Pis'ma v ZhETF, vol.61, iss.10, pp.814 - 818 © 1995 May 25

POSSIBLE FLUCTUATION ORIGIN OF THE ANOMALIES IN THE c-AXIS MAGNETORESISTANCE OBSERVED IN $Bi_2Sr_2CaCu_2O_{8+x}$ ABOVE THE CRITICAL TEMPERATURE

*G.Balestrino, E.Milani, A.A.Varlamov**

Instituto Nazionale di Fisica della Materia – Dipartimento di Ingegneria Meccanica,
Universita di Roma "Tor Vergata", Via della Ricerca Scientifica e Tecnologica,
I-00133 Roma, Italy

* *Instituto Nazionale di Fisika della Materia, Laboratorio Forum – Dipartimento di Fisica,*
Universita di Firenze, I-50125 Florence, Italy
and Department of Theoretical Physics, Moscow Institute of Steel and Alloys,
117936 Moscow, Russia

Submitted 14 April 1995

From the theory of fluctuation contribution to the c-axis conductivity of layered superconductors under an external magnetic field recently developed by Dorin et al. an expression for the transverse magnetoresistance above T_c has been derived. The suppression of fluctuations due to the magnetic field leads to a decrease of the negative fluctuation contribution to 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. Both the quadratic increase of the relative magnetoresistance with field and its temperature dependence are well explained. 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.

Among the most characteristic properties of high T_c superconducting oxides (HTSC) is their layered structure, leading to high anisotropy of their properties due to weak coupling among superconducting Cu-O layers. This gives rise to a peculiar behavior of the c-axis resistivity which is one of the most puzzling and interesting features of the transport properties of these compounds. In fact, the transverse resistivity 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 longly debated, and many attempts to find a physical explaination for it or, at least, to reconstruct its shape using empirical formulae have been undertaken. Moreover, such a striking contrast between the temperature dependencies of in plane and out of plane resistivities was by some authors indicated as a crucial point for the applicability of a Fermi liquid theory to these compounds [7,8]. An explaination of the origin of this peak, based on thermodynamical fluctuations, was recently proposed by Ioffe et al. [9]. According to this theory there is a competition among several fluctuation contributions to the c-axis conductivity. The positive Aslamazov–Larkin (AL) contribution has a temperature dependence more singular in $T - T_c$ but is strongly depressed by its proportionality to the square of transparency [9] above the Lawrence–Doniach crossover point. On the other hand there is a fluctuation decrease of the one-electron density of states (DOS) at the Fermi level close to T_c (opening of the fluctuation pseudogap). The negative DOS contribution is less singular in temperature but proportional to the first order of transparency only. The competition among these contgributions of different signs determines the shape of the resistivity peak close to T_c.

The quantitative agreement of this theory with experimental data was shortly after proved [10, 6, 8] by fitting the resistivity peaks of BSCCO and YBCO samples having good metallic behavior far from the transition, and therefore showing a relatively small peak. In these experiments the carrier concentration and the anisotropy of $Bi_2Sr_2CaCu_2O_{8+x}$ film grown on a misaligned substrate were changed by means of reducing and oxidizing annealing tratments. Being the AL contribution more heavily dependent on the interlayer coupling than 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 a lower fluctuation contribution and a higher normal-state conductivity, therefore strongly reducing the relative change in conductivity. The evolution of the resistivity peak under redox treatments confirmed these predictions.

However, for strongly oxygen deficient YBCO ($\delta \equiv 6.4 - 6.8$) the increase of the c-axis resistivity begins so far from T_c and the peak has such a large magnitude [8] that it cannot be due to fluctuation effects only: in this case the effect is probably due to some metal-insulator transition.

The behavor of the resistivity peak under an external c-axis oriented magnetic field is also very intersting [3]: its magnitude strongly increases with field intensity while the position of the maximum and the zero resistance temperatures are shifted towards 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 full conductivity is interpreted as the sum of several contributions (localization corrections, corrections originated from Coulomb electron-electron interaction, Cooper channel etc.). The crucial point is that the temmperature and magnetic field dependencies of these contributions are very different, and this allowed to separate and identify each of them, extracting important informations 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 monocrystals [15]. From the data reported in Ref.[15] one can see that the effect becomes significant below approximately 120 K and its magnitude increases dramatically as the temperature goes down to 95 K. Applying formulae $(A2) - (A5)$ of Ref.[12] the following expression for the fluctuation c-axis magnetoresistivity close to T_c ($\varepsilon = \ln(T/T_c) \ll 1$) can be easily found:

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

where e is the electronic 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, B is the magnetic field (all measured in c.g.s units). The temperature-dependent factor $f(T)$ is:

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

with $\epsilon = \ln(T/T_c)$, and $r, k, \tilde{k}$ and γ are defined as in Ref.[12] (where units with $c = \hbar = k_B = 1$ have been used), while 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 is the sum of DOS and regular MT contributions and the third is the anomalous MT one. Their different temperature dependences allow to separate their contributions and therefore extract the values of the physical parameters involved.

The relative magnetoresistance is therefore

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

where now $\rho_c(H,T)$ is in Ω cm and B 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 fulfilled 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 life-time τ_ϕ which appears in the definition of γ. The values of the interlayer spacing $s \approx 10^{-7}$cm and of the hopping integral $J \approx 40K$ (which is used in the definition of r) have been taken from literature data [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 $T_c \approx 85K$ have been deduced from Ref.[15] to keep the number of adjustable parameters to a minimum. We stress anyway that all the parameters used are not phenomenological constants, but have a well defined physical meaning, allowing an a posteriori analysis of the consistency of the obtained values.

