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Non-Ohmic behaviour and phase transitions in $YBa_2Cu_3O_{7-\delta}$ with high normal resistivity

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Abstract. The electrical resistivity in polycrystalline $YBa_2Cu_3O_{7-\delta}$ with high normal resistivity has been investigated extensively in the temperature range $78 \leqslant T \leqslant 100$ K by the four-probe method. The electrical resistivity exhibits four pronounced features: (i) the resistivity ρ is independent of the current density above $T_{c0} = 92.24$ K; (ii) for 84 K $< T < T_{c0}$ the I–V relation deviates slightly from Ohm's law, but if it is approximated by $V \simeq \alpha_1 I$, the parameter α_1 can be described by $\alpha_1 \simeq \exp[-2|b(T_{c0} - T_c)/(T - T_c)|^{1/2}]$, with $T_c = 78.9$ K and $b = 3.2$; (iii) in the temperature range $T_c < T < 84$ K the I–V relation deviates strongly from Ohm's law and has the form $V \simeq I^{a(T)}$, where the exponent $a(T)$ increases with decreasing temperature and reaches $a \simeq 3$ at T_c; and (iv) below T_c, the resistivity ρ is reduced to zero. The non-Ohmic behaviour of this compound with high normal resistivity may be explained qualitatively in terms of current-induced dissociation of bound vortex pairs occurring in islands inside the 2D CuO layers. The two phase transitions of this compound at T_{c0} and T_c may be explained in terms of a model used to describe the phase transitions of the stage-2 $CoCl_2$–graphite intercalation compounds at $T_{cl} = 8.0$ K and $T_{cu} = 9.2$ K, where islands play important roles.

1. Introduction

Non-Ohmic behaviour of the electrical resistivity in $YBa_2Cu_3O_{7-\delta}$ near the superconducting transition temperature has been a subject of much interest, both theoretical and experimental. This non-Ohmic behaviour of ρ has been explained in terms of current-induced dissociation of bound vortex pairs. The existence of these bound pairs is characteristic of the Kosterlitz–Thouless (KT) phase transition (Kosterlitz 1974), which is predicted to occur in 2D XY systems, including the 2D superfluids, 2D superconductors and 2D XY spin systems such as the stage-2 $CoCl_2$–graphite intercalation compound (GIC).

Recently several groups have reported the non-Ohmic behaviour of $YBa_2Cu_3O_{7-\delta}$ near the superconducting transition temperature. Sugahara *et al* (1987) have reported such a non-Ohmic behaviour for a polycrystalline Y–Ba–Cu–O compound. They show that (i) the ln ρ data can be described as a linear function of $(T - T_c)^{-1/2}$ in the temperature range $T_c < T \leqslant T_{c0}$ where $T_c = 84.98$ K and $T_{c0} = 88.1$ K (90% of fully normal resistivity) and (ii) the I–V relation ($V \simeq i^{a(T)}$) is Ohmic ($a = 1$) for $T > T_c$ and on approaching T_c, the exponent $a(T)$ rapidly increases and reaches $a = 3$ at $T = T_c$. They conclude that the non-Ohmic behaviour in this compound can be explained by the theory of Halperin and Nelson (1979) developed for the resistive transition in superconducting films.

