The Anomalous Nernst Effect, Diamagnetism, and Cooper Pairing above T_c in Cuprates

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Abstract

Cuprate high temperature superconductors have been known for more than 20 years, but the so-called pseudogap regime that lies above the superconducting dome on the hole-doped side of the phase diagram is still largely unknown. Recently, Li *et al.* (2010) [1] published an extensive examination of fluctuating diamagnetism above T_c in several families of cuprates which indicates the presence of a vortex-liquid state as much as 50-100 K above T_c. They find compelling evidence that the Cooper paired condensate survives above T_c but with an extremely short coherence length that precludes the macroscopic coherence required for phenomena such as the Meissner effect. In this paper I present a basic review of the results obtained by Li *et al.* (2010) as well as results of earlier investigations into both diamagnetism and the Nernst effect.

1 Introduction

When looking at the phase diagram of the cuprates versus temperature and hole doping, superconductivity appears as a dome-shaped region at low temperatures bounded by $T_c(\delta)$, the temperature at which the Meissner effect disappears. At very low doping, antiferromagnetic order sets in. At more moderate temperatures there is a region known as the pseudogap. The nature of the state in this region has been the subject of study for more than two decades, but it is still poorly understood. In this paper, I review experimental progress in understanding the portions of the pseudogap closest to the superconducting dome, known as the fluctuation regime.

The state in the fluctuation regime is a novel emergent state that was until recently very poorly understood. Several different types of symmetry breaking states have been proposed. Some suggest that the strange properties of this phase are the result of spontaneous stripe ordering of the electrons in a nematic phase, e.g., [2]. Others maintain that the state is a vortex liquid state, i.e., some sort of precursor to the full superconducting state that has vortices and local super currents but does not possess the long range phase coherence and off-diagonal long-range order of the Meissner state seen at lower temperatures.

Some of the first clues to the nature of this state came from experiments using the Nernst effect. In the presence of a temperature gradient, vortices flow up the gradient and establish a transverse voltage across a sample. The presence of this transverse voltage is known as the Nernst effect. Nernst data above T_c in the cuprates shows a large increase in this transverse voltage over what would be expected from a normal metal. This signal evolves smoothly into that observed from mobile Abrikosov vortices below T_c and then vanishes at the crystallization temperature of the vortices when transport becomes frozen out.[2, 3, 4] The presence of the anomalously large Nernst signal strongly suggests the presence of vortices and the continuous evolution across the supreconducting phase transition suggests that the vortices producing the Nernst signal are the same type of vortices that exist in the superconducting state below T_c, despite the fact that phenomena such as the Meissner effect are absent above T_c. However, vortices do not give the only contribution to the Nernst signal. Normal state electrons also contribute. Often this contribution has a different sign from that of a vortex contribution, but this is not required and the sign of the normal particle Nernst term is independent of the sign of the carrier charge. Because of the mounting evidence for a Cooper pair condensate above T_c reviewed in this paper, I will henceforth refer to normal electrons or holes as quasi-particle excitations of the condensate.

It is not usual for the quasi-particle contribution to the Nernst signal to be as large as that observed experimentally, but there have been several proposals, such as that of [2], in which unusual circumstances such as modification of the Fermi surface by charge order greatly increase the quasi-particle contribution. Charge ordering has been observed in certain cuprates such as Nd and Eu dopes $\mathrm{La_{2-x}Sr_xCuO_4}$ (LSCO). Therefore the sign, magnitude, and existence of the anomalous Nernst signal in cuprates is not enough to determine its origin. Additional information is required: either a method for separating vortex and quasi-particle contributions to the Nernst signal, or confirmation from another technique which is sensitive only to one of the two possible contributors.

Wang *et al.* (2001) [3] published a paper in which they perform a detailed analysis to separate the vortex and quasi-particle Nernst signals. Other efforts have concentrated on examining fluctuating diamagnetism in the same regime in which the anomalous Nernst signal is found.[1, 5, 6] Below T_c, superconductors are extremely powerful diamagnets. If superconducting vortices survive above T_c, then there should still be a strong diamagnetic signal, strong compared to that of a normal metal. Therefore, these experiments use a combination of torque and squid magnetometry to examine the system's diamagnetic response as a function of temperature and magnetic field.

