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Transport signatures of the pseudogap critical point in the cuprate superconductor $\text{Bi}_2\text{Sr}_{2-x}\text{La}_x\text{CuO}_{6+\delta}$

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Four transport coefficients of the cuprate superconductor $\text{Bi}_2\text{Sr}_{2-x}\text{La}_x\text{CuO}_{6+\delta}$ were measured in the normal state down to low temperature, achieved by applying a magnetic field (up to 66 T) large enough to fully suppress superconductivity. The electrical resistivity, Hall coefficient, thermal conductivity and Seebeck coefficient were measured in two overdoped single crystals, with La concentration $x = 0.2$ ($T_c = 18$ K) and $x = 0.0$ ($T_c = 10$ K). The samples have dopings p very close to the critical doping p^* where the pseudogap phase ends. The resistivity of the sample closest to p^* displays a linear dependence on temperature whose slope is consistent with Planckian dissipation. The Hall number decreases with reduced p , consistent with a drop in carrier density from $n = 1 + p$ above p^* to $n = p$ below p^* . The thermal conductivity satisfies the Wiedemann-Franz law, showing that the pseudogap phase at $T = 0$ is a metal whose fermionic excitations carry heat and charge as do conventional electrons. The Seebeck coefficient diverges logarithmically at low temperature, a signature of quantum criticality. Given the observation of these same properties in other, very different cuprates, our study provides strong evidence for the universality of these four signatures of the pseudogap critical point.

PACS numbers:

I. INTRODUCTION

Since their discovery, cuprate superconductors have captured the imagination of condensed matter physicists in a quest to elucidate the origin of their remarkably high critical temperature. A huge array of experimental probes was also used to scrutinize the exotic phases that emerge alongside superconductivity in these materials. Among these, the pseudogap phase stands out for its enigmatic nature. There is no consensus on the nature of this phase nor its connection to superconductivity [1]. It is characterized by several experimental signatures, in particular the opening of a momentum dependent spectral gap [2] and a loss of density of states detected by specific heat [3] and NMR [4, 5]. Transport measurements in magnetic fields high enough to fully suppress superconductivity down to $T \simeq 0$ have unveiled the otherwise hidden properties of that phase in its ground state [6]. First, there is a drop in the carrier density at the critical doping p^* where the pseudogap phase ends, detected by the Hall number decreasing from $n_H \simeq 1 + p$ above p^* to $n_H \simeq p$ below p^* , in YBCO [7] and Nd-LSCO [8]. Secondly, a T -linear resistivity down to $T \rightarrow 0$, the emblematic signature of quantum criticality [9], is observed

in Bi2201 [10], Nd-LSCO [11], LSCO [12] and Bi2212 [13], at p^* . The slope of the linear regime is consistent with a scattering rate in the Planckian limit, namely $\hbar/\tau \simeq k_B T$ – as also found in organic, heavy-fermion and iron-based superconductors at their respective quantum critical points [14]. Another phenomenon linked to quantum criticality is the logarithmic divergence of the specific heat at low temperature, observed in heavy-fermion metals [15, 16] and also, recently, in the cuprates Eu-LSCO and Nd-LSCO [17]. A logarithmic divergence was also observed in the Seebeck coefficient of Nd-LSCO [18] and Eu-LSCO [19] at p^* , whereby $S/T \propto \log(1/T)$ as $T \rightarrow 0$. Finally, the Wiedemann-Franz law – which states that the thermal and electrical conductivities of electrons are equal in the $T = 0$ limit – was found to be valid in Nd-LSCO, both just above p^* (in the strange metal state of T -linear resistivity) and below p^* (in the pseudogap phase) [20]. This tells us that the pseudogap phase is a metal whose fermionic excitations carry heat and charge as do conventional electrons.

The four transport properties outlined here have been observed all together in only one cuprate material, Nd-LSCO. To establish that they are universal signatures of the pseudogap phase, it is necessary to confirm them

