Nernst effect and disorder in the normal state of high-$T_c$ cuprates

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The nature of the pseudogap phase remains a key issue to understand superconductivity in high-$T_c$ cuprates. Among the variety of scenarios which have been proposed\textsuperscript{1}, an important one is to consider the pseudogap as a precursor to superconductivity, its opening being attributed to a phase-incoherent pairing, the long range coherence occurring only at $T_c$.\textsuperscript{2} An experimental support for this description of the pseudogap regime has been set out recently by the occurrence of a substantial Nernst signal in the normal state of some underdoped cuprates well above the transition temperature $T_c$.\textsuperscript{3,4,5,6}. As this signal is known to be associated with vortex motion in the mixed state of superconductors, it has been suggested that these Nernst effect experiments reveal the existence of vortex-like excitations surviving in the normal state. In any case this Nernst signal can hardly be explained without invoking superconducting fluctuations\textsuperscript{4,7,8,9}. This has been recently reinforced by new measurements of a diamagnetic response which has been found to track the Nernst signal\textsuperscript{10}.

It has been considered somewhat independently by Emery and Kivelson\textsuperscript{11} that in a sufficiently bad metal classical and quantum phase fluctuations of the superconducting order parameter can depress $T_c$ well below its mean-field value. We have previously shown that the defect induced decrease of $T_c$ could be partly explained within this scenario\textsuperscript{12}. One might wonder whether this results as well in a large range of incoherent phase fluctuations above $T_c$. In order to test this possibility, we have undertaken a systematic study on the influence of defects on the Nernst effect. We have chosen to perform experiments in optimally doped YBCO$_7$ and underdoped YBCO$_{6.6}$ compounds which are known to be very homogeneous systems with little intrinsic disorder\textsuperscript{13}. The controlled introduction of defects has been achieved by using electron irradiation at low temperature which results in the creation of point defects such as Cu and O vacancies in the CuO$_2$ planes\textsuperscript{14}. We demonstrate here for the first time that the presence of defects induces the apparition of a Nernst signal in a large temperature range above $T_c$ in both compounds. This is a strong confirmation that phase fluctuations do play a role in the decrease of $T_c$ induced by disorder. Moreover we find that the onset temperature of the Nernst effect is not much dependent on the defect content and remains close to that of the pure system. We shall discuss the implications of these results on the analysis of the existing data on systems with lower intrinsic $T_c$ such as LaSrCuO or La-doped Bi2201\textsuperscript{15}.

The single crystals used in this study were grown using the standard flux method. Very small contacts with low resistance ($< 0.1\Omega$) were achieved by evaporating gold pads on the crystals on which gold wires were attached later with silver epoxy. Subsequent annealings have been performed in order to obtain crystals with oxygen content $7$ and $6.6$. The $T_c$ values are defined here as the zero resistance temperatures. The irradiation were carried out with 2.5MeV electrons in the low temperature facility of the Van der Graaff accelerator at the LSI (Ecole Polytechnique, Palaiseau). During irradiation, the samples were immersed in liquid H$_2$ and the electron flux was limited to $10^{14}e/cm^2/s$ to avoid heating of the samples during irradiation. The thicknesses of the samples (20 to 40 $\mu$m) are very small compared to the penetration depth of the electrons, which warrants an homogeneous damage throughout the samples. We report here data taken on three YBCO$_7$ samples : a pure one with $T_c = 92.6K$ and two irradiated ones at different electron fluences with respective $T_c = 79.5K$ and 48.6K, and four YBCO$_{6.6}$ samples : pure with $T_c = 57K$ and irradiated with $T_c = 45.1K$, 24.2K and 3K.

The Nernst signal $E_y$ is the the transverse electrical response to a thermal gradient $\nabla_x T_y$ in a presence of a perpendicular magnetic field $B//z$. For the measurements the sample was attached on one end to a copper block with the other end free. The temperature gradi-
ent was created with a small RuO$_2$ resistance attached to the free end. The measurements were performed under vacuum (10$^{-2}$ to 10$^{-1}$ mbar) and a heater power ranging from 0.01 to 0.2 mW was used to create temperature gradients from 0.5 to 0.8K/mm depending on the temperature of measurement. The thermal gradient was measured with a differential chromel-constantan thermocouple. The data were taken at fixed $T$ with magnetic field sweeps from 0 to 8T. At some given value of the magnetic field, the thermal gradient is removed, which allows us to subtract offset voltages due to contact misalignment or an eventual contribution of the wires.