Dubson *et al* (1988) have reported non-Ohmic behaviour in polycrystalline $YBa_2Cu_3O_{7-\delta}$ samples that is different from that obtained by Sugahara *et al* (1987). Above T_{c0} (=91.3 K), the I–V relation exhibits an Ohmic behaviour ($a = 1$). The exponent $a(T)$ increases from $a = 1$ with decreasing temperature below T_{c0} and diverges at T_c (=89.8 K). Below T_c, the system behaves as a conventional superconductor with non-zero critical current. Dubson *et al* (1988) find that the exponent $a(T)$ can be expressed as $a(T) = \exp[A(T_{c0} - T_c)/(T - T_c)]$ with $A = 0.3$. Stamp *et al* (1988) show from resistivity measurements for single-crystal $YBa_2Cu_3O_{7-\delta}$ that: (i) the exponent $a(T)$ is nearly equal to unity above 83 K, increases rapidly with increasing temperature, and reaches the value 8.2 at 79.4 K; (ii) the resistivity ρ_{ab} above T_c ($\simeq$80 K) can be described as a linear function of $(T - T_c)^{-1/2}$, and (iii) 3D superconductivity has set in at 76 K. Thus it is concluded from these studies that the non-Ohmic behaviour near the superconducting transition temperature is a common feature of $YBa_2Cu_3O_{7-\delta}$, irrespective of whether the sample is a single crystal or polycrystalline. However, the details of this non-Ohmic behaviour seem to depend strongly on the sample used in the experiment—in particular the temperature separation between T_c and T_{c0}. According to a relation derived by Beasley *et al* (1979) for dirty superconducting films, the $YBa_2Cu_3O_{7-\delta}$ sample with high normal resistivity is expected to exhibit a broad resistivity tail between T_c and T_{c0}. Here it is assumed that the value of normal resistivity gives a measure for the degree of distribution of Cu and O atoms inside the CuO layers. In the compound with high normal resistivity, the 2D CuO layers are assumed to consist of small islands. The island size drastically increases as the normal resistivity decreases. A sample with low normal resistivity may have a perfect alignment of Cu and O atoms inside the CuO layers. In this paper, we have undertaken an extensive study of the I–V relation in polycrystalline $YBa_2Cu_3O_{7-\delta}$ with high normal resistivity near the superconducting transition temperature. The use of this compound makes it easy to study the I–V relation in detail because of the broad resistivity tail between T_c and T_{c0}. The I–V relation will be carefully discussed in light of the KT phase transition with finite-size effects.

Our main interest lies in the origin of the two phase transitions in $YBa_2Cu_3O_{7-\delta}$ samples with high normal resistivity which are assumed to have small islands inside the 2D CuO layers. These islands may be coupled to each other through weak intra-planar Josephson coupling J. If the inter-planar coupling J' between the adjacent 2D CuO layers is very weak compared with J, the phase transition of $YBa_2Cu_3O_{7-\delta}$ with high normal resistivity is expected to be very similar to that of the stage-2 $CoCl_2$–GIC. This GIC is known to behave magnetically like a quasi-2D XY ferromagnet. The intercalate $CoCl_2$ layers are formed of islands which are around 400–800 Å in diameter. This compound also undergoes two phase transitions at T_{cl} (=8.0 K) and T_{cu} (=9.2 K). We will discuss the 2D and 3D ordering of superconductivity in $YBa_2Cu_3O_{7-\delta}$ with high normal resistivity in analogy with the 2D and 3D spin ordering in the stage-2 $CoCl_2$–GIC (Suzuki *et al* 1983, Wiesler *et al* 1987, 1988).

2. Experimental details

The sample was prepared by annealing a mixture of powdered Y_2O_3, $BaCO_3$ and CuO in the ratio 1 : 4 : 6, in air at 920 °C for 18 h. The 5 g sample was pelletised under a pressure of 1.05 kg cm^{-2}. Then the pellet was annealed in oxygen flowing at the rate of 0.006 L min^{-1}, at 920 °C for 18 h. The sample was cooled to room temperature in the furnace at the rate of 50 °C h^{-1}. For resistivity measurements, the pellet was shaped into a rectangular form with width 0.43 cm, thickness 0.42 cm and length 1.78 cm.

Electrical resistivity measurements were made by a four-probe method. The sample was wrapped with aluminium foil with four square holes for four electrodes on the side surfaces of the sample. These electrodes were formed by evaporation of indium through four holes using a Veeco VEM-776 high-vacuum evaporator. Copper wires (0.6 mm in diameter) were connected to the four electrodes by indium solder without flux. The constant current density through the sample was maintained by a current source (Keithley type 225) connected to the two current probes. The voltage produced between the two voltage probes was measured by a nanovoltmeter (Keithley type 181). The temperature of the sample was measured by a Pt resistor installed inside a copper heat sink. The normal electrical resistivity of this compound is $\rho_N = 19.1$ mΩ cm at $T_{c0} = 92.24$ K and 31 mΩ cm at 300 K.