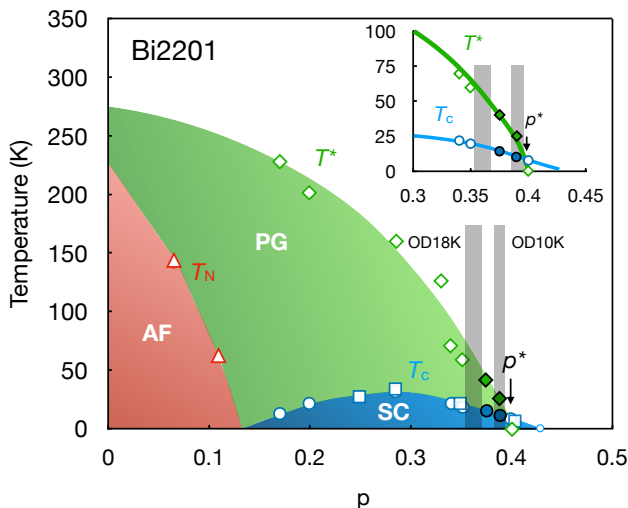


Figure 1: Temperature-doping phase diagram of the hole-doped cuprate Bi2201. The Néel temperature T_N (triangles), the superconducting temperature T_c (circles), and the pseudogap temperature T^* (diamonds) are taken from NMR measurements [21]. The full symbols (diamonds and circles) are from as yet unpublished data [22]. The doping p is defined from T_c , using the experimental relation between T_c (squares) and the area of the associated Fermi surface measured by ARPES [23], which is proportional to $1 + p$ (see text). The two vertical grey bands mark the dopings of our two overdoped samples, respectively labelled OD18K ($T_c = 18$ K) and OD10K ($T_c = 10$ K). *Inset*: Zoom on the region near p^* , the critical doping where the pseudogap phase ends, *i.e.* where T^* (green line, diamonds) goes to zero. We see that for a sample with $T_c = 10$ K, the pseudogap opens at $T^* = 25$ K, and $p^* = 0.40 \pm 0.01$, where $T_c = 8$ K.

in a different cuprate, ideally all together. This is the purpose of our study, which focuses on the material $\text{Bi}_2\text{Sr}_{2-x}\text{La}_x\text{CuO}_{6+\delta}$ (Bi2201).

A number of transport studies have been reported for this material, in high fields and / or at high doping [24–30], but to our knowledge, there is no prior report of thermal conductivity or Seebeck coefficient in the normal state of overdoped Bi2201 at $T \rightarrow 0$, close to p^* . This material presents multiple advantages, starting with a low maximal T_c , which allows for a complete suppression of superconductivity down to $T \simeq 0$ by application of a magnetic field that can easily be achieved in high-field facilities [5]. It is a single-layer cuprate, which facilitates the interpretation of Fermi surface properties. Its Fermi surface has been carefully delineated by angle-resolved photoemission spectroscopy (ARPES), all the way to the highest dopings, beyond p^* [23, 31]. The boundary of its pseudogap phase in the temperature-doping phase diagram has been mapped by both ARPES [32] and NMR [21], and the two techniques agree on the pseudogap temperature $T^*(p)$ and on the critical doping $p^* \simeq 0.4$ (Fig. 1).

Finally, its superconducting dome extends over a significantly different doping range than in other cuprates,

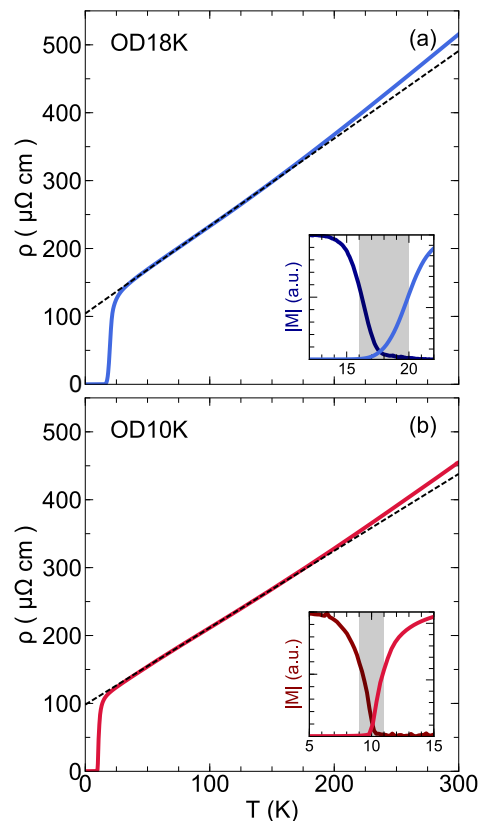


Figure 2: In-plane electrical resistivity of overdoped Bi2201 in zero magnetic field, as a function of temperature, for our two samples: (a) OD18K; (b) OD10K. The dashed line is a linear fit to the data over the interval from 60 K to 160 K. It yields the residual resistivity ρ_0 by extrapolation to $T = 0$, namely: (a) $104 \pm 2 \mu\Omega \text{ cm}$; (b) $98 \pm 2 \mu\Omega \text{ cm}$. *Inset*: Zoom on the magnetization (dark curve, absolute value) and the resistivity (pale curve) near T_c . Together, the two curves allow us to define the bulk value of T_c for each sample (grey band), namely: (a) 18 ± 2 K; (b) 10 ± 1 K.

namely up to $p \simeq 0.42$ (ref. 23), much higher than in Bi2212 or LSCO [23], for example, where it ends at $p \simeq 0.27$, thereby making Bi2201 an important candidate to test the universality of the transport signatures at p^* .

In this Article, we present measurements of the resistivity, Hall and Seebeck coefficients in high magnetic field, along with the thermal conductivity at very low temperature, for Bi2201 at two dopings very close to p^* . Our study reveals signatures of the pseudogap critical point that are very similar to those observed in Nd-LSCO: the carrier density drops, the T -linear dependence of $\rho(T)$ has a slope consistent with Planckian dissipation, the Wiedemann-Franz law holds, and the Seebeck coefficient diverges logarithmically as $T \rightarrow 0$. This shows that these four signatures are very likely to be universal amongst hole-doped cuprates.

