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RESISTIVE TRANSITION IN $Bi_2Sr_2Ca_2Cu_3O_{10+x}$ PHASE

F.Fontana, V.Persico, D.V.Livanov, G.Balestrino+*

Dipartimento S. A. V. A., Universita Campobasso, I-80125 Napoli, Italy

**Department of Theoretical Physics, Moscow Institute of Steel and Alloys 117936 Moscow, Russia*

+Dipartimento di Ingegneria Meccanica, Universita di Roma "Tor Vergata", via della Ricerca Scientifica, I-00133 Roma, Italy

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Electrical resistance of $Bi_2Sr_2Ca_2Cu_3O_{10+x}$ c–oriented platelets in proximity of the superconducting transition have been studied. The analysis of data was performed self-consistently in terms of the Aslamazov–Larkin theory of fluctuation conductivity well above the transition and within the context of the Coulomb gas analogy for vortex fluctuations at temperatures below the mean-field transition temperature. We found for the first time the values of anisotropy parameter and effective interlayer hopping energy in $Bi_2Sr_2Ca_2Cu_3O_{10+x}$ phase.

The temperature dependence of the electrical resistivity $\rho(T)$ in the proximity of superconducting transition is one of the main characteristics of a superconductor. The distinctive features of high-T_c superconductors, such as the large structural anisotropy and short coherence lengths, result in some inherent pecularities in their resistivity temperature dependence. The first one concerns the pronounced effect of the fluctuations of order parameter above the mean-field (Ginzburg-Landau) critical temperature T_{GL}. Such superconducting fluctuations determine both in-plane ρ_{ab} and out-of-plane ρ_c components of the resistivity tensor in the overall temperature range from T_{GL} up to roughly $2T_{GL}$ [1, 2]. Another important pecularity is the manifestation of fluctuations of the phase of order parameter below T_{GL}, which lead to the strong reduction of the critical temperature by the external magnetic field due to melting of the vortex lattice [3]. In zero magnetic field these fluctuations show up as an additional dissipation caused by dissociation of vortex-antivortex pairs at the temperature of Kosterlitz–Thouless (KT) transition T_{KT} [4], which lies below T_{GL}. This results in an intrinsic broadening of the resistive transition with the characteristic parameter $\tau_c = (T_{GL} - T_{KT})/T_{GL} \approx 0.01 - 0.05$ for different high-T_c compounds [5, 6].

The purpose of the present paper is to study the in-plane $\rho_{ab}(T)$ dependence for the $Bi_2Sr_2Ca_2Cu_3O_{10+x}$ (2223 BSCCO) phase self-consistently within the fluctuation theory applied below and above mean-field critical temperature. We analyze the overall $\rho_{ab}(T)$ in terms of the theory of paraconductivity above T_{GL} and the Coulomb gas model for vortex fluctuations based on the KT theory below T_{GL}. Notice, that the growth of single-crystals or well-oriented epitaxial films of 2223 BSCCO phase presents severe problems what makes impossible the direct measurements of such an important characteristic of a layered material as the anisotropy of resistivities $\gamma = (\rho_c/\rho_{ab})^{1/2}$. This anisotropy parameter, directly connected with the effective quasiparticle interlayer hopping energy J, defines the pinning and vortex interaction energies in layered superconductors [7] and hence is crucial for understanding a number of properties of the superconductive state in high-T_c cuprates. We present here the first estimate of the γ and J values for the 2223 BSCCO phase.

The resistance measurements were carried out on single-phase 2223 BSCCO platelets grown by a novel method described in details in Ref. [8]. This method, based on a thermal gradient enhanced KCl flux, allows us to grow 2223 BSCCO platelets with a thickness about 0.5 μm and surface areas of several mm^2. Using this technique platelets of the 2223 BSCCO phase were grown in a time interval of about 10 min (extremely short in comparison with that required for the formation of this phase by solid state reaction). Platelets were fully characterized by X-ray diffraction, micro-probe analisys and transport electrical measurements. They were found to be strictly c – oriented and to have low residual resistances and a sharp of superconducting transition. To resistance measurements aim, an original apparatus based on a pressurizable LAr bath was used in order to get the sensitiveness in temperature control required by measurements made very close to the critical region [9]. The sensitivity achieved in this way was better than 5 mK, temperature being measured with a Lake Shore PT111 platinum sensor in the d.c. four probe configuration by a 6 digit Keithley multimeter. Resistance measurements were performed by the standard d.c. four probe technique using a μ-metal shield to avoid the influence of the external magnetic field on the measurements.