In the conventional four-probe method, two current probes are attached to both of the end surfaces of the rectangular sample, so that the current can flow along the direction parallel to the side surface, from one end surface to the other end surface. In the present work, the current and voltage probes are attached on one of the side surfaces for the convenience of making four electrodes at the same time by evaporation. The current is emitted from one of the current probes and focused at the other current probe on the same side surface. The current may not flow homogeneously through the sample. Since the effective cross section is much smaller than the cross section ($A = 18.1 \times 10^{-2}$ cm^2), the real value of the resistivity is considered to be smaller than the value of ρ calculated from the expression $\rho = (V/I)(A/d)$, where d is the distance between two voltage probes ($d = 0.55$ cm).

3. Background

3.1. Non-Ohmic resistivity due to the dissociation of vortex pairs below T_c

The Hamiltonian of the 2D superconductor is exactly the same as that of the KT theory originally developed for the 2D *XY* spin system (Kosterlitz 1974, Halperin and Nelson 1979). At temperatures below the KT transition temperature T_c, the system is formed of bound vortex–anti-vortex pairs. At $T = T_c$, the vortex pairs begin to unbind. The vortex and the anti-vortex attract each other. The attractive force between vortex pairs is given by

$$F_R(r) = -\partial U_R/\partial r = -\pi n_s \hbar^2/2mr. \tag{1}$$

Here U_R is the vortex–anti-vortex pair energy,

$$U_R(r) = 2E_c + (\pi n_s \hbar^2/2m)\ln(r/\xi) \tag{2}$$

where n_s is the superconducting electron density, m is the electron mass, E_c is the vortex core energy and ξ is the effective vortex core radius. The supercurrent density J_s exerts Lorentz forces on vortices given by

$$F_L = (1/c)\varphi_0 J_s \tag{3}$$

where $\varphi_0\,(=\pi\hbar c/e)$ is the flux quantum and J_s is defined by $J_s = en_s v_s$. Equation (3) also means that the current gives rise to the magnetic induction $B = n_s \varphi_0$ in the dissociation of bound vortex pairs. The direction of the force is opposite for vortices of opposite sign. When the Lorentz force becomes larger than the force of mutual attraction of the vortex pair ($F_R(r) \leqslant F_L$ for $r \geqslant r_c$), the vortex pair can be regarded as two free vortices. The value of the characteristic length r_c is estimated from

$$r_c = \hbar/2mv_s = e\hbar n_s/2mJ_s. \tag{4}$$

In the limit where $\xi \ll r_c < \xi_+$ corresponding to the condition $J_1 < J_s \ll J_0$, we have

$$U_R(r_c) \simeq 2E_c - (\pi n_s \hbar^2/2m) \ln(J_s/J_0) \tag{5}$$

where $J_0 = e\hbar n_s/2m\xi$, $J_1 = e\hbar n_s/2m\xi_+$, and ξ_+ is the average distance between free vortices, to be defined later. The generation rate of free vortices by dissociation of bound vortex pairs, Γ_e, is given by

$$\Gamma_e \simeq \exp(-U(r_c)/k_B T) = (J_s/J_0)^{\pi n_s \hbar^2/2mk_B T} \exp(-2E_c/k_B T). \tag{6}$$

The density of free vortices n_f in the equilibrium state is determined by the balance between the generation rate and recombination rate given by n_f^2:

$$n_f \simeq \Gamma_e^{1/2} = (J_s/J_0)^{\pi K_R} \exp(-E_c/k_B T) \tag{7}$$

where $\pi K_R = \pi n_s \hbar^2/4mk_B T$.

Since the resistivity ρ can be expressed thus:

$$\rho/\rho_n = 2\pi\xi^2 n_f \tag{8}$$

where ρ_n is the normal resistivity, the I–V relation can be derived as

$$V \sim I^{a(T)} \tag{9}$$

for $J_1 < J_s \ll J_0$, where the exponent $a(T)$ is defined by $a(T) = \pi K_R + 1$. According to the KT theory, the renormalised stiffness constant πK_R undergoes a 'universal jump' at T_c, $\pi K_R(T_c) = 2$. Then the exponent $a(T)$ is predicted to change from $a = 1$ to $a = 3$ at $T = T_c$ on approaching T_c from the high-temperature side.

