Microwave spectroscopy of 3D-XY critical charge dynamics in electron-doped La$_{2-x}$Ce$_x$CuO$_4$ superconducting thin films

H Kitano$^1$, T Ohashi$^2$ A Maeda$^2$ A Tsukada$^3$ and M Naito$^3$

$^1$Department of Physics and Mathematics, Aoyama Gakuin University, Kanagawa 229-8558, Japan
$^2$Department of Basic Science, University of Tokyo, Tokyo 153-8902, Japan
$^3$Department of Applied Physics, Tokyo University of Agriculture and Technology, Tokyo 184-8588, Japan
E-mail: hkitano@phys.aoyama.ac.jp

Abstract. Dynamic fluctuation effects of electron-doped La$_{2-x}$Ce$_x$CuO$_4$ superconducting thin films for a wide range of the Ce concentration (x=0.075 to 0.15) are studied through the microwave spectroscopic measurements in zero magnetic field. Dynamic scaling analysis of the fluctuation-induced microwave conductivity shows that the three-dimensional (3D) XY critical behavior is observed in a wide range of electron dopings, in contrast to our previous results on the hole-doped La$_{2-x}$Sr$_x$CuO$_4$ thin films where three kinds of critical charge dynamics and two kinds of dimensional crossovers were observed by hole doping. Our results clearly indicate that the critical behaviors between hole-doped and electron-doped regions in the phase diagram of high-\(T_c\) cuprates are not symmetric intrinsically. Thus, correct theories describing high-temperature superconductivity in cuprates should meet this criterion.

1. Introduction

Since the discovery of electron-doped cuprate superconductors [1], the similarities and dissimilarities between electron-doped and hole-doped cuprates have been extensively investigated, in order to clarify the essential property of high-\(T_c\) superconductivity. However, the issue of a phase diagram as a function of carrier dopings is still debated, since some theoretical models suggest the symmetric phase diagram between both systems, while others suggest the anti-symmetric phase diagram. We have investigated the critical charge dynamics near the superconducting transition in the hole-doped La$_{2-x}$Sr$_x$CuO$_4$ (LSCO) cuprate superconductor [2, 3] as well as the NbN conventional superconductor [4]. Interestingly, we found that the critical dynamics of LSCO was essentially two-dimensional (2D), except for the three dimensional-XY (3D-XY) critical dynamics observed only near the optimally doped region, while the usual Gaussian fluctuations were observed for the NbN superconductor.

It is quite interesting to ask whether such a unusual critical dynamics is common to the elecron-doped cuprate or not. Thus, we studied the critical charge dynamics in a wide range of the Ce concentration of La$_{2-x}$Ce$_x$CuO$_4$ (LCCO) thin films through the spectroscopic measurements of the fluctuation-induced microwave conductivity up to 10 GHz.
2. Experimental methods
High quality LCCO thin films with a wide doping range from $x=0.075$ to 0.15 were grown on LaSrAlO$_4$ substrates by a molecular-beam-epitaxy (MBE) method [5].

The complex microwave conductivity, $\sigma(\omega)(=\sigma_1(\omega) - i\sigma_2(\omega))$, is obtained from the complex reflection coefficient, $S_{11}(\omega)$, as a function of continuously sweeping frequency, using a non-resonant broadband technique [6]. The critical behaviors near $T_c$ were analyzed by using a general formulation of the dynamic scaling hypothesis for the frequency-dependent complex fluctuation conductivity, $\sigma_{fl}(\omega)(\approx \xi^{z+2-d}S(\omega \xi^z))$, where $\xi$ is a correlation length which diverges at $T_c$, $S(x)$ is a complex universal scaling function, $d$ is a spatial dimension, and $z$ is a dynamic critical exponent, respectively [7].

The most important part of our analyses is that we can check the validity of the dynamic scaling hypothesis, by measuring $\sigma_{fl}(\omega)$. We used both the magnitude, $|\sigma_{fl}|$, and the phase, $\phi_{\sigma}(\equiv \tan^{-1}[\sigma_2/\sigma_1])$, of $\sigma_{fl}(\omega)$ as scaled quantities in the scaling analysis of $\sigma_{fl}(\omega)$. The data sets of $\phi_{\sigma}(\omega)$ and $|\sigma_{fl}(\omega)|$ at different temperatures are scaled by using two normalizing factors, $\omega_0$ and $\sigma_0$, respectively. Note that $\omega_0$ and $\sigma_0$ are independently obtained in our procedure, since the data sets of $\sigma_{fl}(\omega)$ are complex quantities with two independent components. This is a unique feature of our scaling procedure, showing a sharp contrast to other experiments to investigate the critical behavior of high-$T_c$ cuprates [8, 9, 10, 11].

3. Results and discussion
Figure 1 shows the frequency dependence of $\sigma(\omega)$ for a LCCO thin film with $x=0.075$ at several temperatures above $T_c (=25.7$ K, where the dc resistance became zero). We observed that both $\sigma_1(\omega)$ and $\sigma_2(\omega)$ in the low frequency limit diverged rapidly as the temperature approached $T_c$ from above, suggesting that the contribution of the superconducting fluctuations to $\sigma(\omega)$ was evident with decreasing temperature.

