Enhancement of superconducting fluctuation under the coexistence of a competing pseudogap state in $Bi_2Sr_{2-x}R_xCuO_y$

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(Received 25 April 2010; revised manuscript received 29 May 2010; published 23 June 2010)

The onset temperature of superconducting fluctuation T_{onset} of $Bi_2Sr_{2-x}R_xCuO_y$ (R=La and Eu) was studied by measuring the Nernst effect. We found that T_{onset} has a x and R dependence that is quite different from both the pseudogap temperature T^* and the critical temperature T_c. Our results support the picture that the incoherent superconductivity, which has been observed below T_{onset}, is qualitatively different from the pseudogap phenomenon that is characterized by T^*. The experimentally obtained phase diagram indicates that the pseudogap state suppresses T_c and enhances superconducting fluctuation while having only small influence on T_{onset}.

DOI: 10.1103/PhysRevB.81.214520 PACS number(s): 74.72.−h, 74.25.Dw, 74.62.Dh

In conventional superconductors, pairing and the phase coherence occur simultaneously when the sample is cooled through the superconducting transition temperature T_c. Consequently, the superconducting gap, which corresponds to the binding energy of the paired electrons (Cooper pair), appears only in the superconducting state. In high-T_c cuprates, however, an energy gap in the density of states has been experimentally observed even above T_c. This normal-state gap is called pseudogap and whether it is related to fluctuation of the pairing state or a state that is competing with the superconducting order has been one of the fundamental issues for high-T_c cuprates for over a decade.[1–5]

Although fluctuation takes place more or less in any phase transition, the temperature range where it was claimed that pairing is incoherent in cuprates is surprisingly large.[6] It was also reported that the pseudogap has a momentum dependence that is similar to a d-wave superconducting gap.[7–9] These results have been regarded as supporting the preformed pairing picture of the pseudogap state. However, recent studies have shown that there is no direct connection between the superconducting gap and the pseudogap in both momentum and real spaces as was demonstrated by changing carrier concentration[10] or temperature.[11–14] A pseudogap was found also in a nonsuperconducting material,[15] in favor of the view that the pseudogap phenomenon is not directly related to high-T_c superconductivity. These results suggest that the pseudogap has its origin in a competing state rather than preformed pairs. This competing order scenario was supported further in recent experiments by demonstrating the presence of a short range charge-density-wave (CDW) order.[16,17] However, how this competing state suppresses high-T_c superconductivity is still not clear, i.e., whether it affects to the pair formation or prevents the developement of a phase coherence.

The Nernst coefficient is sensitive to superconducting fluctuation.[18–29] The Nernst signal in conventional metals is generally small, but it is enhanced with the growth of superconducting order when a superconducting material is cooled.[20–22] Many reports agree that the behavior of the Nernst signal in cuprates, which increases continuously from a small negative value starting at a temperature T_{onset} to a large positive value by approaching T_c, can be mainly explained based on a large fluctuation of superconducting order.[18–20,23–29] The data of the Nernst signal are consistent with the diamagnetic signal that also survives up to around T_{onset}, supporting the superconducting fluctuation scenario for the enhanced Nernst signal.[19,20,29]

The reported data show that T_{onset} lies far above T_c but below the pseudogap temperature T^* on the phase diagram.[19,30–34] However, it is still not well understood how the phenomena characterized by these three temperatures are related to each other. To answer this question, we focus on the $Bi_2Sr_{2-x}R_xCuO_y$ system. In this system, T_c depends on both x and R.[35–38] Changing x alters carrier doping, while changing R varies T_c without changing carrier doping, which provides us a unique opportunity to unveil how T_{onset} changes when T_c is different while keeping the carrier concentration the same. Combined with the results of our previous ARPES study in which the pseudogap temperature T^* was determined,[39] the three temperatures T_{onset}, T^*, and T_c are shown to be well separated on the phase diagram. Based on these results, we discuss that the presence of three distinct temperatures is a consequence of a coexisting and competing pseudogap state that brings about a large fluctuation of superconductivity.