3.2. *Ohmic resistivity from free vortices above T_c*

Above T_c, essentially all the bound vortex pairs are dissociated into free vortices without current density. The density of the free vortices can be estimated as

$$n_f = C_1/2\pi\xi_+^2 \tag{10}$$

where C_1 is a constant and ξ_+ is the average distance between free vortices. The correlation length ξ_+ is given by

$$\xi_+ = C\xi \exp(|b\tau_c/\tau|^{1/2}) \tag{11}$$

where b and C are dimensionless constants of order unity, $\tau = (T - T_c)/T_c$ and $\tau_c = (T_{c0} - T_c)/T_c$. Then the I–V relation is given by

$$V/I \simeq (\xi/\xi_+)^2 \simeq \exp(-2|b\tau_c/\tau|^{1/2}). \tag{12}$$

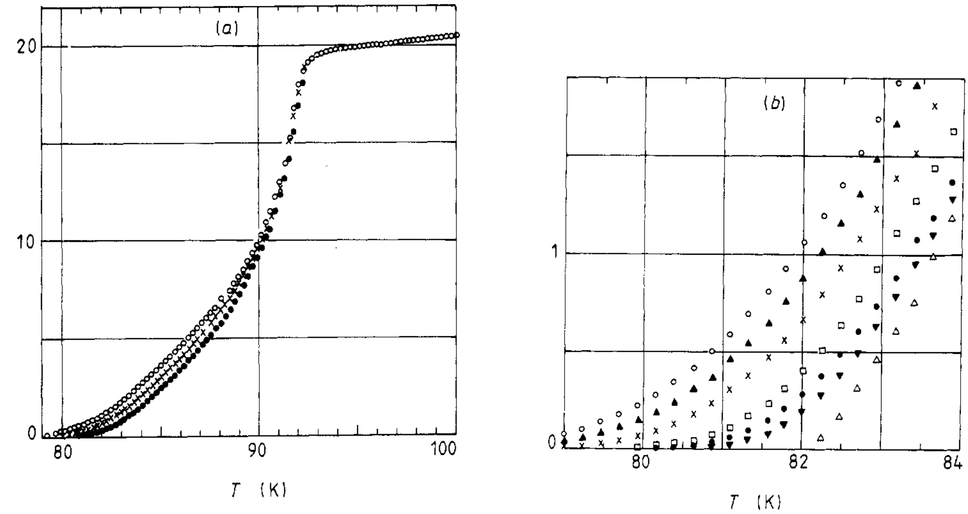

Figure 1. (*a*) The electrical resistivity ρ in $YBa_2Cu_3O_{7-\delta}$ as a function of temperature ($79 \leqslant T \leqslant 100$ K) for several current densities: $J = 55.4$ (●), 277 (×) and 554 mA cm^{-2} (○). (*b*) Detail of ρ versus T in the temperature range $79 \leqslant T \leqslant 84$ K for various current densities: $J = 3.3$ (△), 27.7 (▼), 55.4 (●), 111 (□), 277 (×), 415 (▲) and 554 mA cm^{-2} (○).

4. Results and discussion

We have measured the electrical resistivity ρ in polycrystalline $YBa_2Cu_3O_{7-\delta}$ as a function of temperature, where the current density flowing through the sample is chosen as the parameter. The electrical resistivity ρ is defined as $\rho = (V/I)(A/d)$, where V is the voltage across the sample, and I is the current through the sample. Figure 1(*a*) shows examples of ρ as a function of temperature for the current densities $J = I/A = 55.4$, 277 and 544 mA cm^{-2} in the temperature range $79 \leqslant T \leqslant 100$ K. The resistivity ρ does not depend on the current density J above $T_{c0} = 92.24$ K and is a linear function of temperature in the temperature range $100 \leqslant T \leqslant 300$ K, which is a characteristic feature of high-temperature superconductors. We note that the electrical resistivity ratio from 300 K to T_{c0} is 1.6. Just below T_{c0}, the resistivity becomes dependent on the current density and decreases with decreasing temperature. The resistivity has a broad tail in the temperature range $79 \leqslant T \leqslant T_{c0}$. The temperature width of the tail seems to depend on the normal resistivity of samples: $\Delta T = T_{c0} - T_c = 3.12$ K (Sugahara *et al* 1987), 1.5 K (Dubson *et al* 1988) and $\simeq 3$ K (Stamp *et al* 1988). Now we discuss the relationship between the normalised temperature width τ_c $(=(T_{c0} - T_c)/T_c)$ and normal resistivity ρ_n at T_{c0}. According to Beasley *et al* (1979), the normalised temperature width τ_c is given by

