Unusual Charge Localization in Zn-doped and Heavily Underdoped YBa$_2$Cu$_3$O$_{7-\delta}$ at Low Temperatures

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The in-plane normal-state resistivity of Zn-doped YBa$_2$Cu$_3$O$_{7-\delta}$ and heavily underdoped pure YBCO single crystals is measured down to low temperatures under magnetic fields up to 18 T. We found that the temperature dependence of the normal-state $\rho_{ab}$ does not obey $\log(1/T)$ and tends not to diverge in the low temperature limit. The result suggests that the “ground state” of the normal state of YBCO is metallic.

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In high-$T_c$ cuprates, the low-temperature normal-state resistivity is expected to reflect the electronic structure which underlies the high-$T_c$ superconductivity. In La$_{2-x}$Sr$_x$CuO$_4$ (LSCO) system, the measurement of the normal-state resistivity at low temperatures was performed using a pulsed magnet. The in-plane resistivity $\rho_{ab}$ of underdoped LSCO was reported to show logarithmic divergence in high magnetic fields in the zero-temperature limit. Thus, the “ground state” of the normal state of the underdoped LSCO appears to be insulating. In order to see whether the insulating “ground state” is a common feature of the underdoped high-$T_c$ cuprates or not, one needs to perform the measurement in other high-$T_c$ systems. In the case of YBa$_2$Cu$_3$O$_{7-\delta}$ (YBCO), the normal-state $\rho_{ab}$ has been measured at low temperatures by using 18 T magnetic field. Zn substitution in excess of 2.5% was reported to induce an upturn in the temperature dependence of $\rho_{ab}$ at low temperatures, and the logarithmic temperature dependence of $\rho_{ab}$ was observed; however, it remains unclear whether the logarithmic divergence continues to very low temperatures in the YBCO system, because
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the 18 T magnetic field was insufficient to completely suppress superconductivity at low temperatures in superconducting samples. On the other hand, the superconducting fluctuation in non-superconducting samples can easily be suppressed by 18 T field at low temperatures. Thus the temperature dependence of the resistivity in such non-superconducting samples can be measured down to low temperatures without significant difficulties. If one investigates the temperature dependence of the resistivity in the non-superconducting samples as well as the superconducting Zn-doped samples, the behavior of $\rho_{ab}(T)$ in the low temperature limit is expected to be clarified.

Here we report measurements of the low-temperature normal-state resistivity along the CuO$_2$ planes, $\rho_{ab}$, of Zn-doped YBCO and non-superconducting heavily-underdoped pure YBCO. We found that the normal-state $\rho_{ab}$ is not likely to diverge in the low-temperature limit. The result suggests that the “ground state” of the normal state is metallic in YBCO.

The single crystals of YBa$_2$(Cu$_{1-z}$Zn$_z$)$_3$O$_{7-\delta}$ are grown by flux method in pure Y$_2$O$_3$ crucibles to avoid inclusion of any impurities other than Zn. The oxygen content $y$ ($\equiv 7-\delta$) in the crystals is controlled by annealing in evacuated and sealed quartz tubes at 500-650°C for 1-2 days together with sintered blocks and/or powders and then quenched with liquid nitrogen. The final oxygen content is confirmed by iodometric titration with an accuracy of better than $\pm 0.01$. The measurement of $\rho_{ab}$ is performed with ac four-probe technique under dc magnetic fields up to 18 T applied along the c axis.

Figure 1(a) shows the temperature dependence of $\rho_{ab}$ in 0 and 15 T, for $z=2.7\%$ samples with $y=6.70$ (sample A), 6.75 (sample B) and 6.80 (sample C), and Fig.1(b) shows $\rho_{ab}(T)$ in 0 and 16 T for a sample with $z=1.3\%$ $y=6.50$ (sample D). The $\rho_{ab}(T)$ of these four samples all show an upturn in magnetic fields at low temperatures. Figs.1(c)(d)(e)(f) show the log $T$ plots of $\rho_{ab}(T)$ for samples A, B, C and D, respectively. The temperature dependences of $\rho_{ab}$ of these samples can be seen to be consistent with log $T$ only in the temperature range of 5-12 K, 9-20 K, 7-15 K and 12-20 K, respectively, for samples A, B, C and D. Below those temperature regions, $\rho_{ab}(T)$ starts to deviate downwardly from log $T$. The downward deviation is due to a different temperature dependence of $\rho_{ab}$ at lower temperatures and/or the superconducting fluctuation which is not sufficiently suppressed in 15-18 T magnetic fields. Figures 1(g)(h)(i)(j) show $\sigma_{ab}(T)$ vs $T^{1/2}$ plots for samples A, B, C and D. The temperature dependences of $\rho_{ab}$ are consistent with $\sigma_{ab}(T) \sim a + T^{1/2}$, in the range of 1.5-8 K (1.2-2.8 K$^{1/2}$), 6-12 K (2.4-3.5 K$^{1/2}$), 5-9 K (2.2-3.0 K$^{1/2}$) and 8-20 K (2.8-4.5 K$^{1/2}$), respectively, for samples A, B, C and D. In particular, $\sigma_{ab}(T)$ of sample A is well fitted with
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Fig. 1. (a): $\rho_{ab}(T)$ of $z=2.7\%$ crystals with different $y$ (6.70(sample A), 6.75(sample B), and 6.80(sample C)) in 0 T (solid lines) and in 15 T (open circles). (b): $\rho_{ab}(T)$ in 0, 16 T for $y=6.50$, $z=1.3\%$ (sample D). (c)(d)(e)(f): log $T$ plots of $\rho_{ab}(T)$ for samples A, B, C and D. (g)(h)(i)(j): $\sigma_{ab}(T)$ vs $T^{1/2}$ plots for samples A, B, C and D.
Fig. 2. (a): \( \rho_{ab}(T) \) in 0 T for pure samples with \( y = 6.40 \) (sample E), 6.38 (sample F). (b)(c): \( \log T \) plots of \( \rho_{ab}(T) \) for samples E and F. (d): \( \sigma_{ab}(T) \) vs \( T^{1/2} \) plot for sample E. (e): \( \rho_{ab}(T) \) vs \( T^{-1/3} \) plot for sample F.

