is so large[8] that it cannot be attributed solely to the fluctuation effects: In this case the effect is probably due to a metal-insulator transition.

The behavior of the resistivity peak in an external c-axis oriented magnetic field is also very interesting:[3] Its magnitude strongly increases with field intensity, while the position of the maximum and the zero resistance temperatures are shifted toward much lower values. The full theoretical treatment of the effect of a magnetic field on the fluctuation conductivity of layered superconductors above T_c was given by Dorin *et al.*,[11,12] who considered the AL, DOS, regular, and anomalous Maki–Thompson (MT) fluctuation contributions to c-axis conductivity. A useful analogy for the analysis of c-axis resistivity in HTSC may be the separation of different contributions in amorphous films.[13,14] In these systems in the weak localization regime the total conductivity is interpreted as a sum of several contributions (localization corrections, corrections originated from the Coulomb electron-electron interaction, Cooper channel, etc.). The crucial point is that the temperature and magnetic field dependences of these contributions are very different. This circumstance allowed us to separate and identify each dependence, extracting important information from them concerning microscopic parameters of these systems.

In this letter we apply a somewhat similar approach to the analysis of the anomalous negative c-axis magnetoresistance which was recently observed in strong magnetic fields parallel to the c axis on BSCCO single crystals.[15] From the data reported in Ref. 15 we see that the effect becomes significant below ≈ 120 K, and that its magnitude increases dramatically as the temperature decreases to 95 K. Applying Eqs. (A2)–(A5) of Ref. 12 the following expression for the fluctuation of the magnetoresistivity along the c axis close to T_c $[\varepsilon = \ln(T/T_c) \ll 1]$ can be easily found:

$$\sigma_c(0)-\sigma_c(H)=\frac{e^4 s \nu_F^2 \tau^2}{38.4\hbar^3 c^2} f(T) B^2, \tag{1}$$

where e is the electron charge, c is the velocity of light, s is the interlayer spacing, v_F is the in-plane Fermi velocity, τ is the elastic scattering time, and B is the magnetic field (all measured in c.g.s. units). The temperature-dependent factor $f(T)$ is

$$f(T)=f_0 \frac{r^2}{[\varepsilon(\varepsilon+r)]^{3/2}} \left[\frac{3(\varepsilon+r/2)}{\varepsilon(\varepsilon+r)} - 8k\left[\frac{\varepsilon}{r} + \frac{1}{2}\left(1+\frac{\tilde{k}}{k}\right)\right]\right.$$
$$\left. + \frac{2(\varepsilon+\gamma+r)\{\varepsilon(\varepsilon+r)+\gamma(\gamma+r)+[\varepsilon(\varepsilon+r)\gamma(\gamma+r)]^{1/2}\}}{[\gamma(\gamma+r)]^{3/2}\{[\varepsilon(\varepsilon+r)]^{1/2}+[\gamma(\gamma+r)]^{1/2}\}}\right], \tag{2}$$

where $\epsilon = \ln(T/T_c)$, and $r, k, \tilde{k}$, and γ are defined as in Ref. 12 (where units with $c = \hbar = k_B = 1$ have been used), and f_0 is given by

$$f_0 = -\left[\Psi\left(\frac{1}{2}+\frac{\hbar}{4\pi k_B T\tau}\right)-\Psi\left(\frac{1}{2}\right)-\frac{\hbar}{4\pi k_B T \tau}\Psi'\left(\frac{1}{2}\right)\right]$$

[$\psi(x)$ is the digamma function]. The first term in Eq. (2) represents the AL contribution, the second term is the sum of the DOS and regular MT contributions, and the third term is the anomalous MT contribution. Their different temperature dependences allow us to separate their contributions and therefore extract the values of the physical parameters involved.

The relative magnetoresistance is therefore

$$\frac{\rho_c(H,T)-\rho_c(0,T)}{\rho_c(0,T)} = 1.46\times 10^{16} \rho_c(H,T) s \nu_F^2 \tau^2 f(T) B^2, \tag{3}$$

where now $\rho_c(H,T)$ is in $\Omega\cdot$cm and B is in Tesla. This result is valid in the low-field approximation $\beta \ll \varepsilon$, with $\beta = 2 f_0 v_F^2 \tau^2 eB/\hbar c$, which is satisfied in the experiment reported in Ref. 15. To compare Eq. (3) with the experimental data of Ref. 15, we fitted them using as adjustable parameters v_F, τ and the phase pair-breaking lifetime τ_ϕ which appears in the definition of γ. The interlayer spacing is $s \approx 10^{-7}$ cm and the hopping integral is $J \approx 40$ K (which is used in the definition of r). These values were taken from Ref. 10, since they are not likely to vary strongly from sample to sample (at least for BSCCO samples with metallic behavior far from T_c), while $\rho_c(H,T)$ and $T_c \approx 85$ K were deduced from Ref. 15 in order to keep the number of adjustable parameters to a minimum. We stress that all the parameters used by us are not phenomenological constants, but have a well-defined physical meaning, allowing *a posteriori* analysis of the consistency of the values which we obtained.