The temperature dependence of the in-plane resistance of our sample is shown in Fig. 1. The temperature of zero resistance within our experimental error is 100.5 K.

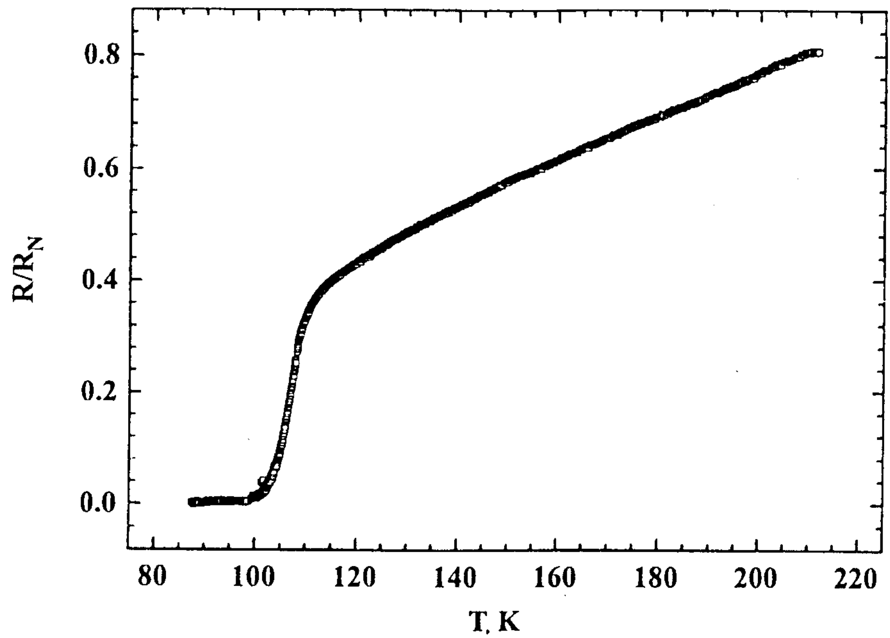

Fig.1. Resistance-vs-temperature curve with a normalizing factor $R_N = 31.6\ \Omega$

We start our analysis with the range of temperature above T_{GL} where the excess conductivity of a number of high-T_c cuprates was found to be well-described within the Aslamazov–Larkin (AL) theory of fluctuation paraconductivity [10]. The

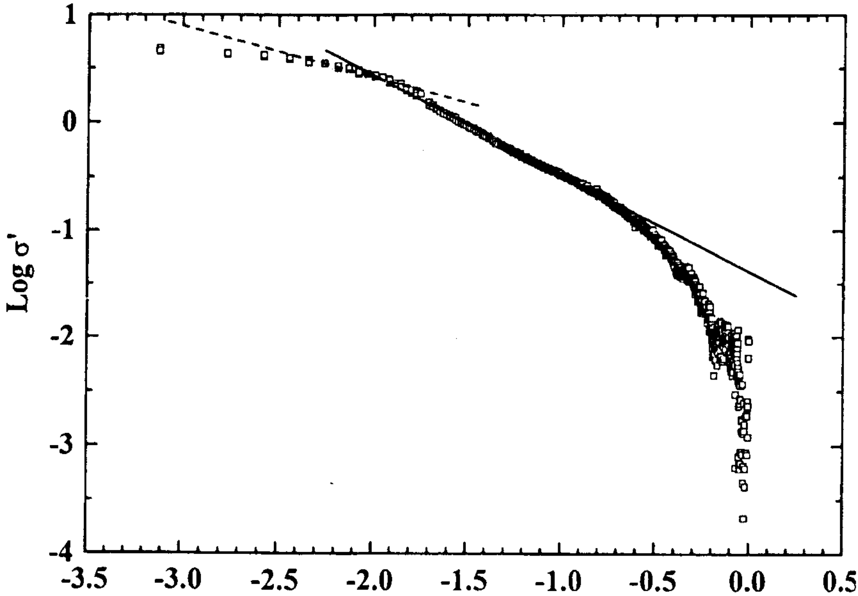

Fig. 2. Excess conductivity σ' vs $(T - T_{GL})/T_{GL}$ in a ln – ln scale. The solid line represents 2D Aslamazov–Larkin result with $T_{GL} = 106.2$ K, $C_2 = 3.28$ mΩ^{-1}; the dashed line represents 3D result with the same T_{GL} and $C_3 = 30.72$ mΩ^{-1}

