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Transport property of a $Nd_{2-x}Ce_xCuO_{4-\delta}$ single crystal in the magnetic-field-driven normal state: in-plane and out-of-plane resistivity

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Abstract

In-plane and out-of-plane resistivities were measured under magnetic fields up to 14 T on $Nd_{2-x}Ce_xCuO_{4-\delta}$ single crystals with $x = 0.14$ and 0.16. A resistivity upturn with $\log(1/T)$ divergence both in plane and out of plane and a deviation from this divergence at low temperatures were observed when the superconductivity was completely suppressed. ρ_c/ρ_{ab} increases with decreasing temperature at high temperatures. In the low temperature range of $\log(1/T)$ behaviour, the field-induced normal-state anisotropy ratio becomes nearly constant for the underdoped sample with $x = 0.14$, and even decreases a little for the optimally doped sample with $x = 0.16$, suggesting a 3D behaviour accompanying the $\log(1/T)$ divergence, similar to the underdoped $La_{2-x}Sr_xCuO_4$ system. This is in contrast to the quasi-2D carrier confinement behaviour of the underdoped regime. The results can be explained well using the granular model.

1. Introduction

The contrasting behaviour of ρ_{ab} and ρ_c is related to the quasi-two-dimensional electronic state, which is well described as 'a confinement of carriers within the CuO_2 planes' in the normal state and is typically seen in the anisotropic resistivity. There is strong evidence that the transition into the 'overdoped' regime involves a crossover from two-dimensional (2D) superconducting to three-dimensional (3D) metallic behaviour in $YBa_2Cu_3O_{6+\delta}$ and $La_{2-x}Sr_xCuO_4$ [1–4]. In order to clarify the nature of the peculiar quasi-2D electronic state, it is of great importance to understand the mechanism of such a unique conduction.

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The normal state transport properties have been investigated in various high T_c cuprate superconductors when the superconductivity is quenched by a strong magnetic field [5–17]. The insulating behaviour of the resistivity at low temperature marked by a logarithmic temperature dependence appears in $La_{2-x}Sr_xCuO_4$ (LSCO) [6], $Bi_2Si_{2-x}La_xCuO_{2-\delta}$ (BSLCO) [7, 12, 16], $Nd_{2-x}Ce_xCuO_{4-\delta}$ (NCCO) [5, 13–15, 17], $Pr_{2-x}Ce_xCuO_{4-\delta}$ (PCCO) [9, 11] and Zn-doped $YB_2Cu_3O_{7-\delta}$ [10]. Therefore, it can be regarded as a universal phenomenon in both hole-doped and electron-doped cuprates. The interesting feature of this logarithmic divergence regime is that in LSCO ρ_c/ρ_{ab} approximately remains constant over the whole temperature range of the logarithmic behaviour [6, 8]. This 3D feature challenges the ordinary 2D weak localization theory. Anderson *et al* [19] argued that it can be understood by Luttinger liquid transport theory. In this theory, the resistivity of in-plane (ρ_{ab}) is proportional to $T^{-2\alpha}$, where α is the Fermi surface exponent. The same power law behaviour exists in c-axis resistivity. Budhani [20] suggested that the constant R_H of the underdoped and optimum doped PCCO samples in the temperature range for absence of superconductivity were consistent with the theory of localization in 2D Luttinger liquids, while the mimic metallic transport TEP and R_H of the overdoped sample were considered to be the consequence of three-dimensional charge distribution.

