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Field-induced thermal metal-to-insulator transition in underdoped LSCO

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Abstract

The transport of heat and charge in cuprates was measured in undoped and heavily-underdoped single crystal $La_{2-x}Sr_xCuO_{4+\delta}$ (LSCO). In underdoped LSCO, the thermal conductivity is found to decrease with increasing magnetic field in the $T \rightarrow 0$ limit, in striking contrast to the increase observed in all superconductors, including cuprates at higher doping. The suppression of superconductivity with magnetic field shows that a novel thermal metal-to-insulator transition occurs upon going from the superconducting state to the field-induced normal state.

Keywords: Thermal transport; Metal–insulator transition; $La_{2-x}Sr_xCuO_4$

In underdoped $La_{2-x}Sr_xCuO_{4+\delta}$ (LSCO), resistivity measurements have revealed the field-induced normal state to be a charge insulator [1]. On the other hand, the superconducting state of underdoped LSCO is a thermal metal, in the sense that there is a clear T-linear contribution to the thermal conductivity at $T \rightarrow 0$ [2,3]. Given that in all superconductors investigated to date (including cuprates) heat transport at $T \rightarrow 0$ is always seen to increase as one goes from the superconducting state to the field-induced normal state, these two observations point to a violation of the Wiedemann–Franz law in underdoped cuprates.

In this article, we show the natural assumption that heat conduction will increase upon going from the superconducting state to the field-induced normal state to be incorrect in underdoped LSCO. Indeed, in the $T \rightarrow 0$ limit the thermal conductivity *decreases* in the vortex state and the residual linear term drops to a value below our resolution limit in the field-induced normal state. This result argues strongly for a thermally insulating normal state and reveals a novel thermal metal-to-insulator transition.

Measurements of the thermal conductivity (κ) were performed down to 40 mK in fields up to 13 T on single crystals of $La_{2-x}Sr_xCuO_{4+\delta}$ with $x = 0$ (not superconducting) and 0.06 ($T_c = 5.5$ K). Additional sample and measurement details are provided elsewhere [4].

In Fig. 1 the thermal conductivity is plotted as κ/T vs. $T^{\alpha-1}$, where α is a free fitting parameter. This type of plot is used to separate the electronic (κ_{el}) and lattice (κ_{ph}) contributions to κ by making use of their different power-law temperature dependences in the $T \rightarrow 0$ limit. In the limit $T \rightarrow 0$, κ_{el} is linear in T for a d-wave superconductor on account of nodal quasiparticle excitations [5]. Quite generally, a linear contribution to κ at $T \rightarrow 0$ is direct evidence for fermionic excitations. The phonon contribution can be modelled as $\kappa_{ph} \propto T^\alpha$ for phonons limited to scattering from the boundaries of the sample (see Ref. [2]). Thus, κ_{el} and κ_{ph} can be separated by fitting the data at low-temperatures to

$$\frac{\kappa}{T} = \frac{\kappa_0}{T} + BT^{\alpha-1}. \quad (1)$$

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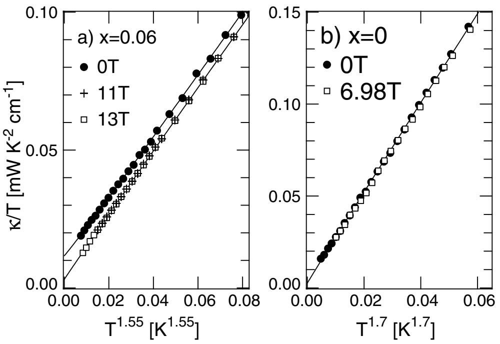

Fig. 1. κ/T vs. $T^{\alpha-1}$ for $La_{2-x}Sr_xCuO_{4+\delta}$ with x as shown. The lines are fits to Eq. (1).

The two distinct contributions are identified in Fig. 1 as the intercept and slope of the curves, respectively, when plotting the data as κ/T vs. $T^{\alpha-1}$.