\[ \rho_{ab} \sim a + T^{1/2} \] down to 1.5 K. This temperature dependence, \( \sigma_{ab}(T) \sim a + T^{1/2} \), is fundamentally different from that of \( \rho_{ab}(T) \sim \log(1/T) \); \( \log(1/T) \) diverges as \( T \to 0 \), whereas \( 1/(a + T^{1/2}) \) remains finite. Thus, the result of Fig.1(g), in which \( \sigma_{ab}(T) \sim a + T^{1/2} \) well fits the measured data, suggest that the in-plane resistivity in YBCO is not likely to diverge in the zero-temperature limit.

However, the resistivity might be reduced by the superconducting fluctuation at low temperatures in those samples. If so, it is possible that the intrinsic \( \rho_{ab}(T) \) is diverging in the low temperature limit if there were no superconducting fluctuations. In order to avoid such uncertainty, we prepared non-superconducting samples by reducing oxygen in pure YBCO. Fig.2(a) shows \( \rho_{ab}(T) \) in 0 T for pure samples with \( y = 6.40 \) (sample E) and 6.38 (sample F). Sample E is close to the superconducting region and its resistivity value corresponds to \( k_F l \sim 2 \), where \( k_F \) is the Fermi wave number and \( l \) is the mean free path. Sample F is strongly insulating and its resistivity corresponds to \( k_F l < 1 \) at low temperatures. Both samples E and F show no superconducting transition. However, in sample E, \( \rho_{ab} \) shows a decrease due to the superconducting fluctuation in 0 T at low temperatures. The superconducting fluctuation in sample E can easily be suppressed in 18 T down to 0.2 K.

Figure 2(b) shows the \( \log T \) plot of \( \rho_{ab}(T) \) for sample E. This \( \rho_{ab}(T) \) is not consistent with \( \log(1/T) \). In contrast, as Fig.2(d) shows, \( \sigma_{ab}(T) \) is
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well fitted with $\sim a + T^{1/2}$ down to 0.2 K (0.45 K$^{1/2}$). We note that Lavrov et al. reported similar $T$-dependence of conductivity in heavily underdoped YBCO whose oxygen content is between samples E and F. However, their data were also consistent with $\rho_{ab}(T) \sim \log(1/T)$ as well as $\sigma_{ab}(T) \sim a + T^{1/2}$ at low temperatures. In contrast to their data, our data definitely show that the increase in $\rho_{ab}$ with decreasing temperature is weaker than $\log T$ at low temperatures. Thus, we may conclude that $\rho_{ab}$ in sample E is not diverging in the low temperature limit.

For sample F, Fig.2(c) shows the log $T$ plot of $\rho_{ab}(T)$. It is clear in Fig.2(c) that the resistivity of sample F tends to diverge more strongly than log $T$ with decreasing temperature. We found instead that $\rho_{ab}(T) \sim T^{-1/3}$ is a better description of the temperature dependence of $\rho_{ab}$ of sample F. Fig.2(e) shows the plot of $\rho_{ab}(T)$ vs $T^{-1/3}$ for sample F, where one can find that the data lie on a straight line reasonably well at low temperatures (right hand side of the plot). Thus, the resistivity of sample F is likely to be diverging in the low temperature limit. In both the superconducting Zn-doped samples and the non-superconducting sample (but close to the superconducting composition), $\rho_{ab}$ does not behave as $\log(1/T)$ at low temperatures. Instead, the behavior of $\sigma_{ab}(T) \sim a + T^{1/2}$ is observed in the low temperature limit. This result suggests that $\rho_{ab}$ does not diverge in the low temperature limit and thus the “ground state” of the normal state of YBCO is metallic. Of course, not all YBCO samples are “metallic”, for example, $y=6.38$ sample remains insulating at low temperatures. The resistivity of the insulating $y=6.38$ sample corresponds to $k_Fl < 1$, whereas that of the “metallic” $y=6.40$ sample corresponds to $k_Fl \sim 2$. This means that the samples with $k_Fl < 1$ cannot be metallic at low temperatures, like conventional metals.

In summary, we measured the in-plane resistivity of Zn-doped YBCO and non-superconducting heavily underdoped YBCO crystals down to low temperatures under magnetic fields up to 18 T. It is found that the temperature dependence of the normal-state $\rho_{ab}$ tends not to diverge in the low temperature limit. The result suggests that the “ground state” of the normal state of YBCO is metallic.

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