As described by Wang et al. [4], the Nernst coefficient $\nu = \frac{E_y}{(-\nabla_x T)B}$ is the contribution of two terms:

$$\nu = \frac{E_y}{(-\nabla_x T)B} = \left[ \frac{\alpha_{xy}}{\sigma} - S \tan \theta \right] \frac{1}{B} \quad (1)$$

where $\alpha_{xy}$ is the off-diagonal Peltier conductivity ($J_y = \alpha_{xy}(-\nabla_x T)$), $\theta = \sigma_{xy}/\sigma$ is the Hall angle and $S$ the thermopower. The quantity of interest is the off-diagonal term $\alpha_{xy}$ which involves the normal-state term $\alpha_{xy}^n$ and the vortex contribution $\alpha_{xy}^v$. In order to probe the influence of disorder on the latter, it is very important to determine as well the influence of disorder on $S \tan \theta$. We have therefore measured $E_y$, $S$ and $\tan \theta$ separately in each sample by using the same electrodes for measuring resistivity and Hall effect in one setup and the thermopower and Nernst coefficients in another one.

Let us present first the results obtained on underdoped crystals. Figure 1 shows several curves of the Nernst signal $e_y = \frac{E_y}{(-\nabla_x T)}$ as a function of magnetic field for the pure crystal.

![FIG. 1: (color online) Nernst signals $e_y = E_y/|\nabla T|$ versus magnetic field in the pure underdoped YBCO$_{6.6}$ crystal for $T$ ranging from 35 to 200K](image)

For $T < 55$K, $e_y$ is zero as long as the magnetic field does not exceed the "melting" field $B_m(T)$ necessary to depin vortices (around 2T and 1T respectively at 35 and 45K). Then the rapid increase of $e_y$ above $B_m$ reflects the motion of vortices induced by the thermal gradient. As $T$ is increased across $T_c$, the Nernst signal initially drops rapidly (curves at 55 and 58K) and then decreases gradually approaching a straight line with negative slope. This behaviour is clearly displayed in Fig. 2a in which we have plotted the $T$ variation of the Nernst coefficient $\nu$ determined as the initial slope of $e_y$ versus $B$. This negative contribution which has been previously observed near $T_c$ [15] is found to display a minimum at 85K and to vanish around 200K. This behaviour which is quite different from that observed in the other underdoped cuprates, will be seen below to result naturally from the high value of $S \tan \theta/B$ in this clean system.

The effect of electron irradiation is recalled in Fig. 2c where the resistivity curves $\rho(T)$ are plotted for the pure and two irradiated samples. As reported previously [16], Matthiessen’s rule is well obeyed at high $T$, which indicates that the hole doping of the CuO$_2$ planes and the pseudogap temperature $T^*$ are not significantly modi-
The temperature dependence of the Nernst coefficient one observes in Fig.2a that the pronounced minimum which is present for the pure sample is smoothed out by the introduction of disorder. We have reported on the same graph the tanθ/B dependence for the pure sample is smoothed out by the introduction of disorder. As for the Nernst coefficient one observes in Fig.2a that the pronounced minimum which is present near 125K in the pure sample both S and tanθ being quite large. −S tanθ/B dominates in Eq.1. Such a negative value of ν has been predicted theoretically in the framework of the Boltzmann theory by taking into account the role of the Fermi surface shape at two dimensions. When increasing the defect content x, we find that S varies slightly while tanθ/B decreases roughly as 1/x, resulting in a decrease of S tanθ/B when Tc decreases. The T variation of the total off-diagonal Peltier term αxy/σB obtained by combining the data for S tanθ and ν is plotted in Fig.2-b. In all samples the normal state contribution αn xy presents a broad peak around 110K and then decreases with temperature. Such a behavior has been quite generally observed in underdoped cuprates and might therefore be characteristic of the normal state quasiparticles. As α2xy/σB corresponds to a carrier-entropy current one expects that it should decrease to zero at T → 0. Therefore it seems legitimate to interpret any deviation from this tendency as a manifestation of a vortex contribution. We have thus indicated by the arrows in Fig.2b the best estimate of the onset temperature Tν of the superconducting contribution. This determination leads in fact to values which nearly coincide with those of the minimum of the Nernst coefficient. Two important results can be deduced from this plot. First it is clearly seen that the onset temperature does not exceed 85K in pure YBCO, showing that the fluctuation regime is quite narrow (~25K) in this compound despite the fact that the pseudogap temperature T* is ≥300K whatever the experimental probe. Second we find that Tν is nearly the same for all the samples while Tc has been decreased down to 5K by irradiation. This is a strong indication that the presence of defects plays a prominent role in the observation of a Nernst signal in the normal state of these samples.