Single crystals of $Bi_2Sr_{2-x}R_xCuO_y$ (R=La and Eu) were grown by the floating zone (FZ) method.[38] All the crystals used in this study were annealed with the same condition and quenched to room temperature.[38] Fig. 1(a) shows the relation between the Seebeck coefficient at 290 K $S(290)$ and x of our single crystals. Inductively coupled plasma (ICP) spectroscopy was employed to determine x. Based on the result shown in Fig. 1(a), the rare earth contents of the particular samples used in the Nernst coefficient measurements were determined by simultaneously measuring the Seebeck coefficient. T_c of the samples used in this study are shown in Fig. 1(b) together with the data of the samples of our previous study.[39,40]

The Nernst coefficient ν is defined as $\nu = E_y/(-\nabla_x T)B$ and can be obtained by measuring the electric field E_y, which is perpendicular to the magnetic field B and the temperature gradient $-\nabla_x T$. The temperature gradient was measured using differential type copper-constantan thermocouples. A heating pulse was applied to generate a temperature gradient in the

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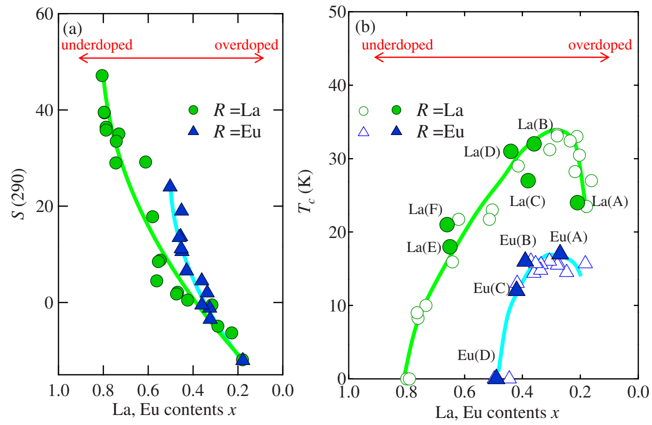

FIG. 1. (Color online) (a) The relation between the rare earth content x and the Seebeck coefficient at 290 K $S(290)$. (b) T_c as a function of x of the crystals used in this study (filled symbols) and those in our previous study (empty symbols) (Ref. 39).

sample. The duration of the heat pulse was a few hundred seconds and the generated signal was measured well after the temperature change became small to avoid mistakenly read the voltage during the transient state between heater on and off. Figures 2(a) and 2(b) show the field dependence of the Nernst signal E_y at constant temperatures and the temperature dependence of E_y at 9 T and -9 T of the sample denoted by La(D) in Fig. 1(b). Nernst coefficient at magnetic field B was determined by calculating $\nu(T)=[\nu(T,B)+\nu(T,-B)]/2$ to eliminate the longitudinal signal and the Seebeck voltage stemming from the electrodes. $\nu(T)$ at 9 T determined from the field and temperature dependencies are both shown in Fig. 2(c). As shown in the figure, $\nu(T)$ obtained from the two methods coincides quite well assuring that both methods have a similar accuracy. Therefore, we show only the Nernst coefficient measured by the temperature sweep mode with a constant rate (slower than 0.5 K/min) with applied fields of $|B|=9$ T in the following. The onset temperature T_{onset} was defined where the $\nu(T)$ signal deviates from a linear extrapolation of the higher temperature data [see Fig. 2(c)].

Figures 3(a)–3(f) show the $\nu(T)$ curves of the $Bi_2Sr_{2-x}R_xCuO_y$ samples with R=La and Figs. 3(g)–3(j) those for R=Eu. For comparison, we also measured $\nu(T)$ of a slightly underdoped $Bi_2Sr_2CaCu_2O_y$ (Bi2212, T_c=86 K) single crystal, and the result is shown in Fig. 3(k). We can see from these results that the Nernst signal shows a continuous change across T_c for all samples and the large signal below T_c survives far into the normal state (here T_c refers to its zero field limit value). This behavior is consistent with the earlier studies that report a large superconducting fluctuation for various cuprates.[19,30–34]

Figure 4(a) shows T_{onset} of the $Bi_2Sr_{2-x}R_xCuO_y$ samples together with our previously reported data of T^* and T_c.[39] As shown in Fig. 4(a), the x dependence of the three characteristic temperatures T_c, T_{onset}, and T^* are clearly different. With decreasing carrier doping from the optimum by increasing x, T_c decreases and T^* increases while T_{onset} of both R=La and R=Eu samples does not change much. At a fixed x, T_{onset} has a very similar value for R=La and Eu, while T_c and T^* depend strongly on the R element. Therefore, it is natural to think that T_{onset} is not much affected by the pseudogap state that is stabilized below T^*.