theoretical functional form for excess conductivity is:

$$\sigma_{fl} = C_d \epsilon^{-n} \tag{1}$$

where $\epsilon = \ln(T/T_{GL}) \approx (T - T_{GL})/T_{GL}$, when $T - T_{GL} \ll T_{GL}$. In 2D case $C_2 = e^2/16s\hbar$, $n = 1$ and in 3D case $C_3 = e^2/16r^{1/2}s\hbar$, $n = 1/2$ (e is the electron charge, s is the effective interplane distance). r is a parameter characterizing the dimensional crossover from 2D to the 3D regime in the thermodynamic fluctuation behavior [11]: $r(T_{GL}) = 4\xi_c^2(0)/s^2$ with $\xi_c(0)$ being the zero-temperature Ginzburg–Landau coherence length in the c – axis direction. The measured excess conductivity $\sigma' = R^{-1}(T) - R_N^{-1}(T)$, where $R_N(T)$ is the normal-state resistance extrapolated from high temperatures, vs ϵ is shown on a ln – ln scale in Fig. 2. The features of this plot are: (i) the 2D behavior of fluctuation conductivity in the range of reduced temperatures $0.01 < \epsilon < 0.2$; (ii) the deviation from the form given by Eq. (1) at $\epsilon > 0.2$ which is a manifestation of dynamical corrections to the 2D paraconductivity found in Refs. [12]; (iii) the clear crossover to the 3D regime takes place as the temperature approachs T_{GL}. The fit of experimental data with Eq. (1) in 2D ($n = 1$) and 3D ($n = 1/2$) regimes gives: $T_{GL} = 106.2 \pm 0.1$ K, $C_2 = 3.28 \pm 0.01$ mΩ^{-1} and $C_3 = 30.72 \pm 0.04$ mΩ^{-1}. It is worth emphasizing that the irregular geometry of the platelet does not allow us to evaluate the absolute value of resistivity, therefore we are not able to extract the interplane distance from coefficients C_2 and C_3 using Eq. (1). Nethertheless we can estimate the r parameter from the ratio: $r(T_{GL}) = (C_2/C_3)^2 = 0.011$. The parameter r is directly related to the interlayer quasiparticle hopping energy J

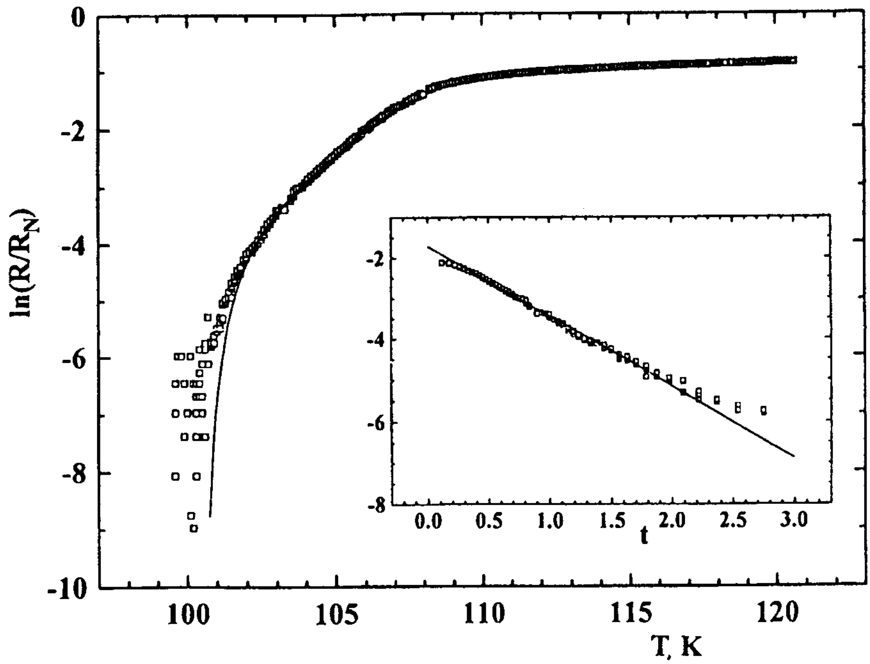

Fig.3. Temperature dependence of resistivity below T_{GL} in $\ln(R/R_N)$ vs temperature plot. Solid line represents the best fit with the Eq. (3) with $T_{KT} = 100.43\,\mathrm{K}$, $A = 1.84$, $b = 0.66$ The inset shows the $\ln(R/R_N)$ vs reduced temperature $t = [(T_{GL} - T)/(T - T_{KT})]^{1/2}$ plot