Low-field magnetization studies [5] found an interesting functional form of the magnetization M and a resulting low-field non-analyticity in the magnetic susceptibility χ which diverges in a manner indicative of a two dimensional Kosterlitz-Thouless-like superconducting transition at a temperature T_{2D} which lies slightly above T_c for the full 3D transition into the Meissner state. This aspect of the magnetization studies will not be discussed in detail in this work. High-field magnetization studies [1, 6] clearly identify a strong and highly non-linear diamagnetic response that sets in at the same temperature as the vortex-like Nernst signal. Therefore, the result of the combined magnetization and Nernst data sets has been to identify a region in the phase diagram of hole-doped cuprates in which a vortex liquid persists despite the absence of the Meissner effect, as shown in Figure 1. The vortex liquid state does not encompass all of the pseudogap region, but it does make up a large portion

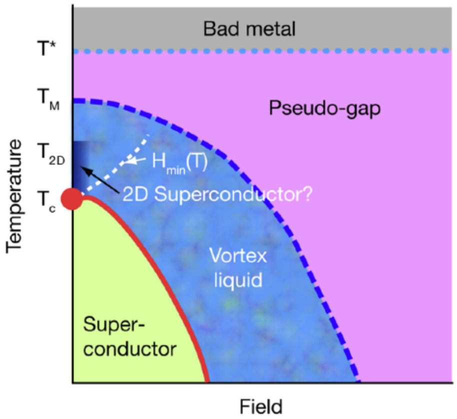

Figure 1: Schematic of the phase diagram of hole-doped cuprates as a function of magnetic field and temperature. The Meissner superconducting state appears in the lower left-hand corner in yellow. Above $T_c(H)$ perfect flux expulsion is no longer possible, but a vortex liquid with very short range phase coherence remains until $T_M(H)$. A region of possible 2D superconductivity appears just above T_c and at low field. H_{min}, the field at which the diamagnetic response reaches a turning point is shown as a dotted line in the vortex liquid phase. This quantity will be discussed in more detail alongside the high field magnetization studies from which is it derived. (Figure taken from [7].)

of it. Current understanding is that,although the macroscopic phase coherence of the superconducting order parameter necessary for the Meissner effect is destroyed at T_c, the electrons remain Cooper paired. This condensate supports vortices, which give rise to the observed magnetization and anomalous Nernst signals.

In the body of this paper I review the aforementioned data and conclusions in detail. In Section 2, I begin by discussing the Nernst effect and its manifestation in cuprates. I will also discuss the technique of Wang *et al.* (2001) [3] for separating the vortex and quasi-particle Nernst signals. In section 3, I will introduce the low- and high-field magnetization studies, and in Section 4, I will discuss the combined results of the two probes.

2 Nernst Data

2.1 The Nernst Effect

When a sample containing vortices is subjected to a temperature gradient and a perpendicular magnetic field, any vortices present will flow down the temperature gradient and give rise to a transverse voltage $\mathbf{E} = \mathbf{B} \times \mathbf{v}$, where $\mathbf{B} = \mu_0 \mathbf{H}$ is the applied magnetic field and $\mathbf{v}$ is the vortex velocity. A typical geometry is shown in Figure 2. The voltage measured is the Nernst signal $\nu \equiv E_y/|\nabla T|$. In general, measurements of the Nernst effect are given in terms of the Nernst coefficient e_ν which is defined as the Nernst signal per unit magnetic field in the weak field limit (where the Nernst signal is linear in B).[3]

The Nernst signal itself has several contributions. (The discussion below is an abbreviated form of that found in the first sections of [3].) To see this, first consider a sample in the normal state in the absence of a magnetic field. The material has some thermopower, so a thermal gradient will drive a current density $\mathbf{J} = \alpha(-\nabla T)$. This current is called the Peltier current, and α_{ij} is the Peltier conductivity tensor analogous to the regular conductivity tenor σ_{ij}. If there are no leads on the sample, then J_x must equal zero. To satisfy this requirement, there must be an electric field which drives a regular current density $\sigma\mathbf{E}$. This gives

$$J_x = \sigma E_x + \alpha(-\partial_x T).$$

Enforcing the boundary codition that $J_x = 0$ forces

$$E_x = -\frac{\alpha}{\sigma}\left(-\partial_x T\right).$$

The thermopower coefficient is defined as $S \equiv \alpha/\sigma$.

