Nernst Effect in Electron-Doped Pr$_{2-x}$Ce$_x$CuO$_4$

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The Nernst effect of Pr$_{2-x}$Ce$_x$CuO$_4$ ($x$=0.13, 0.15, and 0.17) has been measured on thin film samples between 5-120 K and 0-14 T. In comparison to recent measurements on hole-doped cuprates that showed an anomalously large Nernst effect above the resistive $T_c$ and $H_{c2}$ [1–4], we find a normal Nernst effect above $T_c$ and $H_{c2}$ for all dopings. The lack of an anomalous Nernst effect in the electron-doped compounds supports the models that explain this effect in terms of amplitude and phase fluctuations in the hole-doped cuprates. In addition, the $H_{c2}(T)$ determined from the Nernst effect shows a conventional behavior for all dopings. The energy gap determined from $H_{c2}(0)$ decreases as the system goes from under-doping to over-doping in agreement with the recent tunnelling experiments.

INTRODUCTION

Recent Nernst effect measurements [1–4] on hole-doped cuprate high-$T_c$ superconductors have shown very surprising results. Especially in the under-doped regime of these cuprates, an anomalous Nernst signal has been observed to persist to temperatures up to 50-100 K above $T_c$, and to magnetic fields much larger than the resistive $H_{c2}$. The authors have interpreted this anomalous signal above the conventional $T_c$ or $H_{c2}$ (the $T_c$ or $H_{c2}$ of resistivity and magnetization) as evidence for vortex-like excitations, and have defined a new $T_c$ and $H_{c2}$ for Cooper pair formation in these compounds. In this picture there is a temperature (or field) at which the Cooper pairs start to form, and another temperature(or field) below which the Cooper pairs attain phase coherence throughout the sample. Therefore, the $T_c$(or $H_{c2}$) of resistivity measurements corresponds to the temperature (or field) that coherence has been obtained, whereas the onset of the anomalous Nernst signal corresponds to the temperature (or field) of the Cooper pair formation. The authors also suggest that this anomalous Nernst signal is related to the pseudogap or some interaction between the pseudogap state and the superconducting state since the Nernst signal follows a pattern similar to the pseudogap phase diagram(i.e. the signal above $T_c$ is more pronounced in the under-doped regime) [5].

These Nernst effect measurements have inspired a revisit to the theory of superconducting fluctuations in the cuprates. These theoretical studies have proposed that the anomalous Nernst effect can be explained in terms of various types of fluctuations or in terms of a preformed pair model. Kontani suggests that including antiferromagnetic fluctuations in addition to superconducting fluctuations in the under-doped regime would explain the unusually large Nernst signal above $T_c$ [6]. Ussishkin et al. [7] suggest that Gaussian superconducting fluctuations above $T_c$ are able to explain the Nernst effect for the optimally-doped and over-doped regimes. For the under-doped regime they suggest that strong non-Gaussian fluctuations reduce the mean-field transition temperature $T_c^{MF}$ and therefore the mean field $T_c^{MF}$ should be used in calculations instead of the actual $T_c$ in order to take into account the contribution of the non-Gaussian fluctuations to the Nernst effect [7]. Another proposal came from Tan et al. [8] in which they proposed a preformed pair alternative to the vortex-like excitations scenario to explain the anomalous Nernst effect in the under-doped hole-doped cuprates. The work of Carlson et al. [9] is another important study about the nature of superconducting fluctuations that we should mention. In this study the cuprates are classified in terms of their pairing strength (a measure of the superconducting gap) and phase stiffness (a measure of the superfluid density). This theory would predict that in the hole-doped cuprates the fluctuations in the phase of the order parameter would dominate the Nernst signal up to a certain temperature above $T_c$, and at still higher temperatures there should be contributions to the Nernst effect from fluctuations both in phase and the amplitude of the order parameter (Gaussian fluctuations). The same study would predict that these fluctuations should be much less in the electron-doped cuprates. At present, none of the proposed explanations for the large Nernst signal observed in the hole-doped compounds have gained general acceptance.