$$\tau_c = 0.17\,\rho_N/R_c t \tag{13}$$

where $R_c = \hbar/e^2 = 4114\ \Omega$ and t is an effective thickness of the 2D superconductor. This relation is also supported by the data on T_{c0}, T_c and ρ_N for various kinds of superconducting cuprate perovskite (Murphy *et al* 1987). When t is a repeat distance along the c axis ($t = 11.677$ Å) and $\rho_N = 19.1$ mΩ cm at T_{c0}, the value of τ_c is estimated as $\tau_c = 0.144$ with $T_c = 78.9$ K, as will be derived later. We have $\tau_c = 0.144$ if $t = 550$ Å. Murphy *et al* (1987) has reported data on T_{c0}, T_c and ρ_N for $YBa_2Cu_3O_{6.9}$: $T_{c0} = 93.5$ K,

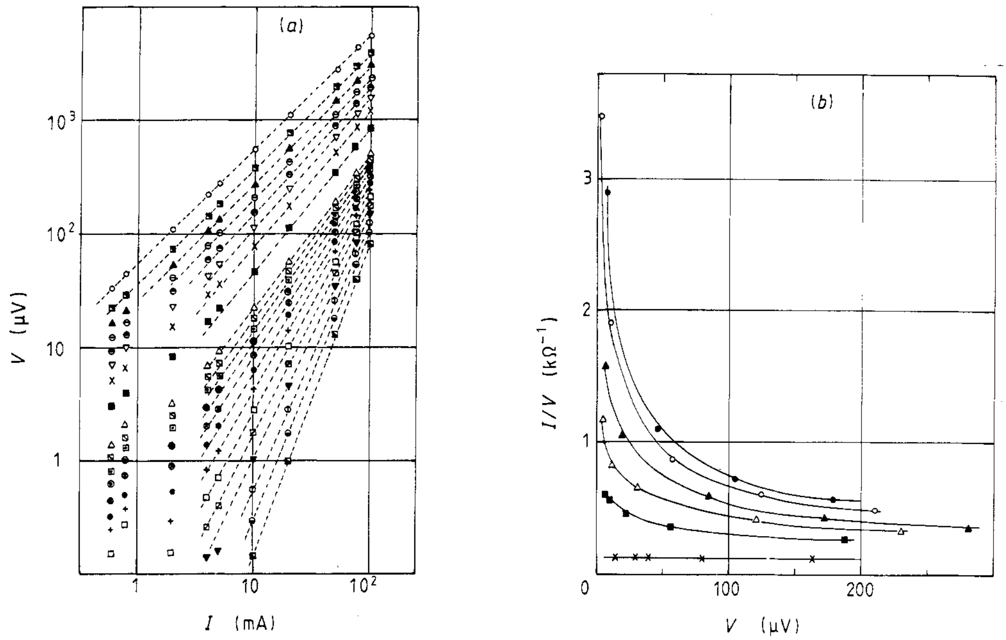

Figure 2. (a) The relation between I and V for various temperatures: $T = 92.24$ (○), 91.07 (◪), 89.91 (▲), 88.75 (⊖), 87.59 (◓), 86.42 (▽), 85.26 (×), 84.10 (■), 82.94 (△), 82.71 (⧅), 82.48 (◫), 82.25 (⊙), 82.02 (⊗), 81.78 (●), 81.55 (+), 81.32 (□), 81.09 (⊠), 80.86 (▼), 80.63 (⦶), 80.39 (◒) and 80.16 K (◩). (b) The current–voltage ratio I/V as a function of voltage V for several temperatures. $J = I/S$ with $S = 18.1 \times 10^{-2}$ cm^2 and $E = V/d$ with $d = 0.55$ cm. $T = 81.09$ (●), 81.32 (○), 81.70 (▲), 82.25 (△), 84.10 (■) and 85.26 K (×).

$T_c = 91$ K and $\rho_N = 260\ \mu\Omega$ cm. Then the value of t is estimated as $t = 39$ Å. This value is also larger than the repeat distance along the c axis. Thus it may be concluded that t should be much larger than the repeat distance for $YBa_2Cu_3O_{7-\delta}$.