When an intense magnetic field is added to the picture, two transverse currents appear. One is simply the Hall current arising from the normal current, and the other is an off-diagonal Peltier current. The boundary condition $\mathbf{J} = 0$ still holds. Thus Wang *et al.* (2001) obtain,

$$J_y = \alpha_{yx}(-\partial_x T) + \sigma_{yx} E_x + \sigma E_y = \left(\alpha_{yx} - \sigma_{yx}\frac{\alpha}{\sigma}\right)(-\partial_x T) + \sigma E_y = 0,$$

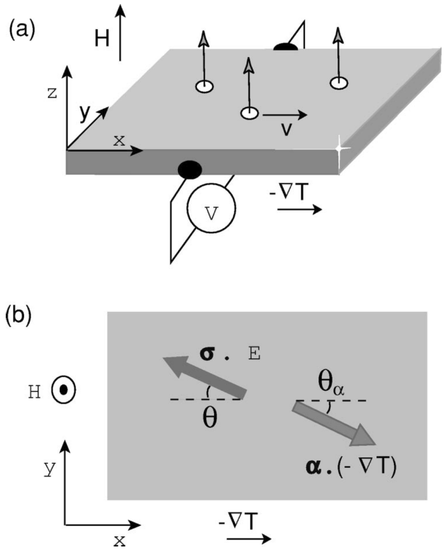

Figure 2: Schematic of the geometry of a Nernst effect experiment. a) shows the sample geometry with the temperature gradient ∇T, the applied field $\mathbf{H}$, and the velocity $\mathbf{v}$ of the vortices. The vortices themselves are indicated by a circle and arrow. A voltage is measured transverse to the temperature gradient and the magnetic field. The Nernst coefficient is derived from this voltage. b) shows the sample in a top view. The normal and Peltier currents are indicated by arrows. The Hall and Peltier angles θ and θ_α are the angles between the respective currents and the direction of the temperature gradient. An important cancellation results from the fact that these two angles are very close but not identical. (Figure taken from [3].)

after dropping a term proportional to $\partial_y T$ which is known to be insignificant in cuprates. By using the definition of the Hall angle $\tan(\theta) := \sigma_{xy}/\sigma$ and defining an analogous Peltier angle $\tan(\theta_\alpha) := \alpha_{xy}/\alpha$, Wang *et al.* obtain a formula for the Nernst coefficient due entirely to the quasi-particles

$$\nu_N = S\left(\tan(\theta_\alpha) - \tan(\theta)\right)\frac{1}{B}. \tag{1}$$

The angles θ and θ_α are indicated in Figure 2 along with their respective currents. The currents are very nearly antiparallel because $\theta \approx \theta_\alpha$. Thus, the cancellation in equation 1 is nearly complete. This phenomenon, known as Sondheimer cancellation, means that the quasi-particle Nernst signal is very small unless something, such as the presence of many electron-like pockets in the Fermi surface, greatly changes the basic picture described above.

Even in the absence of Sondheimer cancellation, the quasi-particle Nernst signal should be considerably smaller than a vortex contribution because it is off-diagonal. The transverse quasi-particle current is a second order effect, whereas the vortex Nernst signal comes from the component of the vortex motion parallel to the thermal gradient, the primary component of the motion. Defining separate Peltier conductivity tensors α^s and α^n for the normal and superconducting components respectively, we expect $\alpha^s_{xy} \gg \alpha^n_{xy}$ when there is a strong superconducting component present. Taking into account both types of contributions, the Nernst signal takes the following form [3]:

$$\nu = \left(\frac{\alpha^s_{xy}}{\sigma} + \frac{\alpha^n_{xy}}{\sigma} - S\tan(\theta) \right) \frac{1}{B}. \tag{2}$$