Early measurements on hole-doped cuprates, which were concentrated on the optimally-doped regime, showed a large Nernst signal below $T_c$ (the well known vortex Nernst effect) which diminished rapidly close to $T_c$ ($H_{c2}$), and merged to the normal state Nernst signal [10]. This behavior was similar to that observed in conventional superconductors, except for a broader fluctuation regime. The Nernst effect studies in the electron-doped cuprate superconductors(all previous measurements were on Nd$_{1.85}$Ce$_{0.15}$CuO$_{4-\delta}$(NCCO)) showed the same behavior in the superconducting state. However, the normal state behavior was quite different [11–13]. An anomalously large Nernst voltage in the normal state was interpreted as evidence for the existence of two types of carriers, not vortex-like excitations. The two carrier interpretation has recently been supported for optimal doping by ARPES measurements which showed electron...
pockets on a hole-like Fermi surface [14]. The doping dependence of the Nernst effect in the electron doped superconductors was studied by varying the oxygen content of NCCO, but the cerium doping dependence was not investigated.

In this paper we report Nernst effect data for the electron-doped superconductor Pr$_{2-x}$Ce$_x$CuO$_4$(PCCO) at different cerium dopings, and discuss some of the important issues that were raised by the recent Nernst effect measurements on the hole-doped compounds. Magnetic field and temperature dependence of the Nernst voltage, and temperature dependence of $H_{c2}$ close to $T_c$ are presented. In addition, $H_{c2}$ values obtained from Nernst effect and resistivity are compared. Unlike the recent results on some hole-doped compounds [1–4], our data does not show an anomalous Nernst signal above $T_c$(or $H_{c2}$) for the optimally-doped and over-doped compounds. However, the under-doped compound shows a larger fluctuation regime. The $H_{c2}(T)$ obtained from the Nernst effect follows a conventional linear temperature dependence close to $T_c$ for all dopings we studied in contrast to an anomalous curvature found in many previous resistivity determinations of $H_{c2}(T)$. The critical field, $H_{c2}(0)$, and the superconducting energy gap deduced from $H_{c2}(0)$ increase with decreasing doping even though $T_c$ has a different doping dependence. The magnitude of the Nernst signal in the normal state is very similar for different cerium dopings. It is too large to be explained by a one carrier (one-band) model and it does not show the temperature dependence to be caused by vortex-like excitations or superconducting fluctuations. This suggests that two types of carriers (bands) exist in all the cerium dopings we studied and they are the origin of the large Nernst signal above $T_c$.

THEORETICAL BACKGROUND

The Nernst effect is a thermomagnetic effect, in which a transverse potential difference is induced in the presence of a longitudinal thermal gradient and a perpendicular magnetic field. Since a detailed account of the theory of Nernst effect is given in literature [2,13,15], we will not repeat it in this manuscript except for a brief summary. The Nernst effect of a normal metal with one band of conduction is known to be small (due to Sondheimer’s cancellation [16]), and this effect is linear in magnetic field since it is induced by the Lorentz force on the charge carriers ($F = qv \times B$). On the other hand, the Nernst effect in the mixed state of a superconductor is due to vortex motion (rather than electrons or holes of a normal metal). A vortex moving in a magnetic field induces an electric field transverse to its motion due to aphase slip effect [17]. The vortex Nernst effect is the dominant thermomagnetic effect and it is much larger than the normal state Nernst effect. In a conventional type-II superconductor the vortex Nernst effect goes through a peak when the magnetic field is scanned at a constant temperature and it merges onto the small normal state Nernst signal around $H_{c2}$. The Nernst effect will be represented as $e_y = E_y/\sqrt{T}$ in the rest of the manuscript.

There are several issues worth mentioning that are special to the normal state of electron-doped compounds. As we said earlier, the Nernst effect of a normal metal with one band of conduction is small. However, the Nernst effect in the normal state of the electron-doped cuprates was observed to be large ($\sim$ two orders of magnitude larger than expected for a one band system). This observation combined with unusually small magnitude for the ratio of Hall angle to the thermal Hall angle (again roughly two orders of magnitude smaller than expected for a one band system) were interpreted as evidences for the existence of two-bands of conduction in these materials [11–13].

SAMPLES AND EXPERIMENTAL SETUP

The measurements were performed on Pr$_{2-x}$Ce$_x$CuO$_4$ (x=0.13, 0.15, and 0.17) thin films grown by the pulsed laser deposition technique on STO substrates. The thickness of the films was between 2000-3000 Å. The sample was attached on one end to a copper block with a mechanical clamp (for better thermal contact), with the other end left free (similar to a diving board—see Ref. [12] for a figure). A temperature gradient was created by heating up the free end with a small heater attached on the film. Two Lakeshore cernox thermometers were attached on the two ends of the sample to monitor the temperature gradient continuously. The temperature gradient was between 1-2.5 K/cm depending on the temperature of the measurement. The temperature of the sample was determined by taking the average of the temperatures at the hot and cold sides. The measurements were performed under vacuum, and the magnetic field was perpendicular to the ab-plane. The Nernst voltage was measured with a Keithley 2182 Nanovoltmeter which has a sensitivity of several nanovolts. The measurements were made at fixed temperatures while the field is scanned slowly at a rate of 20 Oe/sec. The temperature stability was a few millikelvins during the field scan. The Nernst signal is measured at positive and negative field polarity, and (1/2) the difference of the two polarities is taken to remove any thermopower contribution.

