LETTERS

Enhancement of the Nernst effect by stripe order in a high-T_c superconductor

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The Nernst effect in metals is highly sensitive to two kinds of phase transition: superconductivity and density-wave order[1]. The large, positive Nernst signal observed in hole-doped high-T_c superconductors[2] above their transition temperature (T_c) has so far been attributed to fluctuating superconductivity[3]. Here we report that in some of these materials the large Nernst signal is in fact the result of stripe order, a form of spin/charge modulation[4] that causes a reconstruction of the Fermi surface[5]. In $La_{2-x}Sr_xCuO_4$ (LSCO) doped with Nd or Eu, the onset of stripe order causes the Nernst signal to change from being small and negative to being large and positive, as revealed either by lowering the hole concentration across the quantum critical point in Nd-doped LSCO (refs 6–8) or by lowering the temperature across the ordering temperature in Eu-doped LSCO (refs 9, 10). In the second case, two separate peaks are resolved, respectively associated with the onset of stripe order at high temperature and superconductivity near T_c.

The Nernst effect is the development of a transverse electric field E_y across the width (y axis) of a metallic sample when a temperature gradient $\partial T/\partial x$ is applied along its length (x axis) in the presence of a transverse magnetic field B (along the z axis). Two mechanisms can give rise to a Nernst signal, defined as $N = E_y/(\partial T/\partial x)$ (ref. 1). The first is superconducting fluctuations, of either phase or amplitude[1,3], which can only be positive[1]. The second is due to mobile charge carriers, and produces a signal given by[1]

$$N = -eL_0 T \frac{\partial}{\partial \varepsilon}\left(\frac{\sigma_{xy}}{\sigma_{xx}}\right)\Bigg|_{\varepsilon=\varepsilon_F} \qquad (1)$$

where e is the elementary charge, $L_0 \equiv (\pi^2/3)(k_B/e)^2$ (k_B denoting the Boltzmann constant), T is the temperature, ε is the energy, ε_F is the Fermi energy, σ_{xy} is the (transverse) Hall conductivity and σ_{xx} is the (longitudinal) electrical conductivity. This quasiparticle Nernst signal can be either positive or negative.

Whereas in a single-band metal N is generally small, in a multiband metal it can be large[1], as indeed it is in semimetals, where the Nernst coefficient, $\nu \equiv N/B$, is typically very large[1,11]. This implies that the quasiparticle Nernst coefficient should generically undergo a pronounced rise when the Fermi surface of a single-band metal is reconstructed into several pieces by the onset of some density-wave-like order. This is indeed what happens in metals like URu_2Si_2 (ref. 12) as they enter a semimetallic ordered state[1,11].

Evidence that the Fermi surface of high-T_c superconductors undergoes some reconstruction in the underdoped regime came recently from the observation of low-frequency quantum oscillations in $YBa_2Cu_3O_y$ (ref. 13), which are thought to arise from orbits around a small, electron-like Fermi pocket[14]. Indeed, the standard mechanism for producing small electron pockets from a large, hole-like Fermi surface is the onset of some density-wave order that breaks translational symmetry[5,15]. Within such a density-wave picture, the Nernst coefficient of a single-band metal such as LSCO would be expected to undergo a pronounced increase as the material is cooled below its ordering temperature. This is precisely what measurements of the Nernst effect in LSCO have revealed: ν is small (and negative) at high temperature and becomes large (and positive) at low temperature[2,3]. However, this large rise in $\nu(T)$ with decreasing temperature has instead been attributed to a vortex contribution that grows with the approach of superconductivity[3]. Here we present two experiments which show that in some high-T_c superconductors the onset of 'stripe order'—a form of spin/charge modulation—triggers a large enhancement of the Nernst signal, attributed to a change in the Fermi surface. The material used is LSCO with some of the La replaced with either Nd or Eu, a substitution that stabilizes stripe order[7,9].