2.2 Separating Vortex and Quasi-Particle Contributions

Wang *et al.* (2001) detect the onset of a vortex-like Nernst signal by examining when the vortex contribution to the off-diagonal Peltier current becomes visible over the quasi-particle term. Their procedure is to measure the thermopower coefficient S and the tangent of the Hall angle θ separately at each T, as well as the Nernst signal itself. This allows them to subtract off the third term in equation (2) and be left with only the off-diagonal Peltier term per unit magnetic field

$$\frac{\alpha^s_{xy}}{\sigma} + \frac{\alpha^n_{xy}}{\sigma}.$$

In overdoped samples the quasi-particle Nernst signal is small, so the onset of the vortex-like signal can be identified by means of a simple threshold. When the Nernst coefficient is below this threshold, the vortex-like signal is negligible, and when the Nernst coefficient is above this threshold, there is a vortex-like signal. In underdoped samples the thermopower is large (e.g. 300 μV/K at 100 K in the lowest doped sample L1) so the quasi-particle term is also significant. Thus, a simple threshold scheme could easily mistake the onset of the quasi-particle term for that of the vortex-like term and the vortex-like term cannot be isolated without carefully picking the two signals apart. In order to complete the phase diagram of the vortex-like signal, Wang *et al.* concentrated on underdoped samples of $\mathrm{La_{2-x}Sr_xCuO_4}$ (LSCO) and $\mathrm{Bi_2Sr_{2-y}La_yCuO_6}$ (Bi 2201) and undertook to separate the vortex-like and quasi-particle Nernst signals.[3]

Wang *et al.* (2001) examine the off-diagonal Peltier current in multiple LCSO samples with different dopings. Data from three of these samples, labeled as L1, L2, and L3, is shown in Figure 3. Sample L1 has the lowest hole doping ($x = 0.03$ as opposed to $x = 0.05$ and 0.07 for L2 and L3 respectively) and has markedly different characteristics from the other two; its off-diagonal Peltier term α_{xy} falls off to zero as T goes to zero rather than rising rapidly as that of L2 and L3. This is precisely the behavior expected for a signal due entirely to quasi-particle carriers. Furthermore, $T_c = 0$ K for L1, so it makes sense to identify this curve for L1 as typical for a purely quasi-particle signal. The temperatures at which L2 and L3 depart from this behavior are therefore the onset temperature of a different term. This second contribution is identified as a vortex term because it grows rapidly but smoothly into the signal observed below T_c due to Abrikosov vortices. (As the temperature drops far enough below T_c, the superconducting vortices crystallize and the vortex signal drops to zero, but this behavior is qualitatively very different from that seen in L1.) The same analysis was also performed using samples of Bi 2201 and Bi 2212 with very similar results, i.e., a strong vortex term persisting well above T_c.

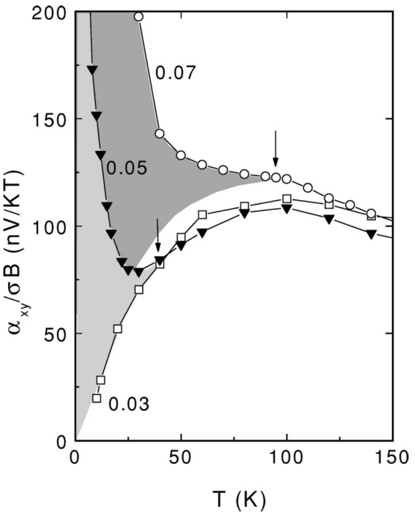

Figure 3: Plot of the temperature dependence of the off-diagonal Peltier term α_{xy} in three LSCO samples: L1 ($x = 0.03$, $T_c = 0$ K), L2 ($x = 0.05$, $T_c < 4$ K), and L3 ($x = 0.07$, $T_c = 12$ K). The sample with the lowest hole doping, L1, behaves noticeably differently from the other two, with α_{xy} tending to zero as T goes to zero. Therefore, it appears that the signal in L1 is due entirely to quasi-particle carriers. The shape of the curve for L1 is used to determine what the quasi-particle contribution should look like for L2 and L3. The temperatures at which the measured values of $\alpha_{xy}^{total} = \alpha_{xy}^{s} + \alpha_{xy}^{n}$ depart from the quasi-particle behavior are indicated by the two vertical arrows. The vortex term is indicated by the shaded region which makes up the difference between the projected normal fluid contribution and the observed α_{xy}^{total}. Note that in samples L2 and L3 the vortex-like term dominates well above T_c. This is strong evidence for the existence of some kind of superfluidity even well above T_c. (Figure taken from [3].)