DATA AND ANALYSIS

Fig.1 shows the resistivity data for the films used in this study. The $T_c$, the sharpness of the superconducting transition, and the behavior of resistivity in high magnetic fields below the zero-field $T_c$(insulating-like for optimally-doped and under-doped samples, and metallic for over-doped samples) show the high quality of the films [12].

Fig.2-a, -b, -c show the low temperature Nernst effect data for the three dopings we studied, and Fig.2-d shows a comparison of the Nernst signal for the three dopings at $T/T_c \approx 0.7$. The superconducting vortex Nernst signal of the over-doped and optimally-doped samples crosses over to the normal-state Nernst signal(linear in magnetic
field) very close to the resistive $H_{c2}$. In the under-doped sample, the transition from the superconducting state to normal state occurs over a wider field range suggesting that the fluctuation regime is broader for the under-doped regime compared to the other dopings.

![Graph showing resistivity vs. temperature for different dopings](image)

**FIG. 1.** Resistivity of the optimal, over, and under-doped PCCO as a function of temperature at zero field (dark symbols) and $H=14$ T (open symbols). The inset shows the resistivity of the same samples as a function of field at $T=2$ K.

Nevertheless in all three dopings the Nernst signal behaves very differently from the hole-doped cuprates in which an anomalous Nernst signal has been observed [1–4]. In the electron-doped PCCO the peak of the vortex Nernst signal is quite sharp in all the dopings we studied. However, these hole-doped compounds [1–4], particularly the under-doped compounds, show an extended peak for the vortex Nernst signal that persists to fields much larger than the resistive $H_{c2}$ even at temperatures very close to $T_c$.

Fig. 3-a shows the typical Nernst effect for $T > T_c$ for the optimally-doped sample. The linear field dependence of the charge carrier Nernst effect is clearly seen, and no anomalous behavior is observed even at temperatures very close to the resistive $T_c$. Under-doped and overdoped samples behave very similarly to the optimally-doped sample, therefore the data for these dopings is not shown here. Fig. 3-b summarizes the temperature dependence of the Nernst signal at 9 T for $T > T_c$. The dome-like behavior that was observed in $\text{Nd}_1.85\text{Ce}_{0.15}\text{CuO}_4$ for different oxygen dopings [12,13] is also observed in PCCO for different cerium dopings. The large magnitude of the Nernst signal is also similar to that observed in NCCO for $T > T_c$. This large magnitude of the Nernst signal and some other observations that are discussed in detail in Ref. [12] were interpreted as evidence for the existence of two-types of carriers in electron-doped cuprates. In consistency with this previous interpretation, our present Nernst effect studies suggest that two-types of carriers exist in PCCO for all cerium dopings we studied. Quantitative analysis of how two types of carriers are introduced in the system, and the variation of their concentration with cerium and oxygen doping requires further systematic studies. We should also mention that the Nernst effect of some hole-doped compounds (especially at optimal doping) has been measured to high accuracy in the normal state up to room temperature. These experiments have shown that the Nernst signal decreases dramatically just above $T_c$, and remains less than 50 nV/K for temperatures up to 330 K [18,19]. These signal levels are much smaller than what is found in PCCO suggesting one-type of carrier in the hole-doped cuprates.

Whether the fluctuation region observed in the under-doped PCCO is related to the pseudogap state is an important issue. The experiments that studied the pseudogap state in electron-doped compounds have not yet produced conclusive results about either the magnitude or the onset temperature ($T^*$) of the pseudogap. The experiments in which evidence for the pseudogap state has been claimed are tunnelling spectroscopy ($T^* \leq T_c$) [20,21], optical conductivity ($T^* > 292$ K [22] to $T^*=110$ K [23]), photoemission [24], and Raman spectroscopy [25] ($T^*=220$ K).