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 put more 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 is valid in the limit $\epsilon \ll 1$, while at 105 K we have already $\epsilon = 0.21$, and the theory cannot therefore be quantitatively used at these temperatures. However, the theoretical curve at 105 K has been drawn 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 qualitatively in agreement with the experimental data.

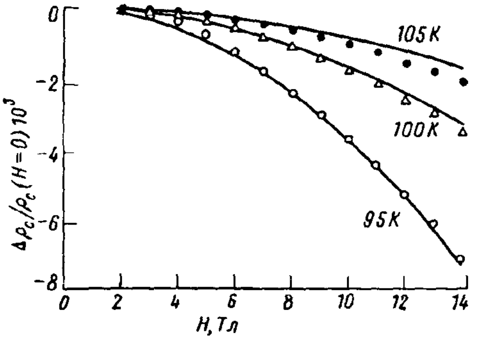

Fig.1

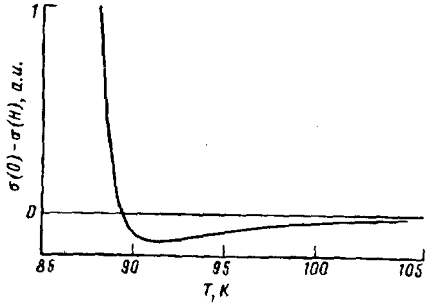

Fig.2

Fig.1. Fit of transverse magnetoresistance data of a BSCCO crystal with the proposed theory of its fluctuation origin. Curves at 95 K and 100 K have been actually simultaneously fitted, while curve at 105 K is drawn using parameters given by the fit of curves at 95 K and 100 K and reported for reference only (see text)
Fig.2. Calculated temperature dependence of magnetoresistivity in BSCCO (Eq. 2)

The values of the fitting parameters extracted from the fit are $v_F = 3.1\cdot 10^6\,\mathrm{cm/s}$, $k_B/\hbar T_c\tau = 0.11$ and $k_B/\hbar T_c\tau_\phi = 0.96$. Reliable values for the errors on these parameters cannot be calculated, partly because of their strong correlation, but we estimate them not to be negligible with respect to parameter values themselves. The ratio $\tau_\phi/\tau \approx 10$ is in a good agreement with the expexted one [9], while the values of v_F and τ are on the lower side of literature data. Anyway, considering the large errors on the parameters best values, the fact that the temperature dependencies of τ_ϕ and τ have been neglected 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 magnetoconductivity is simply B^2, its behavior with temperature given by Eq.(2) is much more interesting. In Fig.2 we plot Eq.(2) using the above values 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, of course, that the calculated T_r lies in the region of applicability $\epsilon(T_r) \ll 1$ of theory). The physical origin of this change of sign is the same as for appearance of the peak found above [8]: relatively far from T_c the AL negative magnetoconductivity is supressed by its dependence on the square of transparency and the positive DOS contribution dominates, while very close to T_c the very singular temperature dependence of the negative AL contribution ($\sim \epsilon^{-4}$) makes it preval on the less singular DOS one (ϵ^{-2}) in spite of the linear dependence on the transperency of the latter. Unfortunately the temperature range of the data of Ref.[15] does not allow to check this prediction (in our simulation T_r is about 88 K). Nevertheless, data of the c-axis magnetoresistance of YBCO in the immediate vicinity of T_c show an effect of positive sign, rapidly decreasing as the temperature is increased [16], providing indirect support of the temperature dependence of magnetoresistivity calculated in Eq.(2) for layered superconductors. This fluctuation magnetoresistivity contribution should also depend, through the parameter r, on sample anisotropy (and therefore oxygen content), a higher effect being expected for the more anisotropic samples.

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

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

---

1. T.Penney, S. von Holnar, D.Kaiser et al., Phys. Rev. B **38**, 2918 (1988).
2. S.Martin, A.T.Fiory, R.M.Fleming et al., Phys. Rev. Lett. **60**, 2194 (1988).
3. G.Briceno, M.F.Crommie, and A.Zettl, Phys. Rev. Lett. **66**, 2164 (1991).
4. L.Forro, V.Ilakovac, J.R.Cooper et al., Phys. Rev. B **46**, 6626 (1992).
5. T.Yosuda, S.Tanako, and L.Rinderer, Physica C **208**, 385 (1993).
6. G.Balestrino, E.Milani, and A.A.Varlamov, Physica C **210**, 386 (1993).
7. P.W.Anderson, Science **235**, 1196 (1987); P.W.Anderson, Phys. Rev. Lett. **65**, 2306 (1990).
8. B.Veal, private communication.
9. L.Ioffe, A.I.Larkin, A.A.Varlamov, and L.Yu, Phys. Rev. B **48**, 839 (1993).
10. G.Balestrino, M.Marinelli, E.Milani et al., Phys. Rev. B **47**, 6037 (1993).
11. V.V.Dorin, R.A.Klemm, A.A.Varlamov et al., JETP Lett. **58**, 422 (1993).
12. V.V.Dorin. R.A.Klemm, A.A.Varlamov et al., Phys. Rev. B **48**, 12951 (1993).
13. B.L.Al'tschuler and A.G.Aronov, In: *Electron-Electron Interaction in Disordered Conductors*, A.L.Efros and M.Pollak eds., Elsevier, Sci. Ed. (1985).
14. M.E.Gershenson, V.N.Gubankov, and Yu.E.Zhuravlev, Sov. Phys. JETP **58**, 167 (1983).
15. N.P.Ong, Y.F.Yan, and J.M.Harris, CCAST Symposium on High T_c Superconductivity and the C60 Family, Beijing, 1994.
16. W.Holm, M.Andersson, O.Rapp et al., Phys. Rev. B **48**, 4227 (1993).