3 Magnetization Data

The Nernst effect results are all based on interpreting a small signal (the observed Nernst signal) as the difference of two considerably larger ones. Because such a procedure tends to magnify experimental errors, confirmation from another type of probe is important. Magnetization studies are ideal because they can observe strong diamagnetic signals characteristic of superconductivity.

Refs [5, 6, 1] explored the diamagnetic response of several families of cuprates through a combination of SQUID and torque magnetometry. If the Cooper pair condensate is not completely destroyed by the phase transition at T_c, but instead survives with a greatly reduced phase coherence length (as predicted from the Nernst data), then magnetization studies should detect a strong diamagnetic response from the residual condensate. In addition to the strong diamagnetism (i.e., strong compared to a normal metal but weak compared to a superconductor below T_c), there should also be a paramagnetic term which arises due to the anisotropy of the crystal structure of the cuprates.[5, 6, 1] Given a direction of the magnetic field, the magnetic susceptibility $\chi = M/H$ has three contributions: core, orbital, and spin. The susceptibility anisotropy $\Delta\chi = \chi_c - \chi_{ab}$ is affected only by the orbital (Van Vleck) and spin terms. The Van Vleck term is highly anisotropic and is the main reason that $\Delta\chi = \chi_c - \chi_{ab}$ is non-zero. The spin term is temperature dependent due to the growth of a spin gap below T^* where the pseudogap sets in.[6]

In the torque magnetometry experiments the sample is attached to a horizontal cantilever so that the c-axis is $\theta = 15°$ from horizontal and the a- and b-axes are 15° from the vertical plane. A magnetic field is applied horizontally [5], and the interaction of this field with the induced magnetization results in a torque which deflects the cantilever. This deflection is detected capacitively [6].

The total magnetization has two terms: the diamagnetic one that is of primary interest and a paramagnetic one that gets in the way. Therefore it is useful to write the torque as $\vec{\tau} = (\mathbf{m}_p + V\mathbf{M}) \times \mu_0\mathbf{H}$, where $\mathbf{M}$ is the magnetization we wish to study and $\mathbf{m}_p$ is the total magnetic moment resulting from the paramagnetic terms. Papers typically adopt a coordinate system defined by the crystal axes with $\hat{z}||\hat{c}$. Since the magnetic field is predominantly along the $\hat{z}$ direction $M_z \approx M$ and many authors take the two to be equal. Backing out an effective magnetization from the measured torque via $M_{eff} \equiv \tau/(\mu_0 H_x V)$ (which is valid for small deflections) yields

$$M_{eff}(T, H) = \Delta\chi_p H_z + M(T, H),$$

where $\Delta\chi_p$ is the paramagnetic susceptibility anisotropy and $M(T, H)$ is the magnetization of interest.[5] Because of the behavior of the Van Vleck and spin paramagnetic susceptibilities, the first term above should be only weakly temperature dependent. If the second term is present, diamagnetic, and due to vortices, then it is expected to be highly non-linear in both temperature and magnetic field. If, however, the increased Nernst signal is not due to vortices but to some quasi-particle phenomenon, such as in the proposal of Ref [2], then M should be highly linear in both temperature and field.[1]

