Nernst effect of epitaxial $Y_{0.95}Ca_{0.05}Ba_2(Cu_{1-x}Zn_x) _3O_y$ and $Y_{0.9}Ca_{0.1}Ba_2Cu_3O_y$ films

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We report Nernst effect measurements of some crystalline films grown by pulsed laser deposition, namely slightly under- and nearly optimally-doped $Y_{0.95}Ca_{0.05}Ba_2(Cu_{1-x}Zn_x) _3O_y$ (with $x = 0$, 0.02 and 0.04) and over-doped $Y_{0.9}Ca_{0.1}Ba_2Cu_3O_y$. We argue that our results and most of the data for LSCO [1] are consistent with the theory of Gaussian superconducting fluctuations [2].

In conventional type II superconductors, the motion of Abrikosov vortices induced by a thermal gradient ($\nabla T$), perpendicular to the magnetic field $B$, gives rise to a transverse electric field $E_y$ and hence a Nernst voltage, $\nu = \nabla E_y$. In some influential papers, measurements of significant Nernst signals over a broad temperature range well above the superconducting transition temperature ($T_c$) have been reported, initially for $La_{2-x}Sr_xCuO_4$ (LSCO) [1] and later for several other cuprate crystals [3]. These results have been interpreted as evidence for the existence of vortex-like excitations above $T_c$, and for two separate temperature scales for phase and amplitude fluctuations of the superconducting order parameter. Because $\nu$ seemed to be particularly large for under-doped samples, in the pseudogap region of the cuprate phase diagram, it was suggested that the pseudogap is actually caused by superconducting fluctuations, in contradiction to arguments based on heat capacity studies [4]. More recently, by introducing controlled amounts of disorder by electron irradiation [5] or by Zn doping [6] other authors have shown that the onset of a larger Nernst signal is not linked to $T^*$, the characteristic energy scale of the pseudogap. The Nernst data [1, 3] have also been cited by many authors in support of the scenario in which the pseudogap remains finite over the whole superconducting region of the cuprate phase diagram rather than going to zero for slightly over-doped samples.

Nernst effect studies of the cuprates inspired an extension of the theory of superconducting fluctuations [7] by Ussishkin et al. [2] who showed that for weak (Gaussian) fluctuations (GF), the off-diagonal term, $\alpha^{xy}$, of the Peltier tensor is given by:

$$\alpha^{xy} = \frac{k_B e \xi_{ab}^2}{3h} \frac{1}{l_B^2 s \sqrt{1 + (2\zeta_c/s)^2}}$$

(1)

where $\zeta_c$ is the coherence length, $l_B = (\hbar/eB)^{1/2}$ is the magnetic length and the anisotropy $\gamma = \xi_{ab}/\xi_c$. The fluctuation contribution to the Nernst coefficient is given by:

$$\nu_s = \frac{\alpha^{xy} \sigma}{\sigma(T)B}$$

(2)

where $\sigma(T)$ is the total electrical conductivity. Ussishkin et al. [2] found that Gaussian superconducting fluctuations account well for Nernst data of optimally doped and over-doped $La_{2-x}Sr_xCuO_4$ crystals with $x = 0.20$ and 0.17 but for an under-doped sample with $x = 0.12$ they suggested that stronger non-Gaussian fluctuations give a larger Nernst signal and also reduce $T_c$ from the mean field value. Recently their GF theory [2] was verified over a wide temperature range by experiments on thin amorphous low-temperature superconductors [8], this is especially important in view of an alternative theoretical viewpoint reported recently [9].

Here we report measurements of the Nernst effect for the same Ca and Zn substituted $YBa_2Cu_3O_{6+x}$ (YBCO) epitaxial films for which in-plane resistivity and magnetoresistivity $\rho(B,T)$, and Hall coefficient $R_H$, data were previously reported [10]. We show that our Nernst data above $T_c$ are consistent with GF theory [2]. Although the Nernst signal is more clearly visible in our Zn-doped samples, we argue that this is primarily because of their smaller conductivity. In contrast to the suggestion ofRefs. [5] and [6] for our samples there is no evidence for the Nernst signal being enhanced by another mechanism such as inhomogeneous superconductivity. We also show that GF can account for the general behavior of Nernst data of LSCO [1] over the whole doping range.