Here we assume that the 2D CuO layers are composed of islands for $YBa_2Cu_3O_{7-\delta}$ compounds with high normal resistivity. If the mean free path of electrons is limited by the size of islands, L_0, the normal resistivity ρ_N may be expressed as

$$\rho_N = 12\pi^3\hbar/e^2 S_F L_0 \tag{14}$$

where S_F is the area of the Fermi surface. It may be concluded that τ_c is inversely proportional to the size of islands L_0.

The detailed behaviour of the resistivity tail also depends on the current density, as a consequence of the non-Ohmic behaviour of the I–V relation. Figure 1(b) shows the behaviour of ρ as a function of temperature in the temperature range $79 \leqslant T \leqslant 48$ K for various current densities ($3.3 \leqslant J \leqslant 554$ mA cm^{-2}). The superconducting transition temperature, below which the resistivity is reduced to zero, decreases as the current density increases.

Figure 2(a) shows the voltage across the sample as a function of current for various temperatures. The notable feature is that on a log–log plot the set of curves tends to fit a straight line over a large range of currents and voltages. This linear fit on a log–log plot means that the voltage varies as a power of the current I, i.e. $V \simeq I^{a(T)}$, where $a(T)$ is an

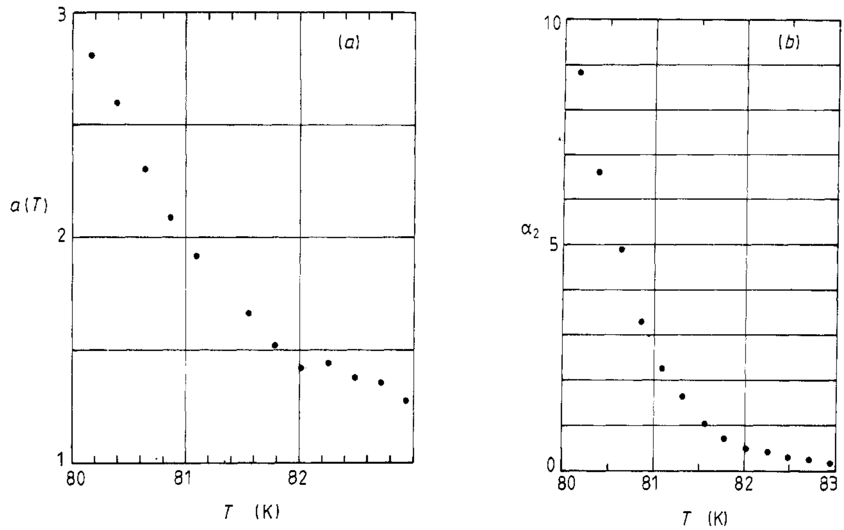

Figure 3. (a) The exponent $a(T)$ (where $V \sim I^{a(T)}$) and (b) the parameter α_2, as functions of temperature for $80 \leqslant T \leqslant 83$ K, where $I/V \simeq \alpha_2 V^{-(1-1/a)}$ with I and V in units of mA and μV, respectively.

exponent that is a function of temperature and increases with decreasing temperature. The ratio I/V can be expressed as

$$I/V = \alpha_2 V^{-(1-1/a)} \tag{15}$$

where α_2 is a temperature-dependent parameter. The data are least-squares fitted to equation (15) to determine α_2 and $a(T)$. It is found that: (i) the exponent $a(T)$ has $a = 3$ at 80 K decreasing to unity with increasing temperature, as shown in figure 3(a), and (ii) α_2 decreases with increasing temperature and is nearly equal to zero at 84 K, as shown in figure 3(b). Thus it follows that a remarkable non-Ohmic behaviour in the I–V relation is observed in the temperature range close to 80 K. The transition temperature T_c is determined in the following way. For $84 \leqslant T \leqslant T_{c0}$, the resistivity is still very weakly dependent on the current density. The data on ρ in the temperature range $84 \leqslant T \leqslant 90$ K are least-squares fitted to equation (12):

$$\ln \rho = -2|b(T_{c0} - T_c)|^{1/2}/(T - T_c)^{1/2} + \text{constant}. \tag{16}$$