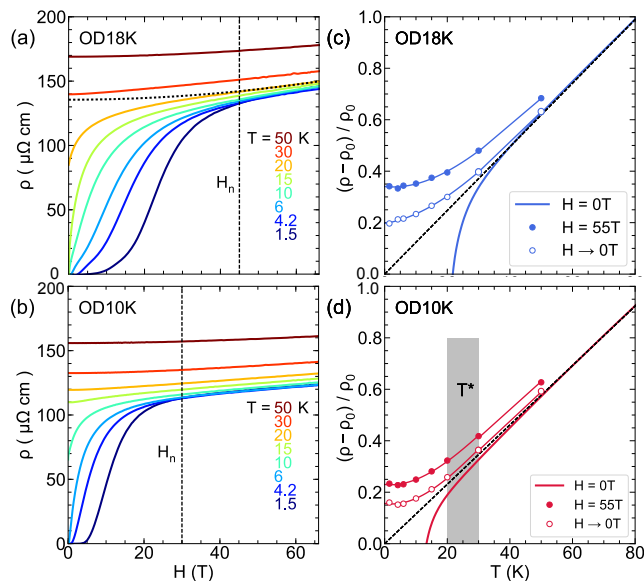


Figure 3: *Left panels:* Resistivity as a function of magnetic field at different temperatures, as indicated, for (a) OD18K and (b) OD10K. The black vertical dashed lines mark the magnetic field H_n above which the normal-state resistivity is reached, namely $H_n \simeq 45$ T for OD18K and $H_n \simeq 30$ T for OD10K. *Right panels:* Intrinsic resistivity, $\rho(T) - \rho_0$,

normalized by the residual resistivity ρ_0 , as a function of temperature for (c) OD18K and (d) OD10K. ρ_0 is obtained using a linear fit to $\rho(T)$ in zero field above T_c (dashed line in Fig. 2). Solid colored lines represent zero field data, full circles data taken at $H = 55$ T (from isotherms in left panels) and open circles represent data obtained in high magnetic field for which a correction has been applied to remove the magnetoresistance (see text). Dashed black lines are linear fits of zero field data above T_c (same as dashed lines in Fig. 2). The solid coloured lines that go through the data points are a guide to the eye. In panel (d), the vertical grey band marks the pseudogap temperature T^* determined by NMR Knight shift measurements at that doping, *i.e.* at $T_c = 10$ K (Fig. 1).

II. METHODS

Two single crystals, of composition $\text{Bi}_{2.05}\text{Sr}_{1.95}\text{CuO}_{6+\delta}$ and $\text{Bi}_2\text{Sr}_{1.8}\text{La}_{0.2}\text{CuO}_{6+\delta}$, were grown by the floating-zone technique [33]. They are thin rectangular platelets, with a length of 2.5 mm, a width of 0.5 mm and a thickness of 0.04 mm (normal to the CuO_2 plane). Characterization by SQUID magnetization measurement yielded sharp superconducting transitions with $T_c = 10 \pm 1$ K and $T_c = 18 \pm 2$ K (insets of Fig. 2). We label the samples OD10K and OD18K, respectively.

The resistivity ρ , Hall coefficient R_H , thermal conductivity κ and Seebeck coefficient S were measured for both samples. Contacts were prepared using silver epoxy, annealed at 400°C for 10 minutes and quenched at room temperature. The resulting contact resistances were less than 4 Ohms at room temperature. The currents (electrical and thermal) were applied in the CuO_2 planes,

that is along the length of the samples and the magnetic field was applied along the c axis. Electrical transport was first performed in Sherbrooke at $H = 0$ and $H = 16$ T in a PPMS, then in pulsed magnetic fields up to $H = 66$ T at the LNCMI in Toulouse, and in a static field of $H = 33$ T at the HFML in Nijmegen (for OD10K). Thermal conductivity was measured in Sherbrooke using a dilution refrigerator down to 80 mK, with an applied field up to $H = 15$ T. Thermoelectricity was first measured in Sherbrooke using a cryostat with a VTI and a superconducting magnet up to $H = 18$ T, and then at the LNCMI in Grenoble under a static field up to $H = 34$ T.

The question of doping in the cuprate Bi2201 is a delicate one, since there are many ways to dope the compound, *e.g.* La/Sr substitution [21], Bi/Sr ratio [29] and excess oxygen [30] (Bi/Pb substitution also allows to suppress the superstructure [31]). These differences affect the maximum T_c in different ways, which makes a comparison between studies difficult, especially when several doping methods are combined. In order to connect the relative position of our La-doped samples to the pseudogap phase and p^* , we compare the T_c values of our samples to the T_c values of the samples used in the NMR study by Kawasaki *et al.* [21], where the same doping method is used, *i.e.* La/Sr substitution. This NMR study clearly reveals a closing of the pseudogap for the La composition $x = 0$ ($T_c \simeq 8$ K). The inset of Fig. 1 shows a zoom on the region near p^* , including unpublished data from two additional samples (solid symbols, ref. 22): one sample has $T_c = 10$ K and $T^* = 25 \pm 5$ K; the other sample has $T_c = 14$ K and $T^* = 40 \pm 10$ K. The end of the pseudogap phase is seen to correspond to $T_c \simeq 8$ K. So according to this NMR-derived phase diagram, our sample OD10K is located just below p^* .