However, there is an interesting connection between the width of the superconducting fluctuation regime and T^*. As mentioned above, T_{onset} of La- and Eu-doped samples are not much different at a fixed x despite the large difference in T_c. This means that the temperature range of fluctuation is wider for an Eu-doped sample than that of a La-doped sample when compared at the same x. Figure 4(b) is a plot of $(T_{onset}-T_c)/T_c$ which corresponds to the width of the temperature range where the superconducting order is fluctuating. As shown in this figure, $(T_{onset}-T_c)/T_c$ and T^* have a similar x and R dependence, suggesting an intimate relation between the superconducting fluctuation and the pseudogap state characterized by T^*. This result can be coherently understood by recalling that the presence of a competing pseudogap state decreases the density of states that can participate in forming electron pairs below T_{onset}. Consequently, the overlap of the wave function of the paired electrons reduces and it becomes more difficult to form a coherent superconducting order. As a result, T_c decreases and a large

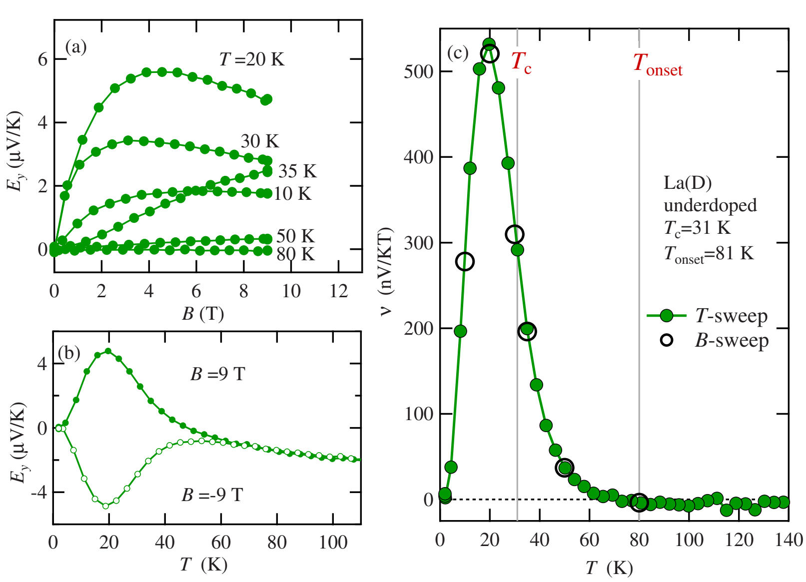

FIG. 2. (Color online) The field (a) and temperature (b) dependence of the Nernst signal E_y of the sample denoted by La(D) in Fig. 1(b). (c) A comparison of the temperature dependence of the Nernst coefficient $\nu(T)$ at 9 T determined from the field-sweep (a) and temperature-sweep (b) methods. The dotted line is a linear extrapolation of the higher temperature data.