Having described our analysis, several observations can be made. Firstly, in zero field (solid circles) the $x = 0.06$ data reproduces the results of Refs. [2,3] whereby a finite residual linear term in $\kappa(T)$ is observed at all superconducting dopings. This proves the existence of delocalized zero-energy quasiparticles in the superconducting state. In other words, the d-wave superconducting state is a thermal metal (see also [2]). In the $x = 0$ sample, however, κ_0/T becomes extremely small (3 $\mu W\,K^{-2}\,cm^{-1}$). Now, even though Eq. (1) provides a good description of the data, all the way up to 0.4 K, the fact that κ_0/T is five times smaller than the value of κ/T at the lowest data point (40 mK) means that one has to view the extrapolated value with caution. The conservative position is to assume that the parent compound $x = 0$ is a heat insulator as well as a charge insulator, and regard this minute linear term of 3 $\mu W\,K^{-2}\,cm^{-1}$ as the resolution limit of our technique, and treat the $x = 0$ data as our reference (for an insulating state in LSCO). By contrast, the linear term in the $x = 0.06$ sample (at 0 T) of 12 $\mu W\,K^{-2}\,cm^{-1}$ is clearly above the reference limit (by a factor 4) and is thus unambiguously a thermal metal.

This brings us to the principal observation of this article: *κ decreases with increasing field for the $x = 0.06$ sample*, as shown in Fig. 2 by the field evolution of κ_0/T. This decreasing field dependence is in stark contrast to the increase in the electronic heat conductivity in all other known superconductors at $T \to 0$, including cuprates at higher doping [4,6]. Note that κ is totally independent of magnetic field in our reference sample ($x = 0$). This shows that field dependence is a property of the superconducting state. We can therefore use this criterion to establish that the non-superconducting normal state is reached in the bulk by 11 T in sample $x = 0.06$. Indeed, as seen in Fig. 1a, a further increase of the field to 13 T causes no further change in κ. This claim is supported by resistivity measurements on the same sample where the resistive onset of superconductivity is entirely absent for fields of 12 T and above (down to 40 mK) [4]. We take this as an additional indication that the field-induced (non-superconducting) normal state has been reached by 13 T at $x = 0.06$ (in the bulk). Moreover, as seen in Fig. 2, κ_0/T drops by a factor 4 from $H = 0$ to $H = 13$ T, where it reaches a value equal to that of the reference sample, namely $\kappa_0/T = 3\ \mu W\,K^{-2}\,cm^{-1}$. We thus conclude that the field-induced normal state in underdoped LSCO is a thermal insulator. *This implies the existence of an unprecedented kind of thermal metal-to-insulator transition*. The superconducting state is a thermal metal by virtue of its delocalized nodal quasiparticles, while the field-induced normal state in the same sample is a thermal insulator, with either no fermionic excitations or localized fermionic excitations.

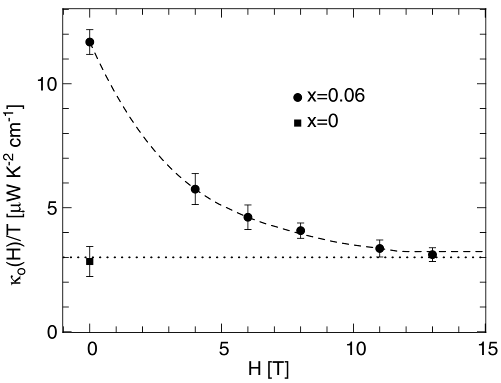

Fig. 2. $\kappa_0(H)/T$ vs H. κ_0/T is also shown for $x = 0$ at zero field. The dotted line represents the estimated resolution of our experiment (see text). The error bars are statistical errors in the fitted values of κ_0/T.

In summary, we have observed in underdoped LSCO a decrease in thermal conductivity with magnetic field upon going from the superconducting state to the field-induced normal state. We show that this result is due to a novel thermal metal-to-insulator transition.

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