[14]:

$$\tau = -2\frac{J^2}{T^2}F(T\tau), \quad F(x) = x^2\left(\psi\left(\frac{1}{2} + \frac{1}{4\pi x}\right) - \psi\left(\frac{1}{2}\right) - \frac{1}{4\pi x}\psi'\left(\frac{1}{2}\right)\right) \tag{2}$$

with τ being quasiparticle scattering time, $\psi(x)$ and $\psi'(x)$ are the digamma function and its derivative respectively. Assuming for temperatures close to T_{GL} $T\tau \approx 0.5 - 1$, in accordance with values for other high-T_c cuprates [13, 6, 14], and taking into account, that the function $F(T\tau)$ changes slowly in this region (i.e. $F(0.5) = 0.0046$, while $F(1) = 0.0042$), we find for our case from Eq. (2) $J \approx 25 - 30\,\mathrm{K}$.

Our next step is to fit the resistance data below T_{GL} using the Coulomb gas analogy of vortex fluctuations introduced by Minnhagen [15]. The interpretation of resistivity data below T_{GL} in two-dimensional superconductors is based on the following ingredients: the analogy between the physics of the Coulomb gas of particles and vortices in 2D superconductor, KT charge-unbinding renormalization theory and Bardeen–Stephen model of flux-flow resistivity [15]. This approach was checked to describe satisfactory the resistivity of "old" 2D superconductors as well as high-T_c cuprates below the mean-field critical temperature [16, 6]. Within the context of this model the resistance at the edge of the transition satisfies the scaling relation [17, 15]:

$$\frac{R}{R_N} = A \exp\left[-2b\left(\frac{T_{GL} - T}{T - T_{KT}}\right)^{1/2}\right]. \tag{3}$$

Here A and b are nonuniversal constants of order unity which depend on the sample characteristics. Eq. (2) describes the resistivity of the 2D superconductor in the temperature range between T_{KT} and T_{GL} and therefore can be applied to high-T_c cuprates only as far as effects of interlayer coupling are negligible. Recently the problem of vortex fluctuations in quasi-2D superconductors (with finite Josephson coupling between layers) was widely discussed [18]. It was found that vortices can be considered as two-dimensional only if the temperature exceeds the characteristic temperature:

$$T^* = T_{KT} + \frac{T_{GL} - T_{KT}}{1 + \frac{1}{b^2}\ln^2(\gamma s/\xi_{ab})} \qquad (4)$$

(ξ_{ab} is the Gizburg–Landau in-plane coherence length), so for temperatures $T^* < T < T_{GL}$ Eq. (2) is still justified, while at lower temperature a more comprehensive theory is required.

In Fig. 3 we have plotted the behavior of $\ln(R/R_N)$ as a function of temperature. Inset shows the same data in the $\ln(R/R_N)$ vs reduced temperature $[(T_{GL} - T)/(T - T_{KT})]^{1/2}$ plot. A good agreement with the Eq. (2) is evident for temperatures from 106 K down to approximately 102 K. Fitting of data with Eq. (2) within the temperature range 102 – 106 K provides: $T_{KT} = 100.43$ K, $A = 1.84 \pm 0.09$, $b = 0.66 \pm 0.09$. However below 102 K the deviation from 2D behavior was found in analogy with the same analisys on 2212 BSSCO epitaxial films [6]. We attribute this deviation to the crossover from 2D to 3D vortex configuration [19]. The rough estimate of γ parameter from the Eq. (3) taking $T^* \approx 102$ K implies $\gamma \approx 50$ (we adopt $s \approx \xi_{ab}(0)$).