3.1 Low Field Non-Analyticity and Fragile London Rigidity

Li *et al.* (2005) [5] performed torque magnetization studies of $\mathrm{Bi_2Sr_2CaCu_2O_{(8+\delta)}}$ (Bi 2212) at low field. They looked at the behavior of $M(T, H)$ and tried to understand it in terms of a power law with a temperature dependent exponent

$$M(T, H) = A(T)H^{1/\delta(T)}.$$

Figure 4 shows their data in a log-log plot to examine δT which shows up as one over the slope of the $\ln(M)$ vs. $\ln(H)$ curves as H tends to zero. They find that $\delta > 1$ for temperatures between 84 K and 105 K, and thus $\chi = M/H$ is non-analytic in the small H limit. Even well above $T_c = 86$ K, if the applied field is small enough, the magnetic susceptibility diverges, as it would when entering the Meissner state below T_c by decreasing the applied magnetic field across $H_{c1}(T)$. This suggests that some of the phase or "London"

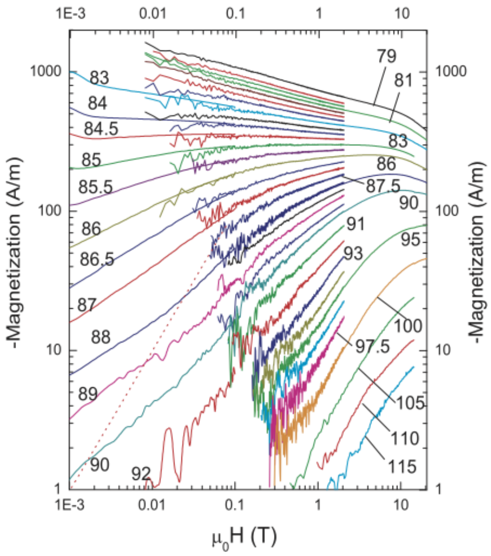

Figure 4: Log-log plot of the modulus of the diamagnetic magnetization at low field in a Bi 2212 sample. The paramagnetic term has already been subtracted away. Each curve is labeled by the temperature at which it was taken. Low field curves were measured using SQUID magnetometry and higher field ones using torque magnetometry. The power law exponent $1/\delta(T)$ is equal to the slope at $H = 0$. Clearly $\delta(T)$ varies strongly with temperature. $\delta(T) > 1$ for 86 K $< T <$ 105 K, thus $\chi = M/H$ is non-analytic. (Figure taken from [5].)

rigidity of the superconducting wave function which results in the Meissner effect when $T < T_c$ is preserved above T_c, but only in extremely weak fields. This phenomenon is known as "fragile London rigidity." [5]

3.2 High Field Response

Wang *et al.* (2005) [6] and Li *et al.* (2010) [1] examined the diamagnetic response of cuprates near and above T_c using torque magnetometry. Both groups found a strong diamagnetic response that is non-linear in both T and H. Li *et al.* (2010) examined LSCO, Bi 2201, and Bi 2212 at fields up to 45 T. They found that below $T_{onset} > T_c$ a strong diamagnetic response is visible on top of the paramagnetic background. As seen in Figure 5, initially the magnitude of the response grows linearly in H until 5-15 T at which point a broad minimum develops. At very high fields, the magnitude of the diamagnetic response decreases toward zero as the applied field increases toward the depairing field H_{c2}. The marked non-linearity of the data in H, visible only with access to very high fields, is evidence against purely quasi-particle theories of the anomalous Nernst effect in cuprates.[1]

Li *et al.* (2010) plot their data versus magnetic field in constant temperature contours. This makes them somewhat hard to compare with Nernst data, which is generally plotted