Different ways are used to define the doping p in Bi2201. Here, we use the relation between T_c and doping p established from ARPES studies by Kondo *et al.* [23], where the value of p is obtained from the area of the measured Fermi surface, which is proportional to $1 + p$ by the Luttinger theorem. From this relation, the end of the superconducting dome in Bi2201 is located at $p \simeq 0.42$ (Fig. 1). (A recent ARPES study [31] obtained a similar relation between T_c and p in Pb-doped Bi2201.)

III. RESISTIVITY: T -LINEAR DEPENDENCE AND PLANCKIAN DISSIPATION

In Fig. 2, the zero-field resistivity is plotted as a function of temperature up to 300 K. The residual resistivity ρ_0 is obtained by extrapolating to $T = 0$ a linear fit to the data above T_c (between 60 K and 160 K). In Fig. 3(c) and (d), the zero-field resistivity is plotted as $\rho - \rho_0$ divided by ρ_0 (continuous curve). This way of plotting the data allows for a more precise comparison of the inelastic resistivity in the two samples.

In Fig. 3(a) and (b), we show the isotherms of resistivity as a function of field up to $H = 66$ T for OD18K (a)

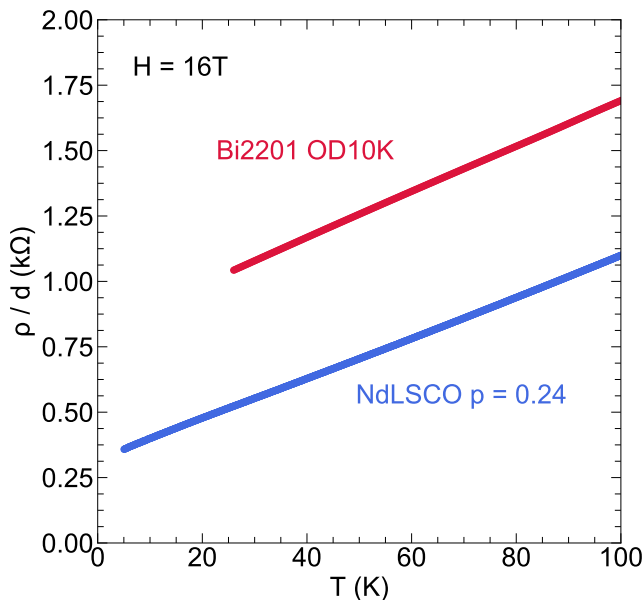


Figure 4: Normal-state resistance per CuO_2 plane, defined as the resistivity ρ divided by the distance d between CuO_2 planes, as a function of temperature, measured in a field $H = 16$ T, for two hole-doped cuprates close to their respective pseudogap critical points: Bi2201 at $p = 0.39$ (red, our OD10K sample), for which $p^* = 0.40$, and Nd-LSCO at $p = 0.24$ (blue, ref. 8), for which $p^* = 0.23$. The two show a nice T -linear dependence, with slopes that are very similar, namely $A = 9.0 \pm 0.9$ Ω/K and $A = 7.4 \pm 0.8$ Ω/K (ref. 13), respectively.

and OD10K (b), at various temperatures from 1.5 K to 50 K. The normal state at $T = 1.5$ K is reached when the field exceeds $H_n \simeq 45$ T for OD18K and $H_n \simeq 30$ T for OD10K. For both samples, we observe a small positive magnetoresistance above H_n . At $T = 50$ K, the resistivity is well described by $\rho(0) + bH^2$ over the entire field range, where $\rho(0)$ is the resistivity at $H \rightarrow 0$. To obtain the underlying normal state resistivity in zero field at lower temperatures, we fit the data above H_n to the form $\rho(0) + bH^2$, and extract $\rho(0)$, as illustrated by the dotted line in Fig. 3(a) – the fit to the $T = 20$ K isotherm of sample OD18K. In the right panels of Fig. 3, we plot the $\rho(0)$ values thus obtained vs T (open circles), and compare them with the data taken at $H = 55$ T (solid circles). The difference between the two is due to the magnetoresistance, seen to grow with decreasing T .

In Fig. 3(d), we see that in the absence of superconductivity, the resistivity free of magnetoresistance continues to be linear in T below 60 K, down to about 20 K. This is also seen in Fig. 4, where $\rho(T)$ at $H = 16$ T is linear down to $T \simeq 25$ K. However, the linearity does not persist as $T \rightarrow 0$, whereas it does in Nd-LSCO at $p = 0.24$, for example (Fig. 4). The difference in this case is that $p > p^*$ in Nd-LSCO whereas $p < p^*$ for Bi2201. In Nd-LSCO at $p < p^*$, an upturn at low T develops [8, 11], and the temperature below which the resistivity deviates upward from its high-temperature linear

behaviour corresponds to the temperature T^* measured by ARPES for the opening of the anti-nodal pseudogap [34]. In Fig. 3(d), we observe the same correspondance for Bi2201. Indeed, for the sample with $T_c = 10$ K, the resistivity upturn begins at the temperature T^* measured by NMR for the onset of the pseudogap phase (grey band) [22], see also Fig. 1. As we lower the doping to OD18K, the upward deviation gets more pronounced, a typical trend that was observed in underdoped Bi2201 [33], LSCO [35] and Nd-LSCO [8].