There also exist many other theories [8, 13, 14, 17, 21–23] related to this behaviour. Sekitani *et al* [13, 14, 17] recently give the results that in underdoped $(Nd, Ce)_2CuO_4$, $(Pr, Ce)_2CuO_4$ and $(La, Ce)_2CuO_4$ the resistivity shows a $\log(1/T)$ upturn and saturates toward the lowest temperature. They suggested that this divergence can be explained by Kondo scattering due to the Cu^{2+} spins in the CuO_2 planes. The electron–electron interaction in the 2D system can give a $\log(1/T)$ resistivity behaviour and negative magnetoresistance [21]. Recently, Beloborodov *et al* [22] investigated transport in granular metallic system and made the corrections to the density of states of granular metals due to the electron–electron interaction. They gave interesting results which compare favourably with the logarithmic temperature dependence of resistivity in high T_c cuprate. So it is of great importance to measure the in-plane and out-of-plane resistivity. Furthermore, the obtained behaviour of ρ_c/ρ_{ab} can help to understand the $\log(1/T)$ behaviour. In electron type cuprates, the in-plane resistivity has been measured by many groups before, while as far as we know the reports about c-axis resistivity measurements were limited to thin film samples. Therefore, the measurements performed on c-axis transport properties are valuable.

In this paper, the temperature and magnetic-field-dependent in-plane and out-of-plane resistivity of $Nd_{2-x}Ce_xCuO_{4-\delta}$ were measured on high quality NCCO single crystals with $x = 0.14$ and 0.16 down to the lowest temperature which we can achieve (1.8 K). It is observed that below the superconducting transition temperature (T_c), ρ_{ab} and ρ_c induced by the magnetic field show insulating behaviour with a $\log(1/T)$ tendency and a saturation toward lower temperature. ρ_c/ρ_{ab} is temperature independent for the optimum doped crystal and shows a tendency of saturation for the underdoped crystals in the temperature range with $\log(1/T)$ behaviour. It suggests a 3D behaviour in the temperature range with $\log(1/T)$ behaviour, being in contrast to the 2D carrier confinement behaviour in the high temperature normal state.

2. Experiment

Cerium concentrations of $x = 0.14$ and 0.16 for high quality $Nd_{2-x}Ce_xCuO_{4-\delta}$ single crystals were chosen to investigate their charge transport ρ_{ab} and ρ_c under magnetic fields. The single crystals used here were grown by the copper rich self-flux method and the measurement method is the standard six-terminal method. Superconductivity was achieved by annealing the samples in a clean quartz tube in flowing high purity (99.999%) helium at 900 °C for 12 h.