Unlike the experiments on hole-doped compounds that showed the pseudogap to be near the $(\pi, 0)$ region, the location of the pseudogap on the Fermi surface is also controversial for the electron-doped cuprates. Photoemission showed gap-like features near the intersection of the underlying Fermi surface with the antiferromagnetic Brillouin zone boundary whereas
Raman spectroscopy showed a suppression of spectral weight for the B$_{2g}$ Raman response in the vicinity of $(\pm \pi/2, \pm \pi/2)$.

Our Nernst effect data does not show a strong signal that could be related to a pseudogap. For example, in the hole-doped compounds where the anomalous Nernst effect has been observed [1–4], there is no distinctive feature in the Nernst signal when crossing $T_c$ (i.e. $T_c$ does not seem to be a special temperature). This suggests that these excitations, which could originate at the pseudogap temperature ($T^*$) dominate the signal around $T_c$. However, we should mention that this type of behavior is not found in all hole-doped cuprates. For some cuprates (i.e. the distinctive vortex Nernst signal goes to zero just above $T_c$) the under-doped sample at $T_c$ does not seem to be a special temperature). This suggests that these excitations, which could originate at the pseudogap temperature ($T^*$) dominate the signal around $T_c$.

We now discuss the $H_{c2}(T)$ extracted from the Nernst signal (see Fig.4-a). The dashed lines in Fig.4-b show our method of extracting $H_{c2}(T)$. The uncertainty in the value of $H_{c2}(T)$ is found from the difference between the point of intersection of the dashed lines and the point one would get from extrapolating the vortex Nernst signal to zero. In our case extrapolating the vortex Nernst signal to zero is the same as extrapolating $S_o$, the transport entropy per unit length of flux line, to zero since the flux flow resistivity is constant in the relevant field range ($S_o = \phi_0 \rho_f / \rho_ff$, where $\rho_ff$ is the flux flow resistivity and $\phi_0$ is flux quantum). Due to the complications of extracting the $H_{c2}(T)$ from $S_o$ that are detailed in Ref. [13] (usually $H_{c2}(T)$ is overestimated in this method), $H_{c2}(T)$ is not extracted from $S_o$. In particular it was shown that determining $H_{c2}(T)$ from $S_o$ does not work at all for under-doped NCCO [13]. Therefore the errors in the value of $H_{c2}(T)$ are taken large enough to take into account this uncertainty. Considering the small difference between the $H_{c2}(T)$ values one would get by using different methods to determine it, some of the important results of this study would be valid in any of the methods used. One of these results is that $H_{c2}(0)$ increases with decreasing doping, since for a given $T/T_c$ the signature of the normal state is seen at a larger field as the doping decreases. The other conclusion that would not change by the uncertainty in determining $H_{c2}(T)$ is that the fluctuation regime becomes narrower as the doping increases. This can be seen by comparing the close proximity of the vortex Nernst peak and the linear field dependent normal state contribution in the over-doped sample vs the broad transition region between these two typical regimes in the under-doped compound. However, one conclusion that would change for the under-doped compound is the linear temperature dependence of $H_{c2}(T)$. Using $S_o$ to determine $H_{c2}(T)$ would make it very difficult to observe any systematic temperature dependence for $H_{c2}(T)$ as was also found in Ref. [13].

The $H_{c2}(T)$ of the optimally-doped sample shows a linear temperature dependence in the range of our Nernst effect data. $H_{c2}(0)$ is estimated using the Helfand-Werthamer formula [26]

$$H_{c2}(0) \approx 0.7 \times T_c \times \frac{dH_{c2}}{dT},$$

where $dH_{c2}/dT$ is measured at $T_c$. $H_{c2}(0)$ for optimal dop-
ing is found to be 6.3±0.2 T, and therefore the coherence length of the optimally-doped sample is \( \xi(0) \approx 75 \pm 2 \text{Å} \) (from \( \xi^2(0) = \frac{\phi_0}{2\pi H_c^2(0)} \)). The \( H_{c2}(T) \) of the overdoped sample also shows a linear temperature dependence except for \( T > 13 \text{K} \) where the superconducting-to-normal state transition starts. Using the Helfand-Werthamer formula \( H_{c2}(0) \) is found to be 3.7±0.4 T, and \( \xi(0) \approx 109 \pm 6 \text{Å} \). Due to the broad fluctuation region, where the Nernst signal had almost no field dependence, it was more difficult to determine \( H_{c2}(T) \) for the underdoped sample. However, the fact that the normal state linear field dependence of the Nernst signal in the underdoped sample is observed at fields larger than that in the optimally-doped one suggests that \( H_{c2}(T) \) is larger in the underdoped compound. A Helfand-Werthamer extrapolation to the \( H_{c2}(T) \) vs \( T \) data for the under-doped compound yields \( H_{c2}(0)=7.1 \pm 0.5 \) and \( \xi(0) \approx 71 \pm 3 \text{Å} \). For a summary of these results see Table 1.