Figure 4 shows a plot of $\ln \rho$ for $J = 11.1$ mA cm^{-2} as a function of $(T - T_c)^{-1/2}$ with $T_c = 78.9$ K. Evidently the data on $\ln \rho$ versus $(T - T_c)^{-1/2}$ fit a straight line very well. The value of b is estimated as $b = 3.2$ for $T_{c0} = 92.24$ K. Least-squares fitting of data for several current densities to equation (16) indicates that T_c has some variation in value around $T_c = 78.9$ K. However, there seems to be no correlation between T_c and the current density J. It is found from figure 3(a) that the exponent $a(T)$ is nearly equal to $a = 3$ around 80 K. The HN theory predicts that $a(T)$ decreases discontinuously from $a = 3$ at $T = T_c$ to $a = 1$ for $T > T_c$. Our result in figure 3(a) shows that $a(T)$ decreases gradually from $a = 3$ to $a = 1$ with increasing temperature for $80 \leqslant T \leqslant 84$ K.

The $YBa_2Cu_3O_{7-\delta}$ compound with high normal resistivity may undergo two phase transitions at T_c and T_{c0}. The low-temperature phase below T_c is the superconducting phase with zero resistivity. The intermediate phase between T_{c0} and T_c shows a non-Ohmic behaviour. The high-temperature phase above T_{c0} shows an Ohmic behaviour.

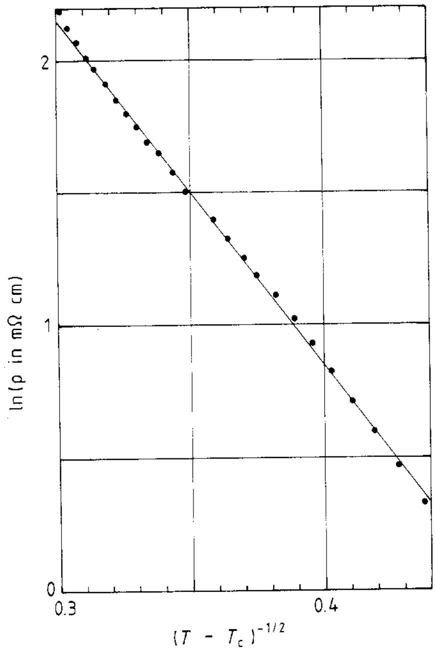

Figure 4. A plot of ln ρ as a function of $(T - T_c)^{-1/2}$ with $T_c = 78.9$ K for the case where $J = 11.1$ mA cm^{-2}.

The origin of the two phase transitions in $YBa_2Cu_3O_{7-\delta}$ with high normal resistivity at T_{c0} and T_c may be closely related to the assumption that the 2D CuO layers are composed of islands whose size is inversely proportional to the normal resistivity (equation (14)). The phase transitions of this compound may be very similar to that of the stage-2 $CoCl_2$ GIC, which behaves magnetically like a quasi-2D XY ferromagnet and undergoes two magnetic phase transitions at T_{cl} (=8.0 K) and T_{cu} (=9.2 K). Below T_{cu}, the 2D spin ordering occurs locally inside the islands. Spin correlation between islands develops with decreasing temperature. The divergence of the spin-correlation length in the $CoCl_2$ layers gives rise to effectively large inter-planar antiferromagnetic exchange interaction between adjacent $CoCl_2$ layers. Below T_{cl}, the $CoCl_2$ layers are stacked antiferromagnetically along the c axis. This ordering has a purely 3D character and has been revealed through magnetic neutron scattering from stage-2 $CoCl_2$ GIC based on a single crystal of Kish graphite (Suzuki *et al* 1983, Weisler *et al* 1987, 1988).

Now we discuss the phase transitions of $YBa_2Cu_3O_{7-\delta}$ with high normal resistivity at T_{c0} and T_c in analogy with the phase transitions of stage-2 $CoCl_2$ GIC at T_{cu} and T_{cl}. Just below T_{c0}, the superconducting phase coherence may be established inside islands of the 2D CuO layers. The individual islands are composed of the superconducting regions with no phase coherence between islands. The size of isolated islands, L_0, may be smaller than the correlation length ($\xi_+(T)$) which is predicted from the ideal KT theory: $\xi_+(T_{c0}) = C\xi \exp(b^{1/2}) \simeq 6\xi$ with $b = 3.2$. On approaching T_c from the high-temperature side, isolated islands are coupled through the intra-planar Josephson coupling J to an effective island formed of a set of islands with the same phase coherence. The size of effective islands, $L_{eff}(T)$, may be still smaller than the predicted value of $\xi_+(T)$. Just above T_c, the value of $L_{eff}(T)$ becomes of the same order as $\xi_+(T)$. Then the phase of this compound may coincide with the high-temperature phase of the KT theory. The following two conditions should be satisfied for the occurrence of the non-Ohmic behaviour due to the dissociation of bound vortex pairs: $L_{eff}(T) \simeq \xi_+(T)$ and