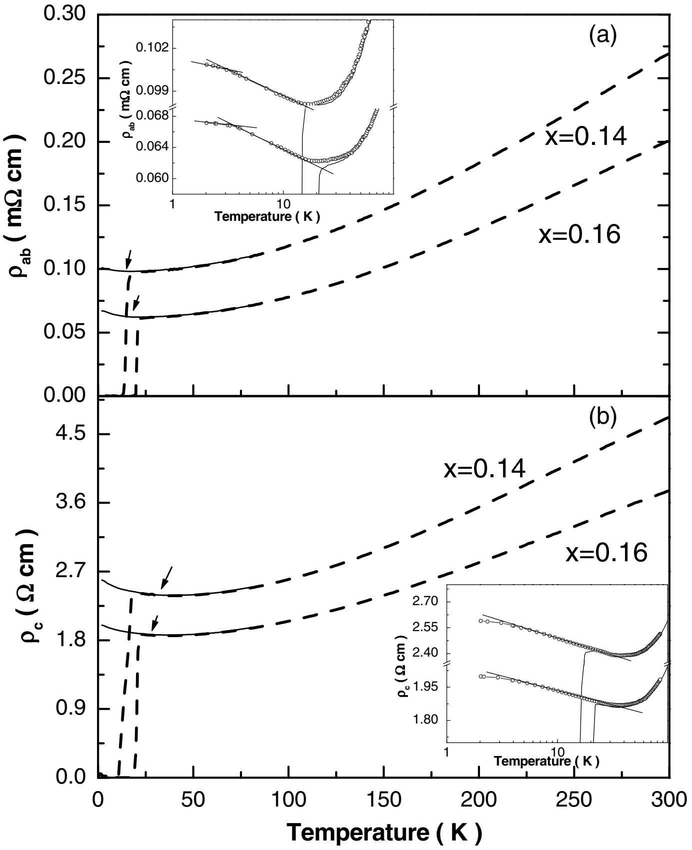

Figure 1. Temperature dependence of ρ_{ab} (a) and ρ_c (b) for $Nd_{2-x}Ce_xCuO_{4-\delta}$ single crystals with $x = 0.14$ and 0.16 under 0 and 14 T magnetic field. The arrow indicates the resistivity minimum. Inset of (a) the same data as in (a) plotted on a $\log T$ scale; inset of (b) the same data as in (b) plotted on a $\log T$ scale.

In order to obtain the coincident results, one single crystal was cut into two pieces. One is for in-plane resistivity measurement and another for out of plane. To ensure a homogeneous current flow in the sample, for *ab*-plane measurements, the current contacts were attached to the two side faces of the plate samples. The contact configuration is the same as that reported by Komiya *et al* [24]. For *c*-axis measurement, two pairs of current contacts are located on the top of the *ab* face and the bottom of the *ab* face of the crystal and the voltage contact is placed in between, respectively. The actual Ce concentration was determined by inductively coupled plasma spectrometry (ICP) analysis experiments. The resistance was measured by an AC resistance bridge (LR-700, Linear Research). A superconducting magnet system (Oxford Instruments) was used to achieve magnetic field up to 14 T. Temperature measurement used a magnetic field insensitive temperature sensor (CERNOX, Lakeshore Cryotronics). The field was applied perpendicular to the CuO_2 plane.

3. Results and discussion

Figure 1 shows the temperature dependence of ρ_{ab} and ρ_c for NCCO single crystals with $x = 0.14$ and 0.16 at magnetic fields of 0 and 14 T, respectively. The normal-state resistivity shows a nearly T^2 temperature dependence, which can also be well understood as a $T^2 \ln T$

behaviour which was associated with the electron–electron interaction in a cylindrical 3D Fermi surface [25] except the temperature range of the resistivity upturn toward insulating behaviour on the c-axis. The superconducting transition temperatures (T_c) (mid-point) of ρ_{ab} are 14.7 and 20.4 K for $x = 0.14$ and 0.16, and 14.8 and 20.3 K for ρ_c, respectively. A resistivity minimum and an upturn toward insulating behaviour was observed clearly in $\rho_c(T)$ as in previous results [9]. For the c-axis, the resistivity minimum appears at about 38 and 36 K for $x = 0.14$ and 0.16, respectively, while for in-plane resistivity this typical localization behaviour does not appear above the superconducting transition temperature for both of the crystals. However, when the superconductivity was completely suppressed by magnetic field of 14 T, the insulating behaviour in $\rho_{ab}(T)$ showed up and a resistivity minimum was observed at a temperature slightly lower than the superconducting transition temperature T_c.