Another important point that we should mention about the upper critical field is the difference in the sensitivity of the Nernst effect and resistivity in determining \( H_{c2} \). Nernst effect is very sensitive to superconducting fluctuations which are difficult to observe in resistivity. This is particularly clear in the under-doped compound in which the onset of the normal state contribution is preceded by a wide fluctuation (Fig.2-a) regime in the Nernst effect whereas the resistivity in the same field range is basically flat (Fig.1). Resistivity measurements on PCCO and NCCO have shown the \( H_{c2} \) of the under-doped compound to be smaller than that of the optimal-doped compound [27] (this can also be seen in the inset of Fig.1). This would imply that the magnitude of the superconducting gap is larger in the optimally-doped compound. However, point-contact tunnelling experiments on similar samples have shown that the superconducting gap amplitude is larger in the under-doped compound compared to the optimally-doped one [20]. Our Nernst effect data explains this contradiction by the insensitivity of the resistivity to superconducting fluctuations, and implies that resistivity is not a proper measurement for determining \( H_{c2} \) in agreement with the conclusion of Ref. [27].

Resistivity and Nernst effect show similar \( H_{c2}(T) \) for all dopings if the initial deviation from the normal state resistivity is chosen as a reference for \( H_{c2}(T) \) (see Fig.5b). The under-doped compound shows a larger difference between the Nernst effect and resistivity in terms of \( H_{c2}(T) \), which suggests that the fluctuation regime is broader in the under-doped compound. A sample curve showing the superconducting-normal state transition from resistivity and Nernst effect is shown in Fig.5-b for the optimally-doped sample.

There are important similarities between our Nernst effect data and the recent Nernst effect data on hole-doped Bi-2212(Bi2Sr2CaCu2O8) and Bi-2201(Bi2Sr2−yLayCuO6) [28]. Similar to our results, \( H_{c2}(0) \) was found to increase with decreasing doping for both single layer and double layer Bi compounds studied in Ref [28]. These observations are consistent with other experiments showing an increasing superconducting gap \( (\Delta_0 \propto v_f \sqrt{T_{c2}} , \text{where} \, v_f \text{is the Fermi velocity}) \) amplitude with decreasing doping both for the n-doped and the p-doped cuprates [13,29].

![Fig. 4. (a) The upper critical field \( H_{c2}(T) \) extracted from the Nernst effect data of Fig.2 (and other data omitted from Fig.2 for clarity). (b) Comparison of Nernst effect and resistivity in terms of \( H_{c2} \) for \( x=0.15 \) sample. The dashed lines show the method used to extract \( H_{c2} \).](image)

| sample | resistive \( T_c \) | \( H_{c2}(0) \) | \( \xi(0) \) | \( dH_{c2}/dT \) |
|--------|----------------|----------------|-------------|----------------|
| x=0.13 | 14 K          | 7.1 T          | 7.1 nm      | 0.41 T/K       |
| x=0.15 | 20.5 K        | 6.3 T          | 7.5 nm      | 0.37 T/K       |
| x=0.17 | 14.4 K        | 3.7 T          | 10.9 nm     | 0.35 T/K       |

TABLE I. Summary of our results.
SUMMARY

In contrast to the hole-doped cuprates where an anomalous Nernst signal has been observed, the vortex Nernst signal in the electron-doped PCCO does not persist above $T_c$ or $H_{c2}$ for over and optimal dopings. The $T_c$ and $H_{c2}$ extracted from our Nernst effect measurements for these cerium dopings are similar to those obtained from resistivity if the start of the resistive superconducting transition is chosen as a reference for $T_c$ or $H_{c2}(T)$. The under-doped compound shows a broader fluctuation regime, and therefore the superconducting to normal state transition looks different in Nernst effect and resistivity. Above $T_c$ the temperature dependence of the Nernst voltage is very similar for different dopings, and the magnitude of the Nernst signal is too large to be explained by a one-carrier model. These results are consistent with our previous experiments on NCCO which were interpreted as evidence for the existence of a two-carrier transport in these materials [12].