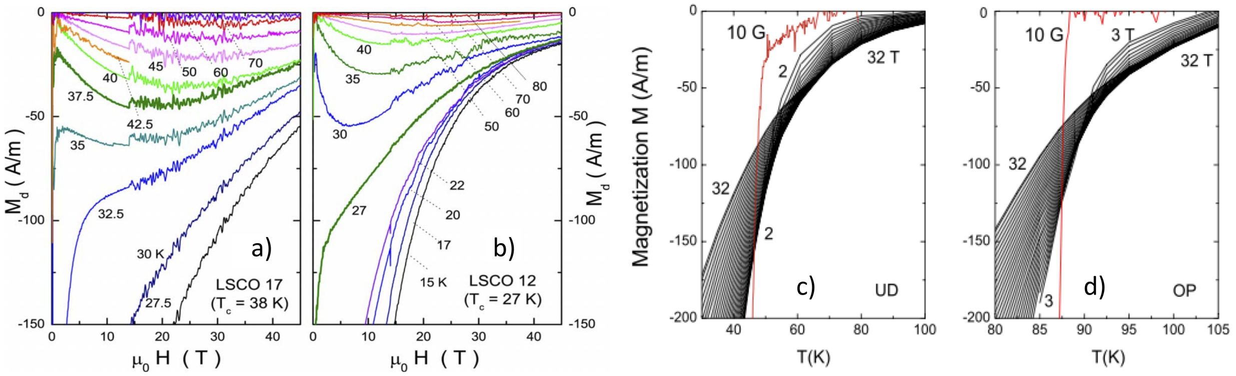

Figure 5: Panels a) and b) show isothermal curves of the diamagnetic response versus magnetic field of two samples of LSCO: LSCO 17 ($x = 0.17$) with $T_c = 38K$ and LSCO 12 ($x = 0.12$) with $T_c = 27K$. The diamagnetic response persists above T_c for as much as 40-50 K and is non-linear, displaying a broad minimum. This marked non-linearity is evidence against this signal being purely quasi-particle in origin. The curves appear to evolve smoothly across T_c. This can be seen more clearly in panels c) and d) which show plots of the diamagnetic magnetization versus temperature at constant magnetic field in underdoped (UD) and optimally doped (OP) Bi 2212. The solid lines are data taken at fields from 2-32 T and these show no singularity at T_c. The red dotted curves show the equivalent measurement taken at a field of 10 G < H_{c1}. At T_c, the Meissner state takes over and the diamagnetic response grows rapidly, resulting in flux expulsion. The continuous evolution of the high field data implies that vortices give rise to the observed magnetization signal both above and below T_c. (Panels a) and b) taken from [1]; c) and d) from [6])

as a function of temperature e.g., [2, 3, 4, 6]. It also makes the continuous temperature evolution less blatantly obvious. Wang *et al.* (2005) conducted very similar magnetization studies on LSCO and Bi 2212. Panels c) and d) of Figure 5 show their data plotted versus temperature. Well above H_{c1}, the diamagnetic signal evolves continuously across T_c into the signal observed from Abrikosov vortices above their crystallization temperature.

These high field magnetization studies are strong evidence that superconducting vortices are present above T_c in cuprates despite the absence of an observed Meissner state. The signal below T_c due to vortex motion evolves continuously into that observed above T_c and persists for as much as 50-100 K above T_c. The signal is non-linear in H and T which is evidence against it arising from a quasi-particle phenomenon such as Landau diamagnetism. Wang *et al.* (2005) and Li *et al.* (2010) conclude the presence of a superconducting condensate without the long range phase coherence necessary for the Meissner effect.

4 Combining Nernst and Magnetization Results

The question then arises how these results are related to the anomalous Nernst effect in the cuprates and the nature of the pseudogap state. The onset temperature of the pseudogap phase T^* is still not very well known. Different types of measurements use different definitions and there are conflicting results; however, the current understanding [1, 6, 7] is that the onset temperatures of the diamagnetic response T^M_{onset} and of the vortex-like Nernst signal T^{ν}_{onset} lie well below T^* and significantly above T_c in LSCO and Bi cuprates. Wang *et al.* (2005) and Li *et al.* (2010) found that $T^M_{onset} = T^{\nu}_{onset}$ to within experimental error. The phase diagram that they obtain for LSCO is shown in panel a) of Figure 6.

