Reentrant Irreversibility and Magnetic Transition in Strongly Underdoped $Y_{0.47}Pr_{0.53}Ba_2Cu_3O_{7-\delta}$ Single Crystals

V. Sandu,[1,*] P. Gyawali,[1] T. Katuwal,[1]
B. J. Taylor,[2] M. B. Maple,[2] and C. C. Almasan[1]

[1]*Department of Physics, Kent State University, Kent, OH 44242, USA*
[2]*Department of Physics, University of California at San Diego, La Jolla, CA, USA*

Abstract. Magnetization measurements on $Y_{0.47}Pr_{0.53}Ba_2Cu_3O_7$ single crystal in the vicinity of the superconducting transition temperature T_c = 7 K revealed a reentrant irreversibility for applied magnetic fields higher than the irreversibility field H_{irr}. The transition to the second hysteresis loop occurs through an irreversible jump in magnetization. The temperature range of this irreversibility extends up to 40 K. Generally, this double hysteretic regime has been associated in low dimensional systems with the pinning of spin and/or charge density waves.

Keywords: magnetization, $Y_{1-x}Pr_xBa_2Cu_3O_7$, density waves, fluctuations.
PACS: 74.25.Ha, 74.25.Op, 74.72.Bk, 75.30.Fv

Underdoped cuprates seem to be an inexhaustible source of new phenomena whose origin is in the low charge carrier density and low dimensional charge conducting substructures. These features represent a very strong hint that an extended fluctuation regime has to accompany the superconducting (SC) to normal phase transition. Recently, Panagopoulos *et al.* [1] reported thermal hysteresis in $La_{2-x}Sr_xCuO_4$ single crystals, which extends up to 290 K, suggesting an association with superconducting fluctuations (SF). However, the question that still remains is: If the low charge carrier density enhances the superconducting fluctuations, why there is no continuous extension of the fluctuation regime with increasing underdoping? It was found that close to the superconducting to antiferromagnetic limit, the range of the superconducting phase fluctuations shrinks (but does not vanish) [2-3]. Therefore, it is of interest to check more carefully the range of carrier concentrations where the superconducting phase is very close to the superconductor to insulator transition. In our investigations, we used the antidoping effect of praseodymium, which partially substitutes for yttrium as $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ and drives the system to the Mott antiferromagnetic state (AF) for x ≥ 0.55. μSR investigations [4] have revealed a smooth crossover and small overlap for x < 0.55 between SC and AF orders of both Pr and planar Cu spins. In these highly underdoped materials we have found a double hysteretic behavior as a function of field. Specifically, a second loop opens close to T_c and remains distinct up to temperatures as high as $5 \times T_c$.

Magnetization M vs H ($H \| c$), M vs T, and magnetic relaxation measurements were performed on $Y_{0.47}Pr_{0.53}Ba_2Cu_3O_7$ (T_c = 7 K) single crystals using a SQUID magnetometer. These measurements give a superconducting volume fraction close to 100% at 4 K. Up to 6 K, the $M(T,H)$ curves are typical for cuprates. With further increasing T, the opening of a new irreversible loop appears after a jump in magnetization. With increasing T, the new hysteresis loop, including the jump, shifts to lower H values. Both loops eventually merge even though they still remain distinct (see Fig. 1 for T = 6.7 K). The second irreversible loop is still visible up to T as high as 40 K (Inset to Fig. 1). Relaxation data, taken above T_c, show an extremely small average relaxation rate, $\Delta M/\Delta t$ = 1.2 × 10^{-11} emu/sec, at 12 K and 0.03 T (data not shown).

$M(T)$ plots show thermal hysteresis (a difference between zero-field-cooled and field-cooled magnetization curves, see Fig. 2) above T_c, which overlaps the expected paramagnetism.

To understand this behavior, we recall that the proximity to antiferromagnetism in strongly underdoped cuprates generates strong antiferromagnetic fluctuations, which, at microscopic level, coexist with the superconducting ordering. Neutron scattering experiments on $La_{2-x}Sr_xCuO_4$, have shown that these remnant antiferromagnetic excitations are consistent with spin density waves [5]. If spin (or charge) modulation is present in the superconducting state, then, above the critical temperature, the competing density wave (DW) type order is dominant since superconductivity is present only through fluctuations of the phase of the order parameter [6].

