Enhancement of superconducting fluctuation under the coexistence of a competing pseudogap state in Bi$_2$Sr$_{2-x}$R$_x$CuO$_y$

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The onset temperature of superconducting fluctuation $T_{\text{onset}}$ of Bi$_2$Sr$_{2-x}$R$_x$CuO$_y$ ($R=$La and Eu) was studied by measuring the Nernst effect. We found that $T_{\text{onset}}$ 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 $T_{\text{onset}}$, 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 $T_{\text{onset}}$.

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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.\textsuperscript{1,2}

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.\textsuperscript{3} It was also reported that the pseudogap has a momentum dependence that is similar to a $d$-wave superconducting gap.\textsuperscript{4,5} 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\textsuperscript{6} or temperature.\textsuperscript{7,8} A pseudogap was found also in a non-superconducting material\textsuperscript{9} 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.\textsuperscript{10,11} 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 development of a phase coherence.

The Nernst coefficient is sensitive to superconducting fluctuation.\textsuperscript{18-21} 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.\textsuperscript{22-25} Many reports agree that the behavior of the Nernst signal in cuprates, which increases continuously from a small negative value starting at a temperature $T_{\text{onset}}$ to a large positive value by approaching $T_c$, can be mainly explained based on a large fluctuation of superconducting order.\textsuperscript{18-20,23-29} The data of the Nernst signal are consistent with the diamagnetic signal that also survives up to around $T_{\text{onset}}$, supporting the superconducting fluctuation scenario for the enhanced Nernst signal.\textsuperscript{15,20,25}

The reported data show that $T_{\text{onset}}$ lies far above $T_c$ but below the pseudogap temperature $T^*$ on the phase diagram.\textsuperscript{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$_2$Sr$_{2-x}$R$_x$CuO$_y$ system. In this system, $T_c$ depends on both $x$ and $R$.\textsuperscript{35,36} Changing $x$ alters carrier doping, while changing $R$ varies $T_c$ without changing carrier doping, which provides us a unique opportunity to unveil how $T_{\text{onset}}$ 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,\textsuperscript{38} the three temperatures $T_{\text{onset}}$, $T^*$, 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$_2$Sr$_{2-x}$R$_x$CuO$_y$ ($R=$La and Eu) were grown by the floating zone (FZ) method.\textsuperscript{38} All the crystals used in this study were annealed with the same condition and quenched to room temperature.\textsuperscript{38} Figure 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.\textsuperscript{39,40}

The Nernst coefficient $\nu$ 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 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 (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 $T_{\text{onset}}$ was defined where the $\nu(T)$ signal deviates from a linear extrapolation of the higher temperature data (see Fig. 2(c)).

Figures 3 (a)-(f) show the $\nu(T)$ curves of the Bi$_2$Sr$_{2-x}$R$_x$CuO$_y$ samples with $R=$La and (g)-(j) those (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.

![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).](image)

![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.](image)
FIG. 3: (Color online) Temperature dependence of the Nernst coefficient $\nu(T)$ at 9 T of Bi$_2$Sr$_{2-x}$La$_x$CuO$_y$ with $R=$La a Eu is shown in (a)-(f) and (g)-(j), respectively. The inset (j) shows the data of sample Eu(D) in an expanded scale. $\nu(T)$ of a slightly underdoped Bi2212 is shown in (k). T shaded region in each figure corresponds to the temperature range between $T_{\text{onset}}$ and $T_c$ (zero field limit). The red line are linear extrapolations of the higher temperature data.

FIG. 4: (Color online) (a) The phase diagram showing the three characteristic temperatures $T^*$, $T_{\text{onset}}$, and $T_c$ of Bi$_2$Sr$_{2-x}$La$_x$CuO$_y$ (R=La and Eu). (b) The relation of $(T_{\text{onset}}-T_c)/T_c$ (left axis) and $T^*$ (right axis) as a function of $x$. (c) The relationship between $(T_{\text{onset}}-T_c)/T_c$ and $T_c$ of Bi$_2$Sr$_{2-x}$Eu$_x$CuO$_y$ (R=La and Eu) and the slightly underdoped Bi$_2$Sr$_2$CaCu$_2$O$_y$ ($T_c = 86$ K) sample shown in Fig. 3 (k).
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 $T_{\text{onset}}$ of the other samples (see the inset to Fig. 3(b)), 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 $T_{\text{onset}}$ decreased in the heavily underdoped region and went to zero with $T_c$. 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 $T_{\text{onset}}$, at least in the heavily underdoped region, while out-of-plane order has only small effect on $T_{\text{onset}}$.

It is meaningful to discuss how the weak $R$ and $x$ dependence of $T_{\text{onset}}$ can be reconciled with the results of ARPES and STM/STS experiments. 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 as $\Delta_{\text{sc}}$) for both $R$=La and Eu. 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 $\Delta_{\text{sc}}$. These weak $R$ dependence of $\Delta_{\text{sc}}$ both in momentum- and real-spaces are probably related to the weak $R$ dependence of the onset temperature of pairing $T_{\text{onset}}$. Interestingly, the mean field superconducting transition temperature calculated from $\Delta_{\text{sc}}$ is comparable to $T_{\text{onset}}$. We think that this agreement suggests that $\Delta_{\text{sc}}$ corresponds to the energy of pairing that starts to form at $T_{\text{onset}}$ when the temperature is lowered. On the other hand, it has been reported that the pseudogap at the antinodes increases 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 $T_{\text{onset}}$ by Nernst effect measurements of Bi$_2$Sr$_{2-x}$CaCuO$_y$. The experimentally obtained phase diagram shows clearly that the three characteristic temperatures $T^*$, $T_{\text{onset}}$, and $T_c$ are different irrespectively 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.

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1. V. J. Emery, and S. A. Kivelson, Nature 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. Huffner, M. A. Hassain, A. Damascelli, and G. A. Sawatzky, Rep. Prog. Phys. 71, 062501 (2008).
5. M. R. Norman, D. Pines, and C. Kallin, Advances in Physics, 54, 715 (2005).
6. J. Corson, R. Mallozzi, J. Orenstein, J. N. Eckstein, and I. Bozovic, Nature 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, 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 382, 51 (1996).
9. A. Kanigel, M. R. Norman, M. Randeria, U. Chatterjee, S. Souma, A. Kaminis, H. M. Fretwell, S. Rosenkranz, M. Shi, T. Sato, T. Takahashi, Z. Z. Li, H. Ruffy, K. Kadowaki, D. Hinks, L. Ozyuzer, and J. C. Campuzano, Nature Phys. 2, 447 (2006).
10. K. Tanaka, W. S. Lee, D. H. Lu, A. Fujimori, T. Fujii, Risidiana, I. Terasaki, D. J. Scalapino, T. P. Devereaux, Z. Hussain, and Z.-X. Shen, Science 314, 1910 (2006).
11. T. Kondo, T. Takeuchi, A. Kaminis, 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 450, 81 (2008).
13. T. Kondo, R. Khasanov, T. Takeuchi, J. Schmalian, and A. Kaminis, Nature 457, 296 (2008).
14. M. C. Boyer, W. D. Wise, K. Chatterjee, M. Y. 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, Z.-X. Shen, Nature 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.-W. 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 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, Nature Phys. 2, 683 (2006).
22. M. S. Nam, A. Ardavan, S. J. Blundell, and J. A. Schlueter, Nature 449, 584 (2007).
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.