The observation of T -linear resistivity has been reported in a Bi2201 crystal $T_c = 7$ K in which the doping is controlled with the ratio Bi/Sr [10] and in a thin film doped with oxygen of $T_c = 8$ K [30]. In both cases, the linearity was measured from room temperature to T_c without the use of a magnetic field. The slope per CuO_2 plane estimated for the Planckian limit in Bi2201 is $A_{sq} \simeq 8 \pm 2$ Ω/K [13], which is in agreement with the mentioned studies. In Fig. 4, we compare the resistivity per plane in OD10K with that of another cuprate near p^* : Nd-LSCO at $p = 0.24$ (ref. 8). The two systems have very similar slopes, namely $A_{sq} = 9.0 \pm 0.9$ Ω/K in Bi2201 and $A_{sq} = 7.4 \pm 0.8$ Ω/K in Nd-LSCO (ref. 13). This is also very similar to the slope reported for Bi2212 at $p = 0.23 \simeq p^*$, namely $A_{sq} = 8.0 \pm 0.9$ Ω/K (ref. 13). We conclude that sample OD10K is also in the Planckian limit.

IV. HALL COEFFICIENT: DROP IN CARRIER DENSITY

The Hall coefficient is presented in Fig. 5(a) and (b) as a function of field up to $H = 66$ T for OD18K and OD10K, at various temperatures. For both dopings, the Hall coefficient is almost field independent above $H_n \simeq 45$ T in OD18K and $H_n \simeq 30$ T in OD10K, in agreement with the ρ vs H data (Fig. 3). In Fig. 5(c), we present the Hall coefficient as a function of temperature at $H = 16$ T (line), $H = 33$ T (pale line, only for OD10K) and $H = 55$ T (circles). We see that R_H at $T \rightarrow 0$ jumps from 0.8 ± 0.1 mm^3/C in OD10K to 1.5 ± 0.2 mm^3/C in OD18K. If we plot this in terms of the Hall number, $n_H = V/(eR_H)$, which corresponds to the carrier density n in a simple isotropic model, we find a pronounced drop in n_H below p^* (Fig. 6).

As shown in Fig. 6, (in which we estimate the doping of Bi2201 using the correspondance between T_c and p obtained via ARPES), this abrupt change in n_H was previously seen in YBCO [7] and Nd-LSCO [8]. The discovery of this signature was recognized as the hallmark of the change in carrier density that occurs as we enter the pseudogap phase. Now, the case of Bi2201 with a p^* value twice that of other cuprates [23] shows that this signature is a robust characteristic of the critical point where the pseudogap phase ends.

In order to compare our data to the data from Putzke *et al.* on (La,Pb)-Bi2201 samples [24], we use the same

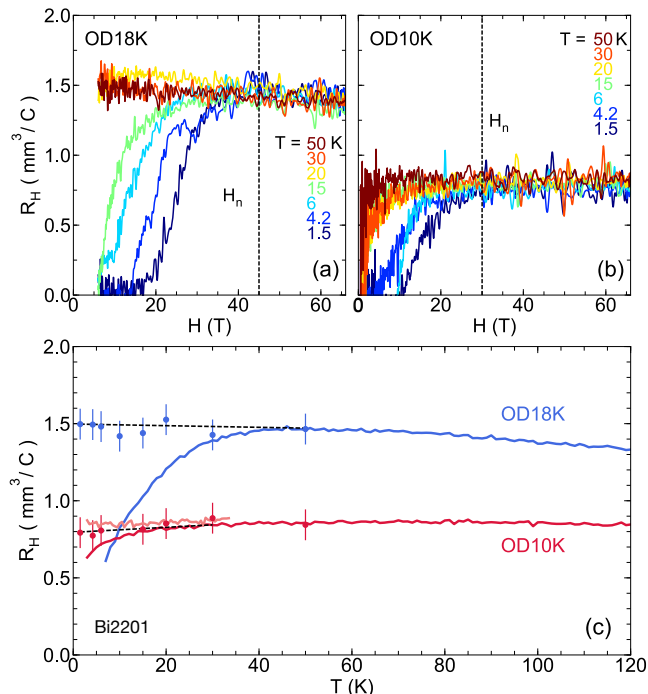


Figure 5: *Top panels:* Hall coefficient of Bi2201 as a function of magnetic field at different temperatures as indicated, for (a) OD18K and (b) OD10K. The black vertical dashed lines mark the magnetic field H_n above which the normal-state Hall coefficient is reached, namely $H_n \simeq 45$ T for OD18K and $H_n \simeq 30$ T for OD10K. *Bottom panel:* Hall coefficient as a function of temperature (c), for samples OD108K (blue) and OD10K (red), at $H = 16$ T (solid lines), $H = 33$ T (pink, OD10K) and $H = 55$ T (dots with error bars, from top panels). The black dashed lines are a guide to the eye through the 55 T data points. They yield the following values at $T \rightarrow 0$: $R_H = 1.5 \pm 0.2$ mm³/C for OD18K and 0.8 ± 0.1 mm³/C for OD10K.