The same data plotted on a $\log T$ scale below 100 K are shown in the insets of figure 1. It clearly shows a insulating behaviour for both in-plane and out-of-plane resistivities when the superconductivity is completely suppressed. The low temperature insulating upturn in resistivity follows a $\log(1/T)$ behaviour for both $x = 0.14$ and 0.16. Furthermore, it should be noted that in the lower temperature region both in-plane and out-of-plane resistivities deviate from the $\log(1/T)$ dependence and tend to saturate toward zero temperature; similar results have been observed in the other cuprates [6, 9, 13, 17]. For $x = 0.14$ the resistivity deviation from $\log(1/T)$ occurs at about 3 and 3.93 K for ρ_{ab} and ρ_c, respectively, while for $x = 0.16$ such deviation appears at about 3.9 and 4.5 K for ρ_{ab} and ρ_c, respectively. Similar behaviour in ρ_{ab} was observed by Sekitani *et al* in the heavily underdoped nonsuperconducting (La, Ce)$_2$CuO$_4$, (Pr, Ce)$_2$CuO$_4$, and (Nd, Ce)$_2$CuO$_4$ system [17], and in the superconducting samples such as PCCO [9], NCCO [13], BSLCO [12] and LSCO [6]. It suggests that such deviation behaviour is universal for cuprates. Although the saturation in LSCO appears in the lightly underdoped sample ($x \sim 0.13$) [6] under 60 T, opposite to NCCO (PCCO) and BSLCO, it cannot be observed widely. A probable explanation suggested in LSCO for the saturation at $x = 0.13$ is attributed to the striking feature close to the 1/8 point [8]. Sekitani *et al* [13] gave a possible explanation for the deviation from the $\log(1/T)$ behaviour at low temperatures since they considered the $\log(1/T)$ behaviour from Kondo scattering. Consequently, below the Kondo temperature the AF coupling between the spin of the conduction electron and the local spin becomes predominant, forming a singlet state, then the resistivity has a finite maximum without the divergence to infinity at 0 K. From the insets in figure 1, the magnetoresistivity seems to show another $\log(1/T)$ behaviour with different slope below the deviation temperature. Due to the limit of our experimental system with the temperature only cooling to 1.8 K, we cannot make any further argument for this region.

In our previous results [15], no resistivity saturation was observed at even the lowest temperature. It also can be noticed that the obvious peak with T_c shifts toward lower temperature with increasing magnetic field and evolves to a $\log(1/T)$ like upturn even in the overdoped regime [15]. Crusellas *et al* [26] have already proposed that an obvious resistance peak just above T_c possibly derives from the intrinsic granularity in n-type high-temperature superconductors based on their careful investigation of the magnetoresistivity of some L$_{2-x}$Ce$_x$CuO$_{4-y}$ (L = Pr, Nd, Sm) superconducting single crystals, and they also suggested that the peak can be modified after an appropriate annealing process. It is well known that the superconductivity in this system is very sensitive to the oxygen stoichiometry. A more adequate annealing process was employed, so that no peak just above T_c is observed in the present data. A striking feature is that ρ_{ab} and ρ_c show two different $\ln T$ behaviours at low temperatures and saturation after superconductivity is completely suppressed.

The in-plane and out-of-plane resistivities as a function of temperature at the different magnetic fields perpendicular to the CuO$_2$ plane for $x = 0.14$ and 0.16 are displayed in the

