Scaling of Conductivity through the Critical Temperature in $Y_{0.54}Pr_{0.46}Ba_2Cu_3O_7$

V. Sandu,[1,2] T. Katuwal,[1] B. J. Taylor,[3] M. B. Maple,[3] and C. C. Almasan[1]

[1]*Department of Physics, Kent State University, Kent, OH 44242, USA*
[2]*National Institute of Materials Physics, 077125 Bucharest-Magurele, Romania*
[3]*Department of Physics, University of California at San Diego, La Jolla, CA, USA*

Abstract. In-plane conductivity σ_{ab} curves of $Y_{0.54}Pr_{0.46}Ba_2Cu_3O_7$ single crystals, measured at constant temperature T in magnetic fields H tilted with an angle θ relative to the *c*-axis, were found to map onto a single curve in a σ_{ab} vs $H\cos\theta$ plot. This scaling occurs both below and above the critical temperature T_c, maintaining the same convexity, and is consistent with the dissipation caused by the motion of two-dimensional (2*D*) vortices. This indicates the presence of 2*D* vortices above T_c. A second scaling $\sigma_{ab}(H\cos\theta)$ takes place at higher *T*, with an opposite convexity. This scaling is consistent with the dissipation of quasiparticles. There is a *T* range between these two regimes where no scaling is found. We attribute the absence of scaling in this intermediate regime to a 2*D* to 3*D* crossover in the vortex matter.

Keywords: angular magnetoresistivity, $Y_{1-x}Pr_xBa_2Cu_3O_7$, phase fluctuations, anisotropy, scaling.
PACS: 74.25.Fy, 74.40.+k, 74.72.Bk, 72.15.Gd

Underdoped cuprate superconductors display an extended regime of fluctuations of the order parameter $\Delta=|\Delta|\exp(i\varphi)$ due to the reduced dimensionality and charge carrier density. Experimental findings [1-3] and simulations using the *XY*-model [4] show that phase φ fluctuations prevail over amplitude $|\Delta|$ fluctuations above the superconducting transition temperature T_c, over an extended temperature range up to $T_\varphi = \zeta T_c$, with $\zeta = 1.5$ for 3*D* and $\zeta = 2$ for 2*D* systems. As a result, up to T_φ, the correlator of the order parameter mirrors only the decay of phase correlations. As long as the phase correlation length does not vanish, i.e., up to T_φ, vortices can exist even above T_c. If so, their motion under a driven current produces an additional dissipation, besides that of quasiparticles.

In angle dependent charge transport experiments, flux-flow and quasiparticle resistivities follow different scaling laws as a function of magnetic field and angle. Therefore, it is expected that each one imposes its scaling in the temperature range where it dominates. Here, we present the evolution of the scaling function of the conductivity with increasing *T* in an attempt to find the limits of the regime of phase fluctuations of the superconducting order parameter.

Resistivity measurements in magnetic field were performed on $Y_{0.54}Pr_{0.47}Ba_2Cu_3O_{7-\delta}$ (T_c = 38 K) single crystals. The experimental procedure is presented elsewhere [5].

Figures 1(a) and 1(b) are plots of the conductivity as a function of $x = H|\cos\theta|$. All data points fall, at constant *T*, on the same curve with positive convexity, $d^2\sigma/dx^2 > 0$ for T ≤ 44 K. For 45 < *T* < 60 K, the conductivity still shows a positive convexity over this large temperature range, but the above scaling fails [(see data of Fig. 1(b) at 45 K]. The failure of the scaling most likely arises from the crossover to the 3*D* vortex regime as the *c*-axis coherence length ξ_c exceeds the interlayer spacing. It is noteworthy that this effect occurs at a higher temperature than expected from the Ginzburg-Landau theory, in which ξ_c diverges at the critical temperature. At even higher temperatures, the conductivity scales with $H^2\cos^2\theta$ (see 60 and 70 K data of Fig. 2).

To understand the behavior of conductivity over the above three regimes, we have to include in dissipation both quasiparticle and flux flow dissipation channels; namely, the conductivity is given by [5]:

$$\sigma = \sigma_0 - ax^2 + \frac{b}{x}, \qquad (1)$$

with $x = H|\cos\theta|$, and a ($ax^2 << \sigma_0$) and b temperature dependent coefficients. At low temperatures, b, which is of the order of H_{c2}, is much larger than H and the last contribution in Eq. (1) is dominant, hence $\sigma \approx \sigma_{FF} = b/x$. Figure 1(a) shows the fits of the data with a $1/x$ function for 20 and 30 K (solid lines). This functional form of conductivity is reasonable. In the intermediate temperature range, the conductivity is given by the whole expression of Eq. (1). For $T \geq 60$ K, the conductivity behaves like $\sigma = \sigma_0 - ax^2$. Figure 2 shows the plot of conductivity data as a function of x^2 measured at 60 and 70 K in a magnetic field of 12 T.