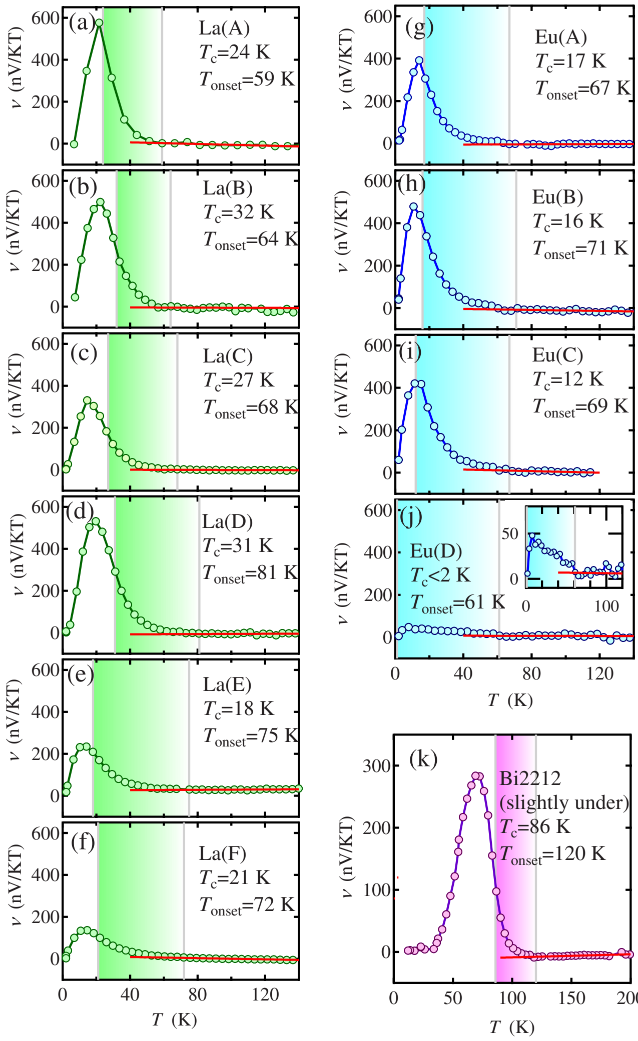

FIG. 3. (Color online) Temperature dependence of the Nernst coefficient $\nu(T)$ at 9 T of $Bi_2Sr_{2-x}R_xCuO_y$ with R=La and Eu is shown in (a)–(f) and (g)–(j), respectively. The inset to (j) shows the data of sample Eu(d) in an expanded scale. $\nu(T)$ of a slightly underdoped Bi2212 is shown in (k). The shaded region in each figure corresponds to the temperature range between T_{onset} and T_c (zero field limit). The red lines are linear extrapolations of the higher temperature data.

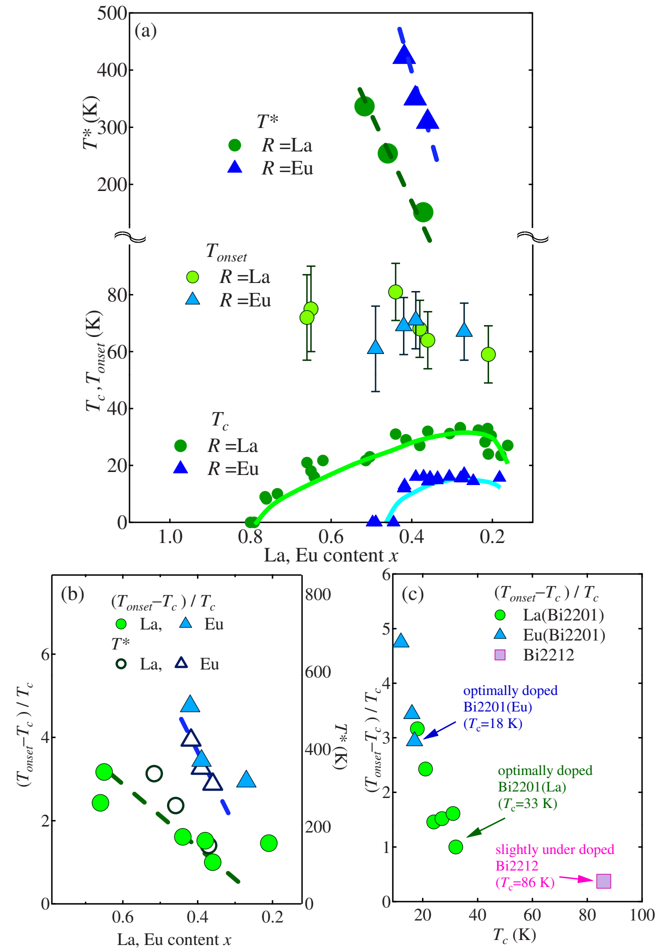

FIG. 4. (Color online) (a) The phase diagram showing the three characteristic temperatures T^* (Ref. 39), T_{onset}, and T_c of $Bi_2Sr_{2-x}R_xCuO_y$ (R=La and Eu). (b) The relation of $(T_{onset}-T_c)/T_c$ (left axis) and T^* (right axis) as a function of x. (c) The relationship between $(T_{onset}-T_c)/T_c$ and T_c of $Bi_2Sr_{2-x}R_xCuO_y$ (R=La and Eu) and the slightly underdoped $Bi_2Sr_2CaCu_2O_y$ (T_c=86 K) sample shown in Fig. 3(k).