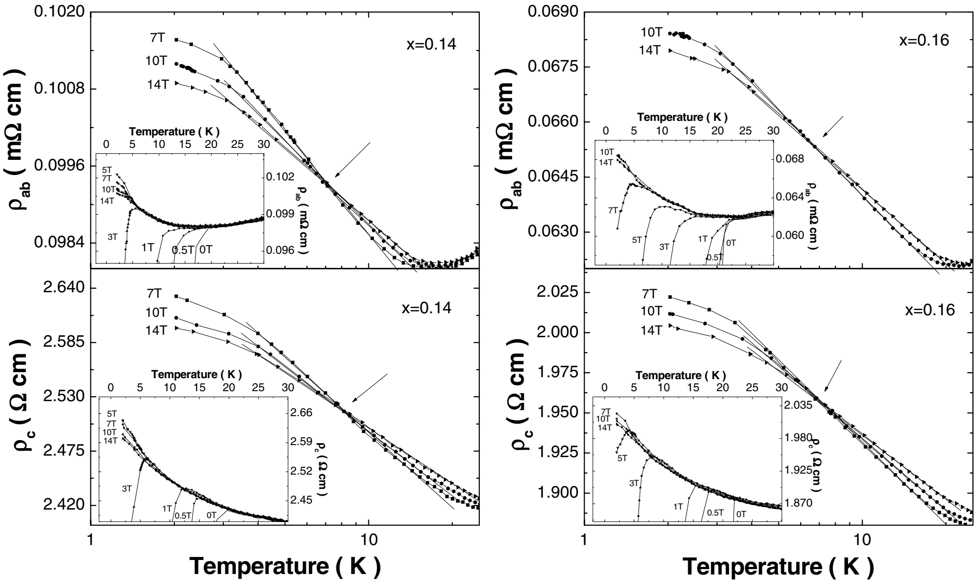

Figure 2. In-plane and out-of-plane resistivities versus log T under different magnetic fields larger than $H_{c2}(0)$ perpendicular to the CuO_2 plane for $x = 0.14$ and 0.16. Insets: The temperature dependence of ρ_{ab} (a) and ρ_c at different applied fields perpendicular to the CuO_2 plane. The arrows indicate the intersection points.

insets of figure 2. The superconducting transition shifts to lower temperature with increasing magnetic field and all the data show an insulating upturn at low temperature at the magnetic field above the zero-temperature upper critical field $H_{c2}(0)$ which is (80 ± 5) kOe for c-axis oriented $Nd_{1.85}Ce_{0.15}CuO_{4-\delta}$ thin films [27]. It should be pointed out that the negative magnetoresistance can be seen clearly at low enough temperature for all the samples. In c-axis resistivity, this insulating behaviour is observed in zero magnetic field above T_c.

The evolution of ρ_{ab} and ρ_c under magnetic fields of 7, 10 and 14 T are shown with a $\log(1/T)$ scale in figure 2. It is clear to see that the resistivity increases quickly and follows $\log(1/T)$ behaviour with lowering temperature, then shows a deviation from the $\log(1/T)$ behaviour at a certain temperature point. It should be pointed out that there exists an intersection for the R–T curves under different magnetic fields. Above the intersection, positive magnetoresistance was observed while below the intersection negative magnetoresistance was observed. For $x = 0.14$ the intersection appears at about 6.8 and 8 K for in-plane and out-of-plane magnetoresistivity, respectively, while for $x = 0.16$ such an intersection was observed at about the same temperature for both in-plane and out-of-plane magnetoresistivity ($\sim$6.8 K). This seems to give evidence that the low temperature behaviours of ρ_{ab} and ρ_c are related to each other for $x = 0.16$. It is also easily seen that in figure 2 for both $x = 0.14$ and 0.16 the temperature corresponding to the resistivity deviation from $\log(1/T)$ behaviour decreases with decreasing applied field above the intersection; for $x = 0.14$, the deviation from $\log(1/T)$ appears at about 14.5, 13 and 10.3 K at the applied field of 14, 10 and 7 T for in plane, while 19, 16 and 11.5 K for out of plane. For $x = 0.16$, the deviation appears at 18.1 and 14.8 K at 14 and 10 T for the ab-plane, while 20.6, 18.6 and 16 K at 14, 10 and 7 T for the c-axis. Ando *et al* have ascribed this different deviation temperature above the intersection to the proximity of the superconducting transition [6]. However, it is difficult to understand the change of the deviation temperature with fields larger than $H_{c2}(0)$ since

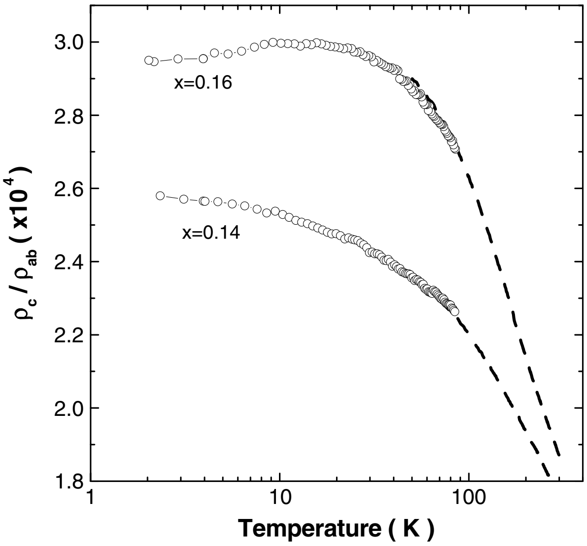

Figure 3. Temperature dependence of the anisotropy ratio ρ_c/ρ_{ab} under 14 T magnetic field for the crystals with $x = 0.14$ and 0.16. The dashed line is the normal state anisotropy ratio in zero field.