As for YBCO7, the Nernst coefficients are reported in Fig.3 for the three samples studied. In the pure crystal the magnitude of the negative value of ν is much smaller than in the underdoped case. This results from the fact that S tanθ/B is also smaller, as shown by the decomposition displayed in the inset of Fig.3. This S tanθ/B term varies very little with defect content and the estimate of Tν is about the same whether we use the raw data for ν or the corrected values αxy/σB. For all the samples the drop of the Nernst signal is very rapid at Tc but while it vanishes at 10K above Tc in the pure sample, it persists up to ~85K, that is to say 35K above Tc, in the most irradiated one. The fairly narrow fluctuation range found in the pure sample is similar to the one deduced from the paraconductivity in the ρ(T) curves.

In order to compare results obtained on YBCO7 and YBCO6.6 we have reported in Fig.4 the values of Tν as a function Tc for the different samples. In both compounds we observe that the Nernst signal extends in a larger temperature range when decreasing Tc. Let us point out that this effect corresponds to very small values of the vortex Nernst signal as one can see that the temperature corresponding to a value of the vortex Nernst signal of 30nV/KT nearly follows the Tc decrease.

These results clearly show that superconducting fluctuations survive in the normal state of both optimally doped and underdoped YBCO when Tc is decreased by the introduction of disorder. As Tν can be considered as the characteristic temperature below which local pairing remains significant, the Tc decrease induced by disorder can only be explained by taking into account both phase fluctuations and pair-breaking effects. This gives strong support to our previous interpretation of the quasi linear decrease of Tc with defect content which is observed down to Tc = 0. It is worth mentioning here that the role of quantum phase fluctuations has also been invoked to explain the Nernst effect observed in the normal state of low Tc cuprates when superconductivity is suppressed by magnetic fields.

One striking point which can be seen here is the small range of superconducting fluctuations observed in the pure YBCO6.6 and YBCO7 compounds. This is much smaller than the corresponding observations done in other “pure” cuprates such as LaSrCuO or La-doped Bi2201. Let us recall here that the presence of ex-
tended vortex fluctuations in these underdoped cuprates has been invoked as a strong indication that d-wave superconductivity is closely connected to the pseudogap state. Our results show that this argument fails in pure underdoped YBCO$_{6.6}$, suggesting that the energy scales of $T'$ and $T^*$ are not connected. We can even see that in these clean systems $T'$ and $T_c$ increase with increasing hole doping while $T^*$ definitely decreases.

It has been previously suggested that the low $T_c$ in some cuprate families could be due to the presence of intrinsic defects as deduced from the analysis of $^{17}$O NMR data. One can wonder whether this might also explain the magnitude of the Nernst effects. We have therefore compared in Fig.4 the temperature extensions of the Nernst signal of our irradiated samples with those obtained in the Bi$_2$Sr$_{2−y}$La$_y$CuO$_6$ family for $y = 0.4$ ($T_c \sim 36$K) which corresponds to optimal doping and for $y = 0.5$ ($T_c \sim 29$K ) with $T^* \sim 300$K comparable to that of YBCO$_{6.6}$. The quite good agreement between the ranges of vortex Nernst signal found in these different samples indicates that the "intrinsic" disorder in Bi$_2$Sr$_{2−y}$La$_y$CuO$_6$ could also be responsible for the enhanced Nernst signal. Indeed cation disorder on the Sr site has been recently identified. It is then natural to conclude that the "anomalously" high values of $T'$ with respect to $T_c$ found in La-doped Bi2201 are indicative of the values of $T_c$ that these materials should display if they were grown without local inhomogeneities. Such a conclusion might as well apply to the various cuprate families and is reinforced by the fact that the maximum of $T'$ is in most cases of the order of 100K. Moreover our results reveal that defects induce more phase fluctuations in the underdoped phase than for optimal doping, which might be due to lower phase stiffness and less efficient screening. It is therefore our opinion that the link between the large range of Nernst signal and the pseudogap phase has to be found in priority in the occurrence of defects and in the large sensitivity to disorder of the superconducting-pseudogap phase.

FIG. 4: (color online) The values of $T'$ are plotted versus $T_c$, together with the $T$ values corresponding to vortex Nernst contributions of 10 and 30$nV/KT$ for YBCO$_2$ (empty symbols) and YBCO$_{6.6}$ (closed symbols). These data are compared to the temperature ranges of the Nernst signal measured in "pure" single crystals of Bi$_2$Sr$_{2−y}$La$_y$CuO$_6$ with $y = 0.4$ and $y = 0.5$.

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\[ e_y (\mu V/K) \]

\[ B (T) \]

\[ T_c \sim 57K \]
The diagram shows the relationship between temperature $T$ (in Kelvin) and $T_c$ (in Kelvin), with different materials and doping levels indicated. The YBCO family includes YBCO$_{6.6}$, YBCO$_{7}$, and La-Bi2201 with different doping levels $y=0.4$ and $y=0.5$. The vertical line represents $T^v$ and the horizontal line represents $10 \text{ nV/}K T$. The vertical dashed line indicates $30$.