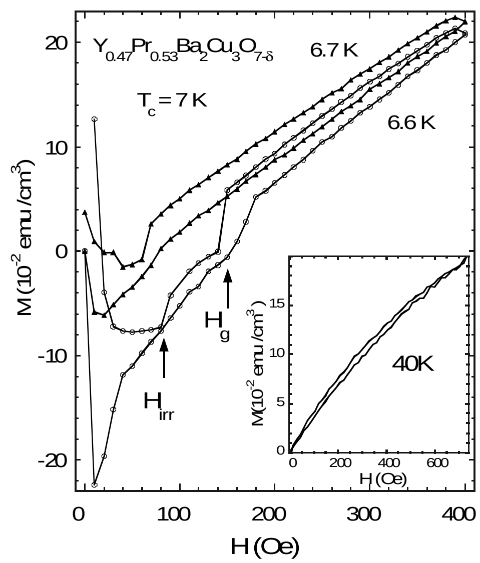

FIGURE 1. Plots of magnetization M vs magnetic field H in the superconducting regime of the $Y_{0.47}Pr_{0.53}Ba_2Cu_3O_{7-\delta}$ single crystal for T = 6.6 (open symbols) and 6.7 K (solid triangles). The two arrows mark the irreversibility field H_{irr} and the opening of the second hysteresis H_g. Inset: the hysteresis curve at 40 K.

The low dimensionality of the cuprates makes them sensitive to modulated ordering [7]. In the case of the present experiments, it is less likely that SF are responsible for the second irreversibility. The pinning becomes negligible once the reversibility is reached and a recovery of irreversibility at higher fields as a result of SF is not physically acceptable at temperatures as high as $5 \times T_c$, where thermal fluctuations become much stronger than the pinning energy. On the other hand, it was shown that both d-wave SC and d-wave DW promote local AF state in the presence of impurities [8]. At low hole concentrations, the carriers are expelled from the AF regions creating nano-scale charge and spin inhomogeneities. Therefore, it is expected the coexistence of AF both with SC, at low temperature, and with DW at high temperature. In the latter T-range, the irreversibility appears due to the infinite number of metastable states of the DW in the presence of impurities, which makes the local magnetic order history dependent, hence, the total moment irreversible.

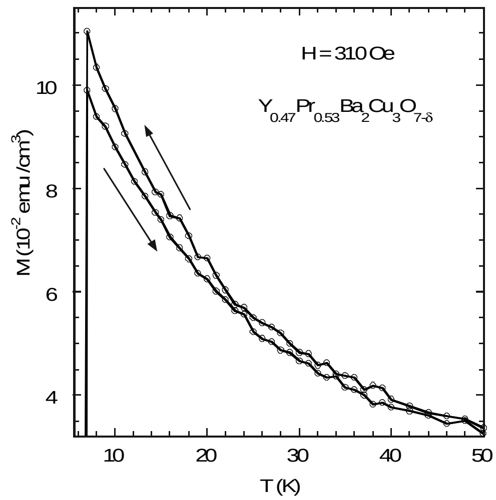

FIGURE 2. Plots of magnetization M vs temperature T for the $Y_{0.47}Pr_{0.53}Ba_2Cu_3O_{7-\delta}$ single crystal measured in a field of 310 Oe.

In summary, we found that in strongly underdoped but still superconducting Pr-doped cuprates there is a second magnetic hysteresis and, associated, a thermal hysteresis in the normal state. We argue that this new irreversibility is consistent with the existence of local antiferromagnetic regions induced by d-wave type density waves in the presence of impurities.

ACKNOWLEDGMENTS

This research was supported by the National Science Foundation under Grant No. DMR-0406471 at KSU and the US Department of Energy under Grant No. DE-FG02-04ER-46105 at UCSD.

***** Permanent address: *National Institute of Materials Physics, Bucharest-Magurele, 01725 Romania.*

REFERENCES

1. C. Panagopoulos, *et al.*, *Phys. Rev. B* **69**, 144508 (2004).
2. Y. Wang, *et al.*, *Phys. Rev. Lett.* **88**, 257003 (2002).
3. T. Katuwal, *et al.*, *Phys Rev B* **72**, 174501 (2005).
4. D. W. Cooke *et al.*, *Phys. Rev. B* 41 4802 (1990).
5. S. Wakimoto, *et al.*, *Phys. Rev. B* **60**, R769 (1999).
6. S. Sachdev and E. Demler, *Phys. Rev. B* **69**, 144504 (2004).
7. B. Grévin, *et al.*, *Phys. Rev. Lett.* **80**, 2405 (1998).
8. Y. Osashi, *Phys Rev B* **60** 15388, (1999).