Values of the hole concentration $p$ determined from the room-temperature thermopower, $S(290 K)$ [11], are given in Table I together with $T_c$ values and transition widths (FWHM, $\delta T_c$, in $dp/dT$). Small changes in $p$ have occurred since the previous work and therefore quantities such as $\rho(B,T)$ and $R_H$ were measured again below 120 K. In the Nernst set-up used here the 10 x 5 x 1 mm$^3$ SrTiO$_3$ substrate was glued between copper and stainless steel posts each holding a heater and a small Cernox thermometer. A sketch of the patterned thin film is shown in the insert to Fig. 1(a). The temperature gradient of 2 or 4 K/cm was applied along the longitudinal direction, $B$ was applied along the c direction of the film (perpendicu-
latter to the surface of the substrate) and the Nernst signal was measured between the “Hall contacts” using a Keithley Model 182 nanovoltmeter. The transverse voltage $V_B$ was measured for $+B$ and $-B$ while sweeping either $T$ or $B$, the Nernst voltage was defined as $\frac{1}{2}(V_B - V_-)$ and converted to electric field using the distance (1.5 mm) between the inside edges of opposite gold contact pads. $\nabla T$ was checked by measuring the thermoelectric voltage between two longitudinal contacts. The precise temperature of the sample was determined by comparing $\rho(T, B)$ data measured with and without an applied temperature gradient.

FIG. 1: Color online. (a) In-plane resistivity versus temperature for YBaCuO ($x = 0, 0.02$ and 0.04) and YBaCuO superconductors. The points at which $\rho(T, B)$ curves show the usual “fanning out” property which is typical of the cuprates but is not observed in conventional type II superconductors. The points at which $\rho(T, B)$ $\simeq 0$ on the scales shown correspond to the irreversibility line $B_{irr}(T)$. Many researchers consider that for $B > B_{irr}(T)$ there is a wide “vortex liquid” region where vortices are still present but no longer form a regular lattice and are no longer pinned. We have argued previously for an alternative viewpoint in which the vortices disappear for $B$ equal to, or slightly greater than $B_{irr}(T)$. In other words $B_{irr}(T)$ could actually be the $B_{c2}(T)$ line which has been heavily suppressed by superconducting fluctuations that may be further enhanced by the magnetic field. This view is still controversial but is not inconsistent with a recent dynamical scaling analysis of voltage-current measurements for YBCO single crystals and films [13].

If one does assume that vortices are still present well above $B_{irr}(T)$ then the ratio $\nu(T, B)/\rho(T, B)$ can be used to determine the entropy per vortex as has been done for LSCO [13]. This assumes isotropic vortex pinning forces, since the resistivity arises from sideways motion of the vortices (perpendicular to the direction of current flow) while the Nernst voltage arises from the flow of vortices along the length of the sample. In Fig. 1(b) the onset of the Nernst signal is the same as the onset of resistivity to within experimental uncertainty of $\pm 0.5$

FIG. 2: Color online. Nernst coefficient, $\nu$, versus reduced temperature $t$ for the Y$_{1-x}$Ca$_x$Ba$_2$(Cu$_{1-z}$Zn$_z$)$_3$O$_y$ ($z = 0.05, 0.1; x = 0, 0.02$ and 0.04) films. Inset shows $S \tan(\theta)/B$ for the same samples, where $S$ is the thermopower and $\theta$ the Hall angle in a field $B = 6T$. Zero-field $\rho(T)$ data for the four films are shown in Fig. 1(a). Representative $\rho(T, B)$ and Nernst data are shown for the over-doped 10 % Ca sample ($p = 0.198$) in Fig. 1(b) and for the most under-doped 5 % Ca sample ($p = 0.136$) in Fig. 1(c). The $\rho(T, B)$ curves show the usual “fanning out” property which is typical of the cuprates but is not observed in conventional type II superconductors. The points at which $\rho(T, B) \simeq 0$ on the scales shown correspond to the irreversibility line $B_{irr}(T)$. Many researchers consider that for $B > B_{irr}(T)$ there is a wide “vortex liquid” region where vortices are still present but no longer form a regular lattice and are no longer pinned. We have argued previously for an alternative viewpoint in which the vortices disappear for $B$ equal to, or slightly greater than $B_{irr}(T)$. In other words $B_{irr}(T)$ could actually be the $B_{c2}(T)$ line which has been heavily suppressed by superconducting fluctuations that may be further enhanced by the magnetic field. This view is still controversial but is not inconsistent with a recent dynamical scaling analysis of voltage-current measurements for YBCO single crystals and films [13].