T_c - p conversion and obtain the open red circles in Fig. 6. We see that their data are reasonably consistent with our data. In Putzke *et al.* though, the value for p^* (obtained using in-plane resistivity measurements) was taken much closer to optimal doping – in contrast with the NMR study that we use in this work to locate p^* , which is found near the end of the superconducting dome – and the absolute value extracted with a different method, namely the conventional law from ref.37. Nevertheless, no matter the absolute doping values chosen, the evolution of n_H with T_c is similar in both studies. Here, we find that the key observation is that n_H drops below p^* , thereby confirming in Bi2201 this important signature of the pseudogap state. It is accompanied by another clear signature observed in Bi2201, obtained from NMR [21]: an abrupt drop in the $T = 0$ normal-state density of states (in the absence of superconductivity) upon crossing below p^* . The combination of these two signatures of p^* in the same material sheds new light on the nature of the non-superconducting ground state of the pseudogap phase.

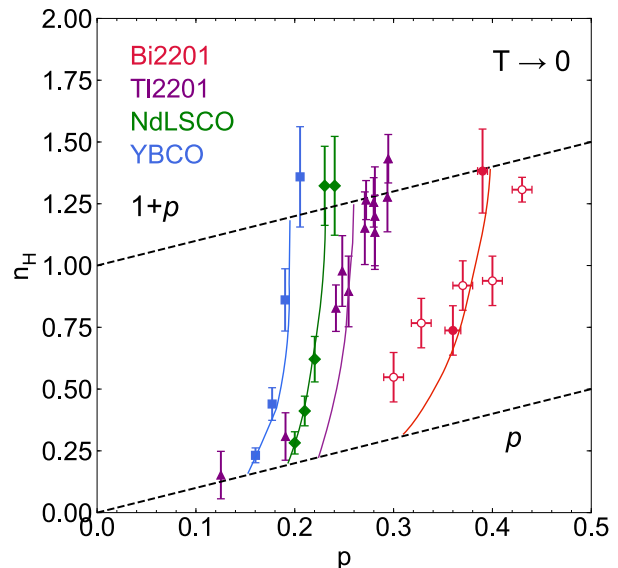


Figure 6: Hall number $n_H = V/(eR_H)$, with V the unit-cell volume, as a function of doping p for four different hole-doped cuprates: Bi2201 (solid red circles, this work; open red circles, ref. 24), Tl2201 (purple triangles, ref. 24), Nd-LSCO (green diamonds, ref. 8), and YBCO (blue squares, ref. 7). Dashed black lines correspond to $n_H = p$ and $n_H = 1 + p$, and colored solid lines are a guide to the eye for each compound. In all four cuprates, we observe a drop of n_H as doping decreases. In Bi2201, Nd-LSCO and YBCO, the start of this drop in n_H coincides with the onset of the pseudogap phase at p^* , where p^* is known from other means ($p^* \sim 0.4$ for Bi2201 [21, 23], $p^* \sim 0.23$ for Nd-LSCO [34] and $p^* = 0.19 \pm 0.01$ for YBCO [36]). In Tl2201, there is currently no other measurement of p^* .

V. THERMAL CONDUCTIVITY: WIEDEMANN-FRANZ LAW

Fig. 7 presents thermal conductivity measurements in OD18K and OD10K at $H = 0, 5, 10$ and 15T. We plot κ/T as a function of temperature so that the residual linear term κ_0/T corresponds to the electronic contribution, and the slope β is associated with phonons. The linear dependence reveals that the latter are subject to electron-phonon scattering. Data at $H = 10$ T and $H = 15$ T are practically superimposed which indicates that the normal state is (or near to be) reached. This is reminiscent of what was found in Nd-LSCO, in which the normal state in thermal conductivity measurements was also reached at a smaller field than in electric transport measurements [20]. This can be understood by the fact that thermal measurements are sensitive to the bulk and cannot be short-circuited by a small superconducting portion of the sample (due to an inhomogeneous doping), as it happens in electric measurements. Comparing the residual linear terms in the superconductive state ($H = 0$ T) and the normal state ($H = 15$ T), we have a ratio of $\kappa_0/\kappa_N \sim 0.7$ which corresponds to what is seen in Nd-LSCO [20]. This suggests a similar level of impurities, both compounds