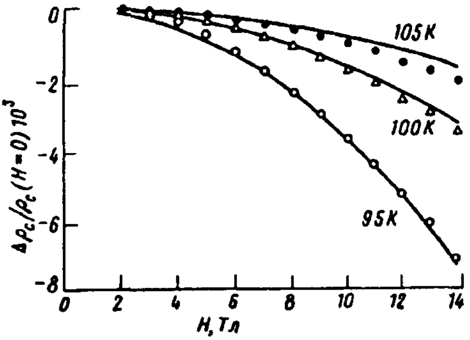

FIG. 1. Fit of the transverse magnetoresistance data of a BSCCO crystal to the proposed theory of its fluctuation origin. Curves at 95 K and 100 K were simultaneously fitted, and at 105 K is drawn using the parameters given by the fit of the curves at 95 K and 100 K, which are given for reference only (see the text).

The results of the fit performed using Eq. (3) on the magnetoresistance curves are shown in Fig. 1. The curves measured at $T=95$ K and $T=100$ K have been fitted simultaneously (i.e., using for both curves the same values of the fitting parameters in order to impose stronger constraints on them), while the curve at $T=105$ K (and curves measured at higher temperatures) have not been considered in the fit, because the theory used by us is valid in the limit $\epsilon \ll 1$, while at 105 K we have already $\epsilon=0.21$, and the theory therefore cannot be quantitatively used at these temperatures. However, the theoretical curve at 105 K is shown in Fig. 1, using the values of v_F, τ, and τ_ϕ found by fitting the curves at 95 K and 100 K in order to show that even at higher temperatures the calculated temperature dependence of the transverse magnetoresistance is in qualitative agreement with the experimental data.

The values of the fitting parameters extracted from the fit are $v_F=3.1\times10^6$ cm/s, $k_B/\hbar T_c \tau=0.11$, and $k_B/\hbar T_c \tau_\phi=0.96$. Reliable values of the errors of these parameters cannot be calculated, partly because of their strong correlation, but we estimate them to be not negligible with respect to the parameter values. The ratio $\tau_\phi/\tau\approx 10$ is in good agreement with the expected ratio,[9] while the values of v_F and τ are on the lower side of the literature data. Taking into account the large errors of the parameters, the fact that the temperature dependences of τ_ϕ and τ were ignored in the small temperature range considered, the difficulties in the experimental evaluation of the c-axis resistivity in single crystals of layered superconductors, and the approximations made in the choice of T_c, s, and J, we believe that these values are quite reasonable.

While the field dependence of the magnetoconductivity is simply B^2, its behavior with the temperature given by Eq. (2) is much more interesting. In Fig. 2 we plot Eq. (2) using the values given above for the fitting parameters. It can be seen that the theory predicts the existence of a temperature T_r, at which there is an inversion in the sign of the magnetoconductivity [provided that the calculated T_r lies in the region of applicability, $\epsilon(T_r)\ll 1$, of the theory]. The physical origin of this change of sign is the same as that for the appearance of the peak found above:[8] Relatively far from T_c the AL negative magnetoconductivity is suppressed by its dependence on the square of the transparency, and

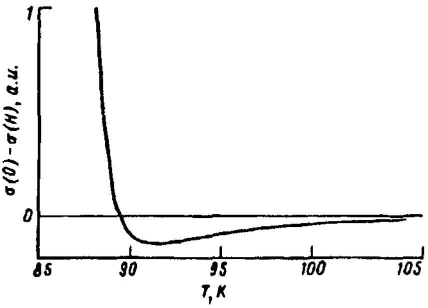

FIG. 2. Calculated temperature dependence of the magnetoresistivity in BSCCO (Eq. 2).

the positive DOS contribution dominates, while very close to T_c the highly singular temperature dependence of the negative AL contribution ($\sim\epsilon^{-4}$) makes it prevail over the less singular DOS contribution (ϵ^{-2}) despite the linear dependence on the transparency of the latter. Unfortunately, the temperature range of the data of Ref. 15 does not allow us to check this prediction (in our simulation T_r is about 88 K). Nevertheless, the data of the c-axis magnetoresistance of YBCO in the immediate vicinity of T_c show an effect of positive sign, which rapidly decreases as the temperature is raised,[16] providing indirect support of the temperature dependence of the magnetoresistivity calculated in Eq. (2) for layered superconductors. This fluctuation magnetoresistivity contribution should also depend, through the parameter r, on the anisotropy of the sample (and therefore on the oxygen content). A stronger effect is expected for more strongly anisotropic samples.

In summary, we have analyzed the magnetoresistance curves of BSCCO single crystals obtained by Ong *et al.*[15] at temperatures 10–20 K above T_c in the framework of the theory of fluctuation effects on the c-axis conductivity of layered superconductors in an external magnetic field. This theory recently developed by Dorin *et al.*[12] leads to a negative fluctuation contribution to the conductance in this temperature range.

The negative magnetoresistance of layered superconductors several degrees above T_c can therefore be attributed to the suppression of fluctuations dues to the magnetic field. A formula describing the magnetoresistance has been derived and compared with the available experimental data. The quadratic increase of the relative magnetoresistance with field and its temperature dependence have been explained well. A quantitative fit to the experimental data shows a remarkable agreement of the theory and experiment, and allows us to determine the values of several physical parameters. The existence of a sign-reversal temperature T_r is predicted.

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