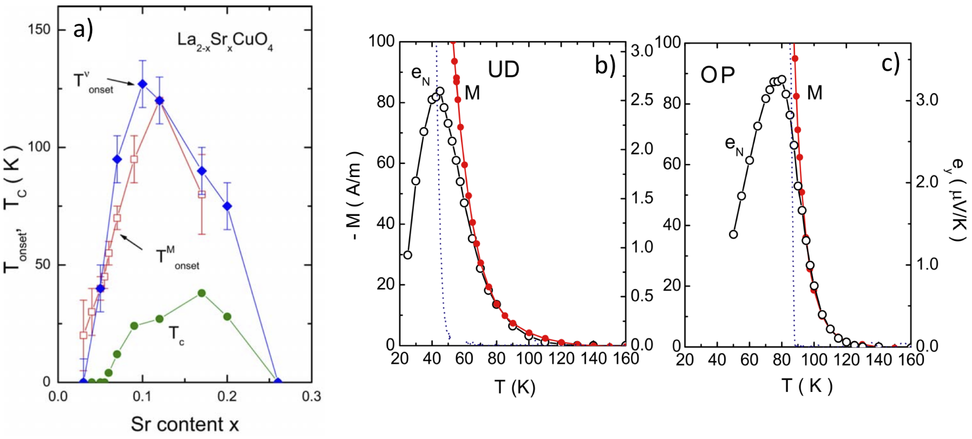

Figure 6: Panel a) shows the phase diagram for LSCO found by Li *et al.* (2010). The superconducting dome is enclosed within what they conclude is a vortex-liquid dome bounded by T^M_{onset} and T^{ν}_{onset}, which are the same up to experimental error. (Except for near $x = 0.1$, but the disagreement is too small to tell whether it is physical.) Values of T_c are indicated by solid circles, T^M_{onset} by empty squares, and T^{ν}_{onset} by filled diamonds. Panels b) and c) show the vortex-like Nernst signal (empty circles) and the magnitude of the diamagnetic response (filled circles) plotted together versus temeprature in b) underdoped and c) optimally doped (OP) Bi 2212. The dotted curve is M plotted for $H = 10$ Oe $< H_{c1}$ which is indicative of the Meissner transition at T_c. At this weak field, the fluctuating diamagnetism above T_c is too weak to be seen. The Nernst and magnetization signals onset together well above T_c. (Panel a) taken from [1]; b) and c) from [6].)

5 Conclusions

The recent paper of Li *et al.* (2010) [1] reports high magnetic field torque magnetometry studies of LSCO and Bi 2212. Building on earlier low-field studies such as Li *et al.* (2005) [5] they find that a strong diamagnetic response is present well above T_c. This diamagnetism evolves continuously across T_c and non-linearly in both temperature and magnetic field. The lack of a singularity at T_c suggests that Abrikosov vortices give rise to the signal observed above T_c despite the absence of the Meissner effect. The non-linearity of the signal in T and H is further evidence that vortices are the source of the signal and not quasi-particle phenomena as has been proposed (e.g., in [2] for pure LSCO). Building upon the work of Wang *et al.* (2001) [3] and other Nernst effect measurements, Li *et al.* find that the anomalous Nernst effect is observed at the same temperatures as the large diamagnetic response they measure.

Thus there is strong evidence to suggest that as T rises above T_c the superconducting state loses its long range phase coherence, but it is not completely destroyed. The depairing (upper critical) field H_{c2} is very large in thses systems ($\approx 50 - 100$ T) even at T_c. Such a vortex-liquid state would no longer exhibit the Meissner effect, but it would still support local supercurrents and superconducting vortices which could give rise to the observed fluctuating diamagnetism and anomalous Nernst effect.

Another possibility is that the presence of vortex-like signatures above T_c is the result of small patches with higher than average T_c. For non-optimally doped samples near T_c this may contribute; however, for optimally doped samples, any regions that deviate from the average doping will have a lower T_c than the majority of the sample, and all of the effects discussed in this paper are observed in optimally doped samples, as well as under and overdoped ones. In addition, vortex-like effects are observed $50 - 100$ K above the maximum T_c, making it highly unlikely that isolated patches with higher T_c are responsible.

Due to varying definitions of T^* and contradictory reports, it is somewhat unclear how T^* compares to T_{onset} at which the vortex-liquid state emerges. However, the understanding of [1, 7] is that T_{onset} lies well below T^* and that the vortex-liquid does not constitute all of the pseudogap regime. The vortex-liquid state emerges continuously from the little-understood spin-gap state that exists at higher temperatures and evolves continuously into the familiar Abrikosov vortex-liquid state below T_c and eventually into the vortex crystal as the temperature decreases still further.

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