$\xi \ll r_c < \xi_+(T)$. These conditions may be satisfied below 84 K, because the parameter α_2, which is a measure of non-Ohmic behaviour, is not zero below 84 K. The effective inter-planar Josephson coupling $J'_{\mathrm{eff}}(T)$ between the adjacent 2D CuO layers can be described thus:

$$J'_{\mathrm{eff}}(T) \simeq J'(L_{\mathrm{eff}}(T)/a_0)^2 \tag{18}$$

where a_0 is a lattice constant and J' is the intrinsic inter-planar Josephson coupling. Very close to T_c, $J'_{\mathrm{eff}}(T)$ becomes very large because of the divergence of $L_{\mathrm{eff}}(T)$. At $T = T_c$, the superconducting phase coherence between the adjacent 2D CuO layers may be established. Then the low-temperature phase below T_c corresponds to a purely 3D superconducting phase with zero resistivity. There may be no bound vortex pairs that are characteristic of the 2D KT ordered phase. The fact that the exponent $a(T)$ becomes $a(T) = 3$ at $T = T_c$ is not inconsistent with a crossover of ordering from 2D to 3D at $T = T_c$. Just at T_c the system seems to be in the 2D KT ordered phase. The crossover of ordering from 2D to 3D may be determined mainly by the divergence of $L_{\mathrm{eff}}(T)$. If the divergence of $L_{\mathrm{eff}}(T)$ is not limited by the size of islands, the crossover may occur at a temperature just below T_{c0}. This is the case for $YBa_2Cu_3O_{7-\delta}$ with low normal resistivity. In this case, non-Ohmic behaviour can be observed in a very narrow temperature range close to T_{c0}.

Finally, it should be noted that the ordering process as described above is valid only for $YBa_2Cu_3O_{7-\delta}$ with high normal resistivity. For $YBa_2Cu_3O_{7-\delta}$ with low normal resistivity, the size of islands may be larger than the correlation length $\xi_+(T)$ predicted from the KT theory even just below T_{c0}.

5. Conclusion

The $YBa_2Cu_3O_{7-\delta}$ compound with high normal resistivity shows two phase transitions at T_c and T_{c0}. The low-temperature phase is a purely 3D superconducting phase. The intermediate phase between T_c and 84 K may correspond to the high-temperature phase of the KT theory. The non-Ohmic behaviour occurs as a result of the current-induced dissociation of bound vortex pairs which exist even above T_c. The high-temperature phase above T_{c0} shows an Ohmic behaviour.

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References

Beasley D G, Mooij J E and Orlando T P 1979 *Phys. Rev. Lett.* **42** 1165–68

Dubson M A, Herbert S T, Calabrese J J, Harris D C, Patton B P and Garland J C 1988 *Phys. Rev. Lett.* **60** 1061–4

Halperin B I and Nelson D R 1979 *J. Low Temp. Phys.* **36** 599–616
Kosterlitz J M 1974 *J. Phys. C: Solid State Phys.* **7** 1046–60
Murphy D W, Sunshine S, van Dover R B, Cava R J, Batlogg B, Zahurak S M and Schneemeyer L F 1987 *Phys. Rev. Lett.* **58** 1888–90
Stamp P C E, Forro L and Ayache C 1988 *Phys. Rev.* B **38** 2847–50
Sugahara M, Kojima M, Yoshikawa N, Akeyoshi T and Haneji N 1987 *Phys. Lett.* **125A** 429–31
Suzuki M, Ikeda H and Endoh Y 1983 *Synth. Met.* **8** 43–51
Wiesler D G, Suzuki M and Zabel H 1987 *Phys. Rev.* B **36** 7051–62
Wiesler D G, Zabel H and Suzuki M 1988 *Synth. Met.* **23** 237–42