Let us discuss the results obtained. The main issue is the consistency of our data with the AL theory of paraconductivity above T_{GL} and the Coulomb gas analogy for 2D vortex fluctuations modified to take into account the weak coupling between superconducting layers below T_{GL}. The parameters we extracted from the fits of data with the above theories are: $T_{GL} = 106.2$ K, $T_{KT} = 100.4$ K, $J = 25 - 30$ K and $\gamma \approx 50$. The last estimate corresponds roughly to the γ factor found for 2212 BSCCO samples after thermal treatments in oxydizing athmosfere, but is significally lower than for as-grown samples [19]. For the reduced intrinsic width of the transition we get: $\tau_c = 0.054$ which is close to the values found earlier for a number of high-T_c compounds [5, 6]. The important parameters which, according to our knowledge, we found for the first time are the anisotropy factor γ and effective interlayer hopping energy J. Comparing these values with those for the 2212 BSSCO phase one has to take into account that the effective anisotropy in Bi – based cuprates is extremely sensitive to the oxygen content [19], so such a comparison could make sense only between samples which are in close oxigenation states. Nevertheless it seems from the data that 2223 BSCCO phase is somewhat less anisotropic than 2212 BSSCO phase, because the clear 2D-3D crossover in fluctuation conductivity was never observed in the latter. The analysis of data below T_{GL} confirms the scenario with KT transition in the system of 3D vortex lines with their further dissociation into 2D pancakes at temperature T^*. Summarizing we have found, that the pecularities of the resistive transition in 2223 BSCCO phase are consistent with the predictions of the fluctuation theory both above and below the mean-field critical temperature.

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1. D.H.Kim, A.M.Goldman, J.H.Kang et al., Phys. Rev. B **39**, 12275 (1989); G.Balestrino, M.Marinelli, E.Milani et al., Phys. Rev. B **46**, 14919 (1992).
2. G.Balestrino, M. Marinelli, E. Milani et al., Phys. Rev. B **47**, 6037 (1992).
3. D.R.Nelson, Phys. Rev. Lett. **60**, 1973 (1988); E.H.Brandt, Phys. Rev. Lett. **63**, 1106 (1989); L.I.Glazman and A.E.Koshelev, Phys. Rev. B **43**, 2835 (1991).
4. J.M.Kosterlitz and D.J.Thouless, J. Phys. C **6**, 1181 (1973); J.M.Kosterlitz, J. Phys. C **7**, 1046 (1974); V.L.Berezinskii, Sov. Phys. JETP **34**, 610 (1972).
5. S.Martin, A.T.Fiory, R.M.Fleming et al., Phys. Rev. Lett. **62**, 677 (1989); D.H.Kim, A.M.Goldman, J.H.Kang, and R.T.Kampwirth, Phys. Rev. B **40**, 8834 (1989); D.P.Norton and D.H.Lowndes, Phys. Rev. B **48**, 6460 (1993).
6. G.Balestrino, D.V.Livanov, and M.Montuori, Physica C **226**, 320 (1994).
7. J.R.Clem, Phys. Rev. B **43**, 7837 (1991); L.N.Bulaevskii, S.V.Meshkov, and D.Feinberg, Phys. Rev. B **43**, 3728 (1991).
8. G.Balestrino, E.Milani, A.Paoletti et al., Appl. Phys. Lett. **64**, 1735 (1994).
9. F.Fontana, V.Persico and M.Valentino, Rev. Sci. Instrum. **65**, 1 (1994) (under patenting).
10. L.G.Aslamazov and A.I.Larkin, Phys. Lett. A **26**, 238 (1968).
11. R.A.Klemm, J. Low Temp. Phys. **16**, 381 (1974); L.G.Aslamazov and A.A.Varlamov, J. Low Temp. Phys. **38**, 223 (1980).
12. L.Reggiani, R.Vaglio, and A.A. Varlamov, Phys. Rev. B **44**, 9541 (1991).
13. G.Balestrino, E.Milani, and A.A.Varlamov, Physica C **210**, 386 (1993).
14. V.V.Dorin, R.A.Klemm, A.A.Varlamov et al., Phys. Rev. B **48**, 12051 (1993).
15. P.Minnhagen, Rev. Mod. Phys. **59**, 1001 (1987).
16. P.Minnhagen, Phys. Rev. B **24**, 6758 (1981); A.T.Fiory, A.F.Hebard, and W.I.Glaberson, Phys. Rev. B **28**, 5078 (1983); P.Minnhagen, Sol. St. Comm. **71**, 25 (1989).
17. B.I.Halperin and D.R.Nelson, J. Low Temp. Phys. **36**, 599 (1979).
18. D.I.Glazman and A.I.Koshelev, Sov. Phys. JETP **70** 774 (1990); L.N.Bulaevskii, M.Ledvij, and V.G.Kogan, Phys. Rev Lett **68**, 3773 (1992).
19. G.Balestrino, D.V.Livanov, and M.Montuori, unpublished; G.Balestrino, D.V.Livanov, E.Milani et al., Phys. Rev. B **50**, 3446 (1994).