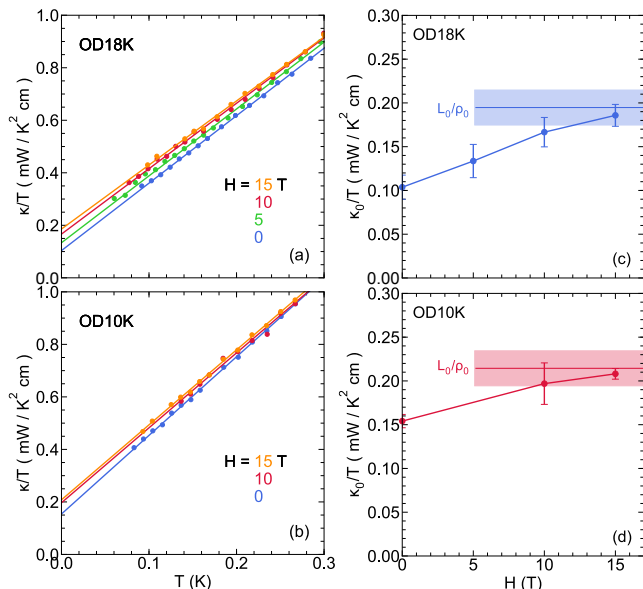


Figure 7: *Left panels:* thermal conductivity divided by temperature as a function of temperature in **a)** OD18K and **b)** OD10K, at different magnetic fields. Solid lines are linear fits to the data, allowing the extraction of the electronic residual linear term κ_0/T . *Right panels:* electronic thermal conductivity as a function of magnetic field in **c)** OD18K and **d)** OD10K. The horizontal lines correspond to the values of κ_0/T expected from the Wiedemann-Franz law *i.e.* $\kappa_0/T = L_0/\rho_0$, with ρ_0 the resistivity in the $T \rightarrow 0$ limit (taken at $H = 15\text{T}$) and L_0 the Lorenz constant (the shaded regions are the error bars).

being in the dirty limit.

We then test the Wiedemann-Franz law in these two samples. This relation between electronic and thermal transport in the $T \rightarrow 0$ limit is given by $\kappa_0/T = L_0/\rho_0$, with ρ_0 the resistivity in the $T \rightarrow 0$ limit and L_0 the Lorenz number, and is a hallmark of metallic behavior. It was found to be satisfied in Nd-LSCO both below and above p^* [20]. In Fig. 7, we plot the electronic residual linear term κ_0/T as a function of magnetic field, along with the expected value in the Wiedemann-Franz law limit, namely L_0/ρ_0 , plotted as a horizontal line. To extract ρ_0 estimated at $H = 15\text{T}$ (same field as the normal state thermal conductivity), we use the $\rho(H) \propto H^2$ fits to the high field isotherms in Fig. 3 (used to correct for the magneto-resistance, as presented with the dotted black curve in OD18K), and then take a cut of these normal state isotherms at $H = 15\text{T}$. We then plot the temperature dependence of $\rho(H \rightarrow 15\text{T})$ and extrapolate to $T = 0$. The use of different contacts for the electrical and thermal measurements (contacts were remade), the geometrical factors and approximation of the magneto-resistance lead to an error of 10% on L_0/ρ_0 which is represented by the band width of the L_0/ρ_0 horizontal lines. As we increase the field to reach the normal state, the electronic linear residual term κ_0/T tends towards the electrical counterpart in both samples, satisfying the Wiedemann-Franz law.

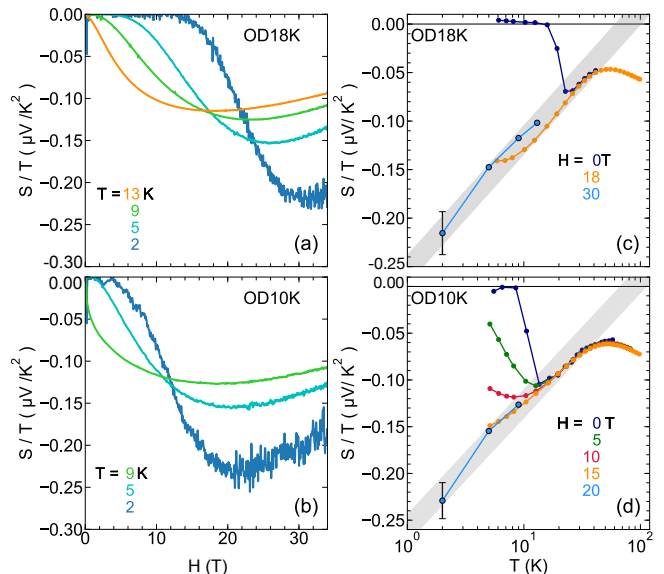


Figure 8: *Left panels:* Seebeck coefficient divided by temperature as a function of magnetic field, at different temperatures, for **a)** OD18K and **b)** OD10K. *Right panels:* Seebeck coefficient divided by temperature as a function of temperature for **c)** OD18K and **d)** OD10K, at different magnetic fields. The shaded region highlights the logarithmic temperature dependence of S/T in high magnetic field.