the magnetic field larger than the zero-temperature upper critical field seems to rule out the possibility of proximity of the superconducting transition. If the $\log(1/T)$ behaviour could be attributed to the contribution of applied fields, the low applied field may not be enough to bring such a $\log(1/T)$ behaviour in a wide temperature range as that at high applied field. Below the intersection, the temperature corresponding to the deviation from the $\log(1/T)$ dependence is almost the same under the different magnetic fields. This implies that the deviation temperature point below the intersection does not depend on the magnetic field when H is larger than the upper critical field. Another point should be noticed: a clear negative magnetoresistance is observed with increasing field larger than $H_{c2}(0)$ below the intersection; similar behaviour has been reported by Fournier *et al* in the PCCO system [9]. However, such negative magnetoresistance behaviour cannot be observed in p-type cuprates. This may be due to the very large $H_{c2}(0)$ for p-type cuprates.

In figure 3, the temperature dependences of the anisotropy ratio ρ_c/ρ_{ab} under magnetic field of 14 T were presented for the crystals with $x = 0.14$ and 0.16. For the $x = 0.16$ crystal, above the superconducting transition temperature the value of ρ_c/ρ_{ab} increases generally with decreasing temperature, while below the superconducting transition temperature ρ_c/ρ_{ab} nearly remains constant and even decreases a little for temperature below 10 K. This decrease can be understood as the more rapid saturation of ρ_c than ρ_{ab} in this crystal. The same feature has been reported in the underdoped LSCO at the low temperature limit by Ando *et al* [6], which was attributed to an anisotropic 3D insulator behaviour. Though large anisotropy was observed in the $x = 0.16$ sample, the scattering mechanism for in-plane and out-of-plane resistivity for the $x = 0.16$ crystal is nearly the same at low temperature. The ρ_c/ρ_{ab} is temperature independent, as seen from the saturation of ρ_c/ρ_{ab} for $x = 0.16$. Furthermore, the same intersection temperature for in-plane and out-of-plane magnetoresistivity in figure 2 for $x = 0.16$ was believed to be further evidence for the same behaviour of $\rho_{ab}(T)$ and $\rho_c(T)$ for $x = 0.16$. It suggests a 3D behaviour at low temperature for $x = 0.16$. For $x = 0.14\rho_c/\rho_{ab}$ increases with decreasing temperature in the whole temperature range. But below the superconducting transition temperature the increase is slower than that above the superconducting transition temperature. Furthermore, an apparent saturation tendency of ρ_c/ρ_{ab} can also be observed in the zero-temperature limit for $x = 0.14$. This is in contrast to the divergence behaviour $\rho_c/\rho_{ab} = aT^{-2/3} + b$ in the strongly underdoped $Y_{0.47}Pr_{0.53}Ba_2Cu_3O_{7-\delta}$, indicating the two-dimensional strong localization [28].