superconducting fluctuation would be observed, which is consistent with our result. Here, it is known that changing the R element to one with a smaller ionic radius increases disorder.[36,37] In general sense, disorder decreases superfluid density (phase stiffness), and hence it may increase the superconducting phase fluctuation. However, the disorder in the present case is induced to out-of-CuO_2 plane. Because this out-of-plane disorder is known as a weak scattering source,[37,44] the naive expectation of its influence on superconductivity would be small, in contrast to the experimental results.[37] On the other hand, it has been suggested that out-of-plane disorder affects much on superconductivity via stabilizing the pseudogap state which competes with superconductivity.[39] Since the formation of the competing pseudogap state reduces the phase stiffness of superconductivity, we think that this is the main reason of the enhanced superconducting fluctuation observed in the present study. Note here that T_{onset} and $(T_{onset}-T_c)/T_c$ of the Bi2212 sample [Fig. 3(k)] were about 120 K and about 0.37, respectively, implying that the fluctuation regime is much narrower than Bi2201 as shown in Fig. 4(c). This is probably related to the smaller difference in the magnitude of the pseudogap and superconducting gap of Bi2212 compared to Bi2201.[11,41]

It is worthwhile mentioning that the sample with the lowest carrier doping of the R=Eu series showed also an increase in the Nernst signal at a temperature similar to T_{onset} of the other samples [see the inset to Fig. 3(j)], although this sample did not show a superconducting transition down to 2 K. This implies that the temperature below which superconducting fluctuation starts to grow is roughly the same as the optimally doped samples even when a coherent superconducting order is not formed at low temperatures. Here, it was reported for some other cuprates that T_{onset} decreased in the heavily underdoped region and went to zero with T_c.[20] The discrepancy may stem from the difference in the doping level where we are focusing on in the present study since T_c of

Eu-doped Bi2201 vanishes at relatively large hole doping. In other words, we may say from this comparison that the doping level has a strong influence on $T_{\rm onset}$, at least in the heavily underdoped region, while out-of-plane order has only small effect on $T_{\rm onset}$.

Finally, it is meaningful to discuss how the weak R and x dependence of $T_{\rm onset}$ can be reconciled with the results of ARPES and STM/STS experiments.[39,41–46] Our ARPES measurement of the superconducting state shows that extrapolating the gap function of the node region to the antinode gives a similar gap magnitude (we define this energy scale as Δ_{sc0}) for both R=La and Eu.[42,46] According to the STM/STS experiments, the magnitude of the energy gap of the regions where relatively large coherence peaks were observed did not depend much on the R element and the gap size was similar to Δ_{sc0}.[41,45] These weak R dependence of Δ_{sc0} both in momentum and real spaces are probably related to the weak R dependence of the onset temperature of pairing $T_{\rm onset}$. Interestingly, the mean field superconducting transition temperature calculated from Δ_{sc0} is comparable to $T_{\rm onset}$.[46] We think that this agreement suggests that Δ_{sc0} corresponds to the energy of pairing that starts to form at $T_{\rm onset}$ when the temperature is lowered.[41,45] On the other hand, it has been reported that both the pseudogap at the antinode[42–44,46] and the spatially averaged energy gap[41] increase with decreasing the ionic radius of the R element. Therefore, it is natural to think that the gap at the antinode is related to T^* and brought about the deviation from the mean field picture by enhancing the superconducting fluctuation.

In summary, we studied the onset temperature of superconducting fluctuation $T_{\rm onset}$ by Nernst effect measurements of $Bi_2Sr_{2-x}R_xCuO_y$. The experimentally obtained phase diagram shows clearly that the three characteristic temperatures T^*, $T_{\rm onset}$, and T_c are different irrespective to the carrier content x and the R element. The results indicate that the pseudogap state suppresses superconductivity while having little influence on the onset temperature of pairing, which in turn causes a large enhancement of superconducting fluctuation.