The frequency-dependent complex fluctuation conductivity, $\sigma_{fl}(\omega)$, was obtained by

![Figure 1](image-url)

**Figure 1.** (a) Frequency dependence of the real part of $\sigma(\omega)$ for a LCCO thin film with $x=0.075$. (b) Frequency dependence of the imaginary part of $\sigma(\omega)$ for the same film. Inset: Temperature dependence of the dc resistivity of this film.
Figure 2. (a) Scaled data of the magnitude of $\sigma_R(\omega)$ for the LCCO film with $x=0.075$. (b) Scaled data of the phase of $\sigma_R(\omega)$ for the LCCO film with $x=0.075$. The phase and the magnitude is normalized by $\pi/2$ and the scaling parameter, $\sigma_0$, respectively. Solid (dashed) lines are the 3D (2D) Gaussian scaling functions.

subtracting the normal-state conductivity with the almost flat frequency dependence. Figure 2 shows that both $|\sigma_R|/\sigma_0$ and $\phi_\sigma$ for the same LCCO thin film ($x=0.075$) were scaled successfully over a wide range of frequencies, confirming that the critical dynamics were indeed observed. The comparison of the experimentally obtained scaling functions with the Gaussian forms strongly suggested that the dimensionality of the critical dynamics in the LCCO film with $x=0.075$ was three dimensional (3D). Note that our scaling procedure needs no assumption on the dimensionality in the critical dynamics. Detailed analyses of the obtained scaling parameters, $\omega_0$ and $\sigma_0$, indicated that the critical charge dynamics for this LCCO film belonged to the 3D-XY universality class.

Similar measurements were also performed for other two LCCO thin films with different Ce concentrations ($x=0.105, 0.15$). We found that the 3D-XY critical charge dynamics was widely observed from $x=0.075$ to $x=0.15$ in the electron-doped LCCO system. As well known, the critical dynamics near a continuous phase transition is expected to be universal and to be independent of the microscopic details. Our results for the electron-doped LCCO are also consistent with the general property of the critical dynamics. However, these behaviors show a sharp contrast to those in the hole-doped LSCO system, where the critical dynamics was essentially two-dimensional (2D), except for the 3D-XY critical dynamics observed only near the optimally doped region [2, 3].

The following two important suggestions are obtained by the direct comparison between the critical behaviors in the electron-doped and the hole-doped cuprates. One is that the critical dynamics in both systems are not symmetric intrinsically. This implies that the mechanism of superconductivity would be different between both systems. The other is that the critical dynamics in the hole-doped system seems to be more unusual than that in the electron-doped
system. As was previously reported, the critical dynamics in the hole-doped LSCO is classified into the following three different universal classes; (i) the 2D-XY universality class in the underdoped region, (ii) the 3D-XY universality class near the optimally doped region, (iii) the 2D-“unknown” universality class in the overdoped region [3]. This suggests that the dimensionality in the critical dynamics is changed twice in the phase diagram of the hole-doped LSCO. It is quite difficult to explain such an unusual dimensional crossover within the classical theory of the critical dynamics, implying a possibility that the effect of the quantum critical fluctuations around a quantum critical point can affect the classical critical dynamics. On the other hand, the 3D-XY universality class is naturally expected in the so-called “$\phi^4$ theory” where the fluctuations in the magnitude and phase parts of an order parameter are equally treated [7]. In this sense, the present results observed for the electron-doped LCCO show a good agreement with the classical theory of the critical dynamics, supporting that our scaling procedure utilizing the frequency-dependent complex fluctuation conductivity is quite useful to explore the critical region in the high-$T_c$ cuprate superconductor.

4. Conclusion
We studied the critical charge dynamics in the electron-doped LCCO system by using the dynamic scaling analysis of $\sigma(\omega)$. Our results clearly show that the 3D-XY critical behavior is observed in a wide range of electron dopings, in contrast to our previous results on the hole-doped LSCO system. Thus, it is concluded that the critical charge dynamics between hole-doped and electron-doped regions in the phase diagram of high-$T_c$ cuprates are not symmetric intrinsically.

Acknowledgments
This work was partly supported by the Grant-in-Aid for Scientific Research (13750005 and 15760003) from the Ministry of Education, Science, Sports and Culture of Japan. T Ohashi thanks the Japan Society for the Promotion of Science for financial support.

References
[1] Tokura Y, Takagi H and Uchida S 1989 Nature 337 345
[2] Kitano H, Ohashi T, Maeda A and Tsukada I 2006 Phys. Rev. B 73 092504
[3] Ohashi T, Kitano H, Tsukada I and Maeda A (Preprint cond-mat.supr-con/0710.4184)
[4] Ohashi T, Kitano H, Maeda A, Akaike H and Fujimaki A 2006 Phys. Rev. B 74 174522
[5] Naito M and Hepp M 2000 Jpn. J. Appl. Phys. 39 L485-L487
[6] Kitano H, Ohashi T and Maeda A 2008 Rev. Sci. Instum. 79 074701
[7] Fisher D S, Fisher M P A and Huse D A 1991 Phys. Rev. B 43 130
[8] On the magnetization, for example, Li Q 1996 Physical Properties of High Temperature Superconductors V, edited by Ginsberg D M (Singapore: World Scientific) p 209
[9] On the specific heat, for example, Ramallo M V and Vidal F 1999 Phys. Rev. B 59 4475 and references therein
[10] On the ac conductivity, for example, K. M. Paget K M, Boyce B R and Lemberger T R 1999 Phys. Rev. B 59 6645
[11] On the $I − V$ curve, for example, Strachan D R, Sullivan M C, Fournier P, Pai S P, Venkatesan T and Lobb C J 2001 Phys. Rev. Lett. 87 067007 and references therein