Let us analyse this divergence behaviour and discuss the results of the MI transition induced by magnetic field using different models. The 2D weak localization theory and Kondo effect have been used to explain the logarithmic divergence and negative magnetoresistivity [17–19, 29]. The Kondo effect can naturally explain the saturation of the divergence in ultra-low temperature and predict an isotropic magnetoresistivity. Although there exists some evidence for this argument [17], current limited experimental data are not adequate to determine if a general angular dependence of the magnetoresistivity exists or not. However, antiferromagnetic order as a possible competing ground state with superconductivity (SC)has been theoretically predicted by Zhang and his co-workers [30]; antiferromagnetic (AF) order (short range or long range) can be induced by external magnetic field. In recent reports [31–34] enhancement of AF order has been observed in the LSCO system by applying magnetic field. Very recently, a static, commensurate, anomalously conducting long range AF state was revealed by external field in superconducting NCCO, and the induced moment scales approximately linearly with the field strength up to upper critical field B_{c2} [35]. Similarly, in superconducting PCCO, field-induced static AF order was observed below T_c [36]. Therefore, an obvious long range ordered antiferromagnetic state in cuprates questions the validity of the Kondo scattering model since the ordinary Kondo single-impurity scattering approximation would not work.

It should be pointed out that the saturation of divergence can also be well understood in 2D weak localization theory. The similar behaviour has been seen even in the early reports of logarithmic behaviour in a 2D weak localized system [29]. In the frame of scaling theory in a disordered system, the fixed point under the variance of some parameters such as temperature and sample size can effectively induce a cut-off for this kind of divergence although the detailed reason for this saturation is not clear now. But it should be noted that the similar logarithmic divergence in both ab-plane and c-axis resistivity with the constant ρ_c/ρ_{ab} at very low temperature observed in LSCO and our NCCO samples blurs the picture of 2D weak localization theory although the magnitude of ρ_c/ρ_{ab} is as large as about 10^4. In addition, as pointed out by Sekitani *et al* [17], 2D weak localization theory may be ruled out because the anisotropy of the negative magnetoresistance does not follow a cosine dependence. Furthermore, the coefficient (α) for $\log T$-dependent conductivity and for $\log B$-dependent magnetoconductivity per sheet should be material-independent universal values in 2D weak localization. However, they found that for the cuprates this is not this case.

Recently, an alternative theory about transport properties in granular metals at low temperature was established by Efetov and his co-workers [22, 23]. It has been found that at low temperature the coherent electron motion at large distances becomes dominant while at higher temperature the granular structure of the array dominates the physics. This gives a $\ln T$ dependence to conductivity σ. It is noted that the logarithmic dependence of conductivity is consistent with the $\log(1/T)$ behaviour in resistivity[2]. Applying their ideas to cuprates is interesting since recent scanning tunnelling microscope studies on underdoped $Bi_2Sr_2CaCu_2O_{8+\delta}$ [37] showed that this system possesses some long range characteristics of a granular superconductor. It is noted that despite the nonexistence of the peak in resistivity as

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[2] One should notice that when the coefficient α of power law T^α is small enough, $T^\alpha \sim 1 + \alpha \ln T$ and $T^{-\alpha} \sim 1 - \alpha \ln T$ (obtained by expansion of T^α in α).

observed by Crusellas *et al* and Li *et al* [15], the possible intrinsic inhomogeneities or phase separation can also induce the properties of granularity.

In order to understand the above results, the theory for transport properties in granular metals [22] is employed to analyse our data in NCCO single crystals. In the granular theory, the scaled conductivity of CuO planes (σ_{plane}) is defined as $\sigma_{\text{plane}} = \sigma c/n$, σ is the reciprocal value of the resistivity obtained directly from the experiment, n is the number of CuO planes and c is the c-axis cell parameter. The scaled conductivity follows the formula $\mathrm{d}\sigma_{\text{plane}}/\mathrm{d}\ln T = (e^2/\pi\hbar)k$; here, $k = 1/2\pi$ at low temperature and $k = 1/d$ in the high temperature regimes where the real dimensionality d is replaced by one half of the average number of adjacent grains around each grain ($d = Z/2$). As shown in figure 1, the deviation part at low temperature can also be plotted as another $\log(1/T)$ behaviour. It indicates two different slopes with $\ln T$ for σ_{plane} in $x = 0.14$ and 0.16. We have estimated the coefficient k according to the formula above for the two different slopes in the $\log(1/T)$ region. The coefficient $k \simeq 0.17$ for the sample with $x = 0.14$ and $k \simeq 0.24$ for the $x = 0.16$ sample are obtained in the low temperature range from 1.8 to 3 K, which agrees quite well with the theoretical prediction $k \simeq 1/2\pi$ [22] at low temperature. When the temperature moves away from 3 K, k quickly increases up to 0.22 for the $x = 0.14$ sample and to 0.95 for the $x = 0.16$ sample in the high temperature $\log(1/T)$ region, clearly exceeding $1/2\pi$. According to the arguments of Beloborodov *et al* [22], one can conclude that the ‘coherent–incoherent’ crossover occurs at $T \sim 3$ K in our samples. Therefore, the ‘saturation’ observed in our samples can naturally be explained by this kind of crossover in the frame of their theory as two different logarithmic behaviours existing in different temperature regimes.