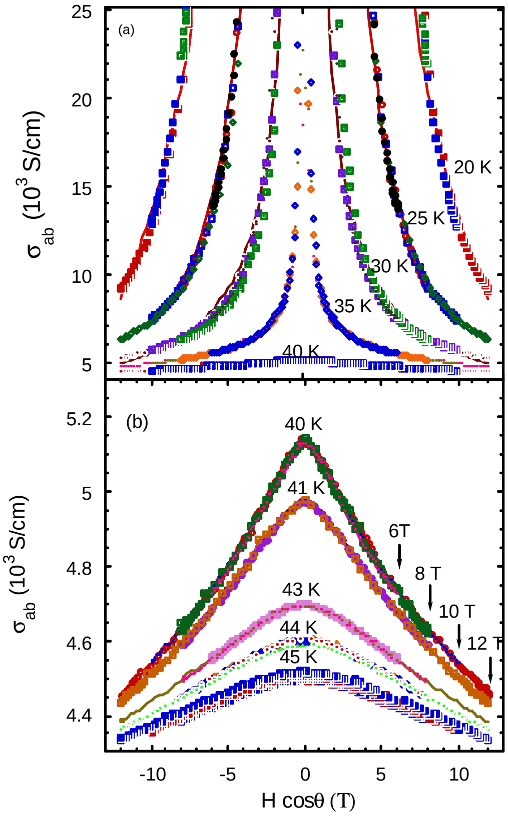

FIGURE 1. In-plane conductivity σ_{ab} as a function of $H\cos\theta$ for applied magnetic fields of 6, 8, 10 and 12 T and a temperature range (a) $20 \leq T \leq 40$ K and (b) $40 \leq T \leq 45$ K. The solid lines in panel (a) are fits of the data with the function $F(x) = const + b/x$, with $x = H\cos\theta$.

The main result of these experiments is that phase fluctuations survive up to a temperature of $1.15 \times T_c = 44$ K as 2*D* vortex like excitations and, further as 3D vortex lines up to $1.5 \times T_c = 57$ K. This is in agreement with the assumption that, in underdoped superconducting cuprates, there is an extended regime above T_c in which the phase fluctuation of the superconducting order parameter is an important ingredient in the dissipation process. It is noteworthy that some experimental data [6] suggest that the amplitude of the order parameter keeps fluctuating up to a much higher temperature, identified with the pseudogap temperature.

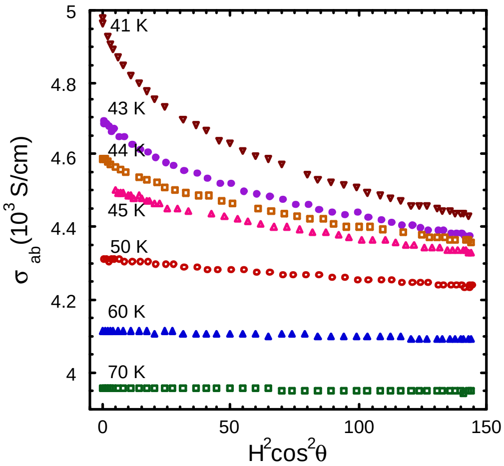

FIGURE 2. In-plane conductivity σ_{ab} measured in a field of 12 T as a function of $H^2 \cos^2\theta$.

In summary, we have found that vorticity is manifested as a continuous process through the critical temperature up to temperatures as high as $T_\varphi = 57$ K which we attribute to the vanishing of the phase correlation length. A two dimensional to three dimensional crossover in the vortex matter was found in the angular dependence of the conductivity at a temperature much higher than the one predicted by the Ginzburg -Landau theory.

ACKNOWLEDGMENTS

This research was supported by the National Science Foundation under Grant No. DMR-0406471 at KSU, the US Department of Energy under Grant No. DE-FG02-04ER-46105 at UCSD, and by the Romanian ME under Grant MATNANTECH No. 260/2004.

REFERENCES

1. J. Corson, *et al.*. *Nature* **398**, 221-223, (1998).
2. Z. A. Xu, *et al.*, *Nature* **406**, 486-488, (1998).
3. Y. Wang, *et al.*, *Phys. Rev. Lett.* **88**, 257003 (2002).
4. C. Meingast, *et al.*, *Phys. Rev. Lett.* **89**, 229704 (2002); R. Markiewicz, *Phys. Rev. Lett.* **89**, 229703 (2002).
5. V. Sandu, *et al.*, *Phys. Rev. Lett.* **93**, 177005 (2004).
6. T. Shibauchi, *et al.*, *Phys. Rev. Lett.* **86**, 5763-5766 (2001).