[1] V. J. Emery and S. A. Kivelson, Nature (London) **374**, 434 (1995).
[2] S. Chakravarty, R. B. Laughlin, D. K. Morr, and Chetan Nayak, Phys. Rev. B **63**, 094503 (2001).
[3] T. Timusk and B. Statt, Rep. Prog. Phys. **62**, 61 (1999).
[4] S. Hüfner, M. A. Hossain, A. Damascelli, and G. A. Sawatzky, Rep. Prog. Phys. **71**, 062501 (2008).
[5] M. R. Norman, D. Pines, and C. Kallin, Adv. Phys. **54**, 715 (2005).
[6] J. Corson, R. Mallozzi, J. Orenstein, J. N. Eckstein, and I. Bozovic, Nature (London) **398**, 221 (1999).
[7] M. R. Norman, H. Ding, M. Randeria, J. C. Campuzano, T. Yokoya, T. Takeuchi, T. Takahashi, T. Mochiku, K. Kadowaki, P. Guptasarma, and D. G. Hinks, Nature (London) **392**, 157 (1998).
[8] H. Ding, T. Yokoya, J. C. Campuzano, T. Takahashi, M. Randeria, M. R. Norman, T. Mochiku, K. Kadowaki, and J. Giapintzakis, Nature (London) **382**, 51 (1996).
[9] A. Kanigel, M. R. Norman, M. Randeria, U. Chatterjee, S. Souma, A. Kaminski, H. M. Fretwell, S. Rosenkranz, M. Shi, T. Sato, T. Takahashi, Z. Z. Li, H. Raffy, K. Kadowaki, D. Hinks, L. Ozyuzer, and J. C. Campuzano, Nat. Phys. **2**, 447 (2006).
[10] K. Tanaka, W. S. Lee, D. H. Lu, A. Fujimori, T. Fujii, Risdiana, I. Terasaki, D. J. Scalapino, T. P. Devereaux, Z. Hussain, and Z.-X. Shen, Science **314**, 1910 (2006).
[11] T. Kondo, T. Takeuchi, A. Kaminski, S. Tsuda, and S. Shin, Phys. Rev. Lett. **98**, 267004 (2007).
[12] W. S. Lee, I. M. Vishik, K. Tanaka, D. H. Lu, T. Sasagawa, N. Nagaosa, T. P. Devereaux, Z. Hussain, and Z.-X. Shen, Nature (London) **450**, 81 (2007).
[13] T. Kondo, R. Khasanov, T. Takeuchi, J. Schmalian, and A. Kaminski, Nature (London) **457**, 296 (2009).
[14] M. C. Boyer, W. D. Wise, K. Chatterjee, M. Yi, T. Kondo, T. Takeuchi, H. Ikuta, and E. W. Hudson, Nat. Phys. **3**, 802 (2007).
[15] N. Mannella, W. Yang, X. J. Zhou, H. Zheng, J. F. Mitchell, J. Zaanen, T. P. Devereaux, N. Nagaosa, Z. Hussain, and Z.-X. Shen, Nature (London) **438**, 474 (2005).
[16] W. D. Wise, M. C. Boyer, K. Chatterjee, T. Kondo, T. Takeuchi, H. Ikuta, Y. Y. Wang, and E. W. Hudson, Nat. Phys. **4**, 696 (2008).
[17] J.-H. Ma, Z.-H. Pan, F. C. Niestemski, M. Neupane, Y.-M. Xu, P. Richard, K. Nakayama, T. Sato, T. Takahashi, H.-Q. Luo, L. Fang, H.-H. Wen, Ziqiang Wang, H. Ding, and V. Madhavan, Phys. Rev. Lett. **101**, 207002 (2008).
[18] Z. A. Xu, N. P. Ong, Y. Wang, T. Kakeshita, and S. Uchida, Nature (London) **406**, 486 (2000).
[19] Y. Wang, L. Li, M. J. Naughton, G. D. Gu, S. Uchida, and N. P. Ong, Phys. Rev. Lett. **95**, 247002 (2005).
[20] Y. Wang, L. Li, and N. P. Ong, Phys. Rev. B **73**, 024510 (2006).
[21] A. Pourret, H. Aubin, J. Lesueur, C. A. Marrache-Kikuchi, L. Bergé, L. Dumoulin, and K. Behnia, Nat. Phys. **2**, 683 (2006).
[22] M. S. Nam, A. Ardavan, S. J. Blundell, and J. A. Schlueter, Nature (London) **449**, 584 (2007).
[23] H. Kontani, Phys. Rev. Lett. **89**, 237003 (2002).
[24] I. Ussishkin, S. L. Sondhi, and D. A. Huse, Phys. Rev. Lett. **89**, 287001 (2002).
[25] S. Tan and K. Levin, Phys. Rev. B **69**, 064510 (2004).
[26] C. Honerkamp and P. A. Lee, Phys. Rev. Lett. **92**, 177002 (2004).
[27] E. V. L. Mello and D. N. Dias, J. Phys.: Condens. Matter **19**, 086218 (2007).
[28] R. Daou J. Chang, David LeBoeuf, Olivier Cyr-Choiniere, Francis Laliberte, Nicolas Doiron-Leyraud, B. J. Ramshaw, Ruixing Liang, D. A. Bonn, W. N. Hardy, Louis Taillefer, Nature **463**, 519 (2010).
[29] L. Li, Y. Wang, S. Komiya, S. Ono, Y. Ando, G. D. Gu, and N. P. Ong, Phys. Rev. B **81**, 054510 (2010).
[30] F. Rullier-Albenque, R. Tourbot, H. Alloul, P. Lejay, D. Colson, and A. Forget, Phys. Rev. Lett. **96**, 067002 (2006).
[31] N. Johannsen, Th. Wolf, A. V. Sologubenko, T. Lorenz, A. Fre-