One can notice that the results under 14 T magnetic field are in agreement with the granular metal theory [22]. However, the results under other magnetic fields near the intersection are also worth discussing. The k value at 10 T magnetic field for $x = 0.14$ and 0.16 is calculated with the formula for scaled conductivity. At the magnetic field of 10 T, k is 0.17 and 0.30 for $x = 0.14$ and 0.16 at temperature below 3 K, respectively, while at temperature above 3 K the k value increases quickly to 0.26 and 1.1 for $x = 0.14$ and 0.16, respectively. Furthermore, for the $x = 0.14$ sample, the results under 7 T can be calculated due to the complete suppression of superconductivity, and k is 0.19 in the low temperature regime of $\ln T$ and 0.35 in the high temperature range of $\ln T$. Though slight difference of k were observed under different magnetic field, the results are all in the range of the prediction of [22]. It should be pointed that the large value of k ($\sim$0.95 under 14 T and $\sim$1.1 under 10 T) for $x = 0.16$ can be understood in this theory as that grains are not well packed and each grain on average has approximately two contacts ($Z = 2$). If the temperature goes down further, the interference effect makes their calculation invalid and may cut off this divergence and then give the real saturation of the logarithmic behaviour. However, this effect is beyond the scope of our experiments. In contrast to NCCO, PCCO and BSLCO, the saturation behaviour in magnetoresistivity cannot be observed widely in LSCO and YBCO. At least, it can be believed that in these two systems the granular feature is not so obvious; in particular, in LSCO the stripe phase, distinct from the microscopic granular structure, exists and plays the dominant role. After all, it is concluded that the possibility of intrinsic granularity cannot be excluded as a promising explanation for the $\log(1/T)$ behaviour in cuprates.

4. Conclusion

The in-plane and out-of-plane resistivity measurements under different magnetic fields up to 14 T were performed on high quality $Nd_{2-x}Ce_xCuO_{4-\delta}$ single crystals with $x = 0.14$ and 0.16. Below the transition temperature there exists a resistivity upturn which displays a $\log(1/T)$ behaviour and a deviation at lower temperature is observed in both in-plane and c-axis samples when the superconductivity is completely suppressed. In the nearly optimum doped sample, above the superconducting transition temperature the value of ρ_c/ρ_{ab} generally increases with decreasing temperature, while below the superconducting transition temperature ρ_c/ρ_{ab} nearly remains constant and even decreases a little. For $x = 0.14$, ρ_c/ρ_{ab} increases with decreasing temperature in the whole temperature range; below the superconducting transition temperature the increase is slower than that above the superconducting transition temperature and an apparent saturation of ρ_c/ρ_{ab} can also be observed in the zero-temperature limit. These behaviours are quite similar to that reported in LSCO [6] and PCCO [9]. Therefore, they can be regarded as common features in cuprates. It should be emphasized that the recent granular model gives a good explanation of our experimental data. Further investigation on granularity and anisotropy of magnetoresistivity in cuprates can undoubtedly help us to understand this particular issue.

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