VI. SEEBECK COEFFICIENT: LOGARITHMIC DIVERGENCE

Fig. 8 shows Seebeck coefficient isotherms up to $H = 34\text{T}$. In both OD18K and OD10K, the normal state is reached down to the lowest temperature ($T = 2\text{K}$) at respectively $H = 30\text{T}$ and $H = 20\text{T}$. The first interesting feature of these data is the negative sign of the thermoelectric power which is preserved in field and temperature. Given that, like the Hall coefficient, the sign of the Seebeck coefficient can be linked to the sign of the charge carriers, and that the Hall coefficient is positive in the same crystals, it would be expected to find a positive Seebeck effect. However, this prediction lies on the assumptions that the scattering rate is isotropic and the dispersion parabolic, which does not generally hold in cuprates. Previous Seebeck measurements on Bi2201 [28, 38, 39] as well as computations based on phenomenological theories on cuprates [40] have come to the same result as the present study: a negative Seebeck effect.

The second striking feature in Fig. 8 is the huge growth of $|S/T|$ between 5 K and 2 K, which suggests a divergence in temperature. In order to study the temperature dependence carefully, we take a cut of these isotherms in the normal state (above H_n). The values are plotted as a function of $\log(T)$, along with the data at lower fields measured in Sherbrooke, in Fig. 8. This representation illustrates how $|S/T|$ increases approximately linearly with $\log(1/T)$. Such $\log(1/T)$ diverging behaviour of the Seebeck coefficient was observed in other cuprates. In Fig. 9,

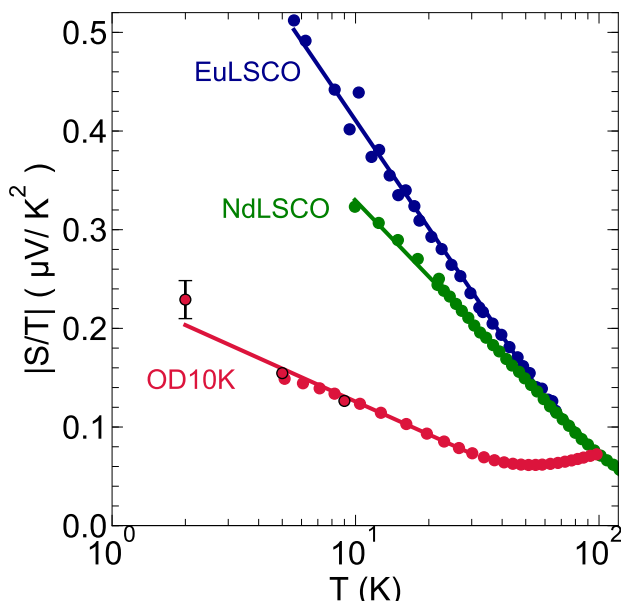


Figure 9: Seebeck coefficient divided by temperature (in absolute value) as a function of temperature for three hole-doped cuprates close to their respective pseudogap critical points: Bi2201 with $p = 0.39$ (this work, OD10K, red), Nd-LSCO with $p = 0.24$ (green, [18]) and Eu-LSCO with $p = 0.24$ (blue, [19]).

we compare Nd-LSCO with $p = 0.24$ and $H = 15$ T [18] and Eu-LSCO with $p = 0.24$ at $H = 10$ T [19] to Bi2201 OD10K. We observe a $\log(1/T)$ behaviour in all three over a comparable temperature range. In Eu-LSCO and Nd-LSCO, a diverging $\log(1/T)$ dependence is also observed in the electronic component of the specific heat (C_{el}/T), thermodynamic evidence of quantum criticality at p^* [17]. The fact that both Bi2201 samples exhibit a logarithmically divergent behavior in the Seebeck coefficient is also reminiscent of these specific heat measurements, in the sense that a divergent electronic specific heat $C_{el}/T \propto \log(1/T)$ was also found at several dopings around p^* in both Eu-LSCO and Nd-LSCO, namely at $p = 0.24$ and $p = 0.21$ in Eu-LSCO ($p^* = 0.23$) and at $p = 0.24$ and $p = 0.22$ in Nd-LSCO ($p^* = 0.23$). We conclude that the observation of a diverging $\log(1/T)$ Seebeck coefficient in Bi2201 makes a strong case for quan-

tum criticality being a universal property of cuprates.

VII. CONCLUSION

We have measured four transport properties of the cuprate material Bi2201 in magnetic fields large enough to suppress superconductivity and reach the normal state in the $T \rightarrow 0$ limit. Two dopings just below the pseudogap critical point p^* were investigated. For the doping closest to p^* , we found a T -linear resistivity down to low temperature with a slope per CuO_2 plane consistent with Planckian dissipation, along with a logarithmically diverging Seebeck coefficient ($S/T \propto \log(1/T)$). These two properties are typical signatures of quantum criticality. We also observed a drop in the Hall number with decreasing doping, consistent with a loss of carrier density below p^* . Finally, the Wiedemann-Franz law is satisfied, confirming that the normal state of the pseudogap phase is metallic. The addition of Bi2201 to the list of materials in which some – but typically not all – of these signatures were already observed (*e.g.* Nd-LSCO, Eu-LSCO, Bi2212, YBCO) makes a strong case for the universality of the pseudogap transport signatures in cuprates.

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