imuth, and J. A. Mydosh, Phys. Rev. B **76**, 020512(R) (2007).
[32] Z. A. Xu, J. Q. Shen, S. R. Zhao, Y. J. Zhang, and C. K. Ong, Phys. Rev. B **72**, 144527 (2005).
[33] A. N. Lavrov, Y. Ando, and S. Ono, EPL **57**, 267 (2002).
[34] K. Kudo, Y. Miyoshi, T. Sasaki, T. Nishizaki, and N. Kobayashi, J. Phys. Soc. Jpn. **75**, 124710 (2006).
[35] H. Nameki, M. Kikuchi, and Y. Syono, Physica C **234**, 255 (1994).
[36] H. Eisaki, N. Kaneko, D. L. Feng, A. Damascelli, P. K. Mang, K. M. Shen, Z.-X. Shen, and M. Greven, Phys. Rev. B **69**, 064512 (2004).
[37] K. Fujita, T. Noda, K. M. Kojima, H. Eisaki, and S. Uchida, Phys. Rev. Lett. **95**, 097006 (2005).
[38] Y. Okada and H. Ikuta, Physica C **445-448**, 84 (2006).
[39] Y. Okada, T. Takeuchi, T. Baba, S. Shin, and H. Ikuta, J. Phys. Soc. Jpn. **77**, 074714 (2008).
[40] The carrier concentration depends not only on x but also on the oxygen content y in this material. However, since we annealed all the samples with the same condition, x can be used as a qualitative measure of the carrier concentration within the purpose of this study.
[41] A. Sugimoto, S. Kashiwaya, H. Eisaki, H. Kashiwaya, H. Tsuchiura, Y. Tanaka, K. Fujita, and S. Uchida, Phys. Rev. B **74**, 094503 (2006).
[42] Y. Okada, T. Takeuchi, M. Ohkawa, A. Shimoyamada, K. Ishizaka, T. Kiss, S. Shin, and H. Ikuta, J. Phys.: Conf. Ser. **150**, 052197 (2009).
[43] Y. Okada, T. Takeuchi, A. Shimoyamada, S. Shin, and H. Ikuta, J. Phys. Chem. Solids **69**, 2989 (2008).
[44] M. Hashimoto, T. Yoshida, A. Fujimori, D. H. Lu, Z.-X. Shen, M. Kubota, K. Ono, M. Ishikado, K. Fujita, and S. Uchida, Phys. Rev. B **79**, 144517 (2009).
[45] T. Machida, Y. Kamijo, K. Harada, T. Noguchi, R. Saito, T. Kato, and H. Sakata, J. Phys. Soc. Jpn. **75**, 083708 (2006).
[46] Y. Okada *et al.* (unpublished).