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FIG. 3: Color online: $\alpha/B = \sigma_{ab}(T)\nu$ versus $t$ for $Y_{0.95}\text{Ca}_{0.05}\text{Ba}_2(\text{Cu}_{1-x}\text{Zn})_x\text{O}_y$ ($x = 0, 0.02, 0.04$) and $Y_{0.9}\text{Ca}_{0.1}\text{Ba}_2\text{Cu}_3\text{O}_y$ films. The thin dotted lines show fits to Eq. 1. The inserts are plots of $\alpha/B$ for the two Zn doped films, $S\tan\theta_H$ is particularly small which makes the GF term more visible.

There are small linear regions extrapolating to $y = 0$ near the measured value of $T_c$. At higher $T$ these cross over to the quadratic law, $\alpha^{-2} \sim (T - T_c)^2$ expected in the 2D limit. A similar analysis of the heat capacity of several cuprate families showed that the difference, $\Delta T_c$, between the measured value, $T_m^c$, and the fitted or linearly extrapolated value, $T_c^f$, was caused by strong (critical) fluctuations. $\Delta T_c$ was $\sim 1$ K for YBCO samples, as found for the present Nernst data, and $\sim 5$ K for other extremely anisotropic cuprates.

The fitting parameters $\xi_{ab}(T)$ and $\gamma \equiv \xi_{ab}/\xi_c$ are summarized in Table I. The value $\xi_{ab}(0) = 1.6$ nm for the 5 % Ca sample corresponds to $B_{c2}(0) = \Phi_0/2\pi\xi_{ab}(0)^2 = 130$ T for $B || c$ and also agrees with the value obtained by GF analysis of heat capacity data. The value of $\gamma$ also agrees with other estimates for well-oxygenated YBCO. The values of $\xi_{ab}(0)$ for the two Zn-doped films are larger. For the 2 % Zn film, $1/\xi_{ab}(0)$ scales with $T_c$ as expected, but for the 4 % Zn film the short mean free path probably reduces $\xi_{ab}(0)$ according to the standard dirty-limit formula. The coherence length of the 10 % Ca, 0 % Zn film is longer than that for the 5 % Ca, 0 % Zn film. This is not understood, however the $\rho(T)$ is a factor of 2 smaller, and also for 10 % Ca, Eq. 1 gives a good fit with $\xi_{ab}(0) = 2.2$ nm and $\gamma = 12$ over a smaller range of $t$ (between 0.03 and 0.2).

The success of the GF analysis described above encouraged us to look again at published data for LSCO samples 

| Sample | $T_c$ (K) | $\Delta T_c$ (K) | $p$ (holes/Cu) | $\xi_{ab}$ (nm) | $\gamma$ |
|--------|----------|-----------------|---------------|----------------|--------|
| 0.05   | 84.2     | 0.6             | 0.136 ± 0.002 | 1.6 ± 0.2      | 6.2 ± 0.5 |
| 0.05, 0.02 | 65.1     | 1               | 0.159 ± 0.004 | 1.9 ± 0.2      | 7.2 ± 0.5 |
| 0.05, 0.04 | 33.3     | 1.5             | 0.164 ± 0.004 | 2.6 ± 0.2      | 5.1 ± 0.5 |
| 0.1    | 80.0     | 0.7             | 0.198 ± 0.004 | 3.4 ± 0.2      | 7.5 ± 0.5 |
crystals, since Fig. 4 of Ref. 1 and other versions 2 18 provide key support for the alternative, widely accepted, phase fluctuation and pseudogap pictures. In Fig. 4(a) we show values of \( \gamma \) obtained from the anisotropy in the London penetration depth at low \( T \) (21) and \( (\Delta_{c}T_{c}) \) vs Sr content \( x \) in LSCO. Straight lines show average values of \( \gamma \) used in calculations. Right hand scale, \( \xi_{ab}(0) \) obtained from a GF analysis 19 of the electronic specific heat 4 above \( T_{c} \), using the same values of \( \gamma \). \( \Delta T_{c}(x) \) is related to the strength of critical (non-Gaussian) fluctuations 19. (b) Calculated constant \( \nu \) contours in the \((T, x)\) plane, using Eqs. 1 and 2, with \( s = 0.66 \) nm, \( \rho_{ab}(x, T) \) from Ref. 24 and \( \xi_{ab}(0) \) and \( \gamma \) from Fig. 4(a).

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