The different behavior of the Nernst effect beyond the resistive $T_c$ (or $H_{c2}$) for n-doped and the p-doped cuprates in which an anomalous Nernst signal is observed in the optimal and over-doping is a puzzling problem that remains to be resolved. However, it is clear that the large Nernst signal seen in the normal state ($T>T_c$) of the n-doped cuprates has a different origin than the anomalous Nernst signal observed in the p-doped compounds. In our data we see a clear distinction between the vortex Nernst effect contribution (a peak in the superconducting state) and the normal state contribution which is linear in magnetic field and which increases with temperature for $T>T_c$ up to $\sim 30$ K above $T_c$. In contrast, the anomalous Nernst signal observed in some of the p-doped compounds is not distinct (there is no feature at or around $T_c$ that would distinguish the two contributions) from the vortex Nernst contribution, and the signal decreases with temperature for $T>T_c$ up to 50 K above $T_c$ [2].

In conclusion, we see a possible explanation in terms of superconducting fluctuations that can reconcile the n-doped and p-doped Nernst experiments. Non-Gaussian fluctuations in the phase of the superconducting order parameter are dominant around $T_c$ and the mean field critical temperature $T^{MF}_c$, but between this $T^{MF}_c$ and the onset of the anomalous Nernst signal, $T_\nu$, fluctuations both in amplitude and phase of the order parameter should be considered in order to explain the anomalous Nernst effect [7]. Vortex-like excitations above $T_c$ might be an ambiguous way of describing this phenomenon since at such conditions (high density of fluctuations) the idea of a vortex becomes unclear. At temperatures $T>T_c^{MF}$ fluctuations in the amplitude of the order parameter are also important. Hence, this would make a vortex description of such fluctuations questionable since a certain amplitude stability is required for a vortex to be created. These fluctuations are smaller in the electron-doped cuprates due to two main reasons:

1. The effect of amplitude fluctuations is smaller in the n-doped cuprates because of a larger coherence length ($\sim 5$ times larger in PCCO compared to LSCO).

2. The phase fluctuations that dominate around $T_c$ for the hole-doped cuprates are smaller in electron-doped compounds since the phase stiffness temperature is comparable to the superconducting gap amplitude in these materials. For more details about this issue see Ref [9].

Another important issue that should be reconciled with the results of other experiments is the relation of the anomalous Nernst signal to the pseudogap. There are two points that should be mentioned. The first is that the onset temperature ($T_\nu$) of the anomalous Nernst signal is still much less than the pseudogap onset temperature observed in NMR or optical conductivity experiments for all the hole-doped cuprates in which an anomalous Nernst signal has been observed. This could imply two things: either the pseudogap observed in NMR measurements is different and independent of the anomalous Nernst signal or there is more than one source for a pseudogap-like behavior (i.e. multiple pseudogaps). The fact that the anomalous Nernst signal is more pronounced in the under-doped regime, similar to the pseudogap observed in other experiments, suggests that the two phenomena are related and hence the pseudogap-like behavior is a result of more than one mechanism. Another important fact that would support this idea is that the anomalous Nernst signal has not been observed in all the hole-doped cuprates that show evidence for a pseudogap above $T_c$. These two different behavior can be reconciled by a multiple pseudogaps model, since the absence of strong superconducting fluctuations would not be the only way for the creation of a pseudogap in this model. In fact there are several proposals for the pseudogap crossover that have nothing to do with superconductivity [30]. But none of these proposals have yet explained the origin of a large Nernst signal for $T_c < T < T^*$. The second point that should be mentioned is related to the pseudogap phenomena in the electron-doped cuprates. Tunnelling studies on electron-doped PCCO show a pseudogap that has an onset temperature $T^*<T_c$ [20,21]. It is not clear at this moment if this behavior can be reconciled with the other experiments that suggest a pseudogap at temperatures much higher than $T_c$. Again considering multiple origins for the pseudogap could explain these different experiments which probe different physical properties. However, having a $T^*<T_c$ would be another plausible explanation for why an anomalous Nernst signal is not observed in electron-doped cuprates above $T_c$.

Clearly, more work on the nature of the pseudogap state in the n-doped cuprates needs to be done before any conclusive explanation of the n-doped and p-doped Nernst effect data can be made. At the present time a superconducting fluctuation induced anomalous Nernst effect would appear to be most consistent with all the known experimental data.

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