In the first experiment, we switched stripe order on and off while keeping the superconductivity constant. This was achieved by measuring two samples of $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$ (Nd-LSCO) with comparable transition temperatures (~20 K) but values of hole concentration on either side of the critical doping, p*, where stripe order sets in[6–9], namely $p = 0.20$ and $p = 0.24$. The Nernst coefficient of this pair of samples is plotted in Fig. 1 as a function of temperature, along with the in-plane resistivity, ρ_{xx}, and the Hall coefficient, $R_H \approx \rho_{xy}/B$. In the sample with $p = 0.24$, all coefficients were monotonic and featureless, whereas in the sample with $p = 0.20$, they all showed a pronounced and simultaneous rise.

For $p = 0.24$, the fact that $R_H(T \to 0) = 1/e(1 + p)$ shows that the Fermi surface remains a single large hole cylinder as $T \to 0$ (ref. 6). In this case, ν is field independent above T_c (Supplementary Fig. 1) and remains small and negative as $T \to 0$, in agreement with previous data from a non-superconducting LSCO sample with $p = x = 0.26$ (ref. 3). This demonstrates that the onset of superconductivity has, by itself, little impact on ν. By dramatic contrast, for $p = 0.20$, $\nu(T)$ increases rapidly below 40 K to become large and positive, until it vanishes when superconductivity sets in. That the upturn in $\nu(T)$ tracks the upturn in $\rho(T)$ provides a second, independent, piece of evidence that the increase in $\nu(T)$ is not caused by incipient superconductivity.

The parallel rise observed in all three coefficients displayed in Fig. 1 demonstrates that the onset of a large positive Nernst coefficient is due to an enhancement of the quasiparticle contribution rooted in a

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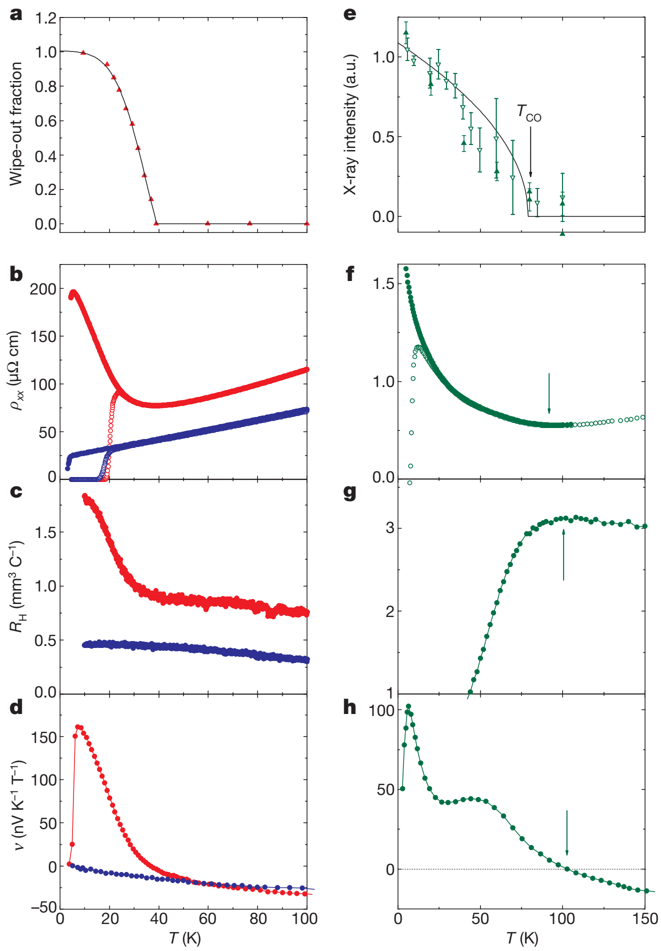

Figure 1 | Transport coefficients and stripe order in Nd-LSCO and Eu-LSCO. **a**, Charge stripe ordering in Nd-LSCO with $p = 0.20$, as measured by the loss of intensity in nuclear quadrupole resonance (NQR; from ref. 9). At dopings $p = 0.12$ and $p = 0.15$, where both X-ray diffraction and NQR were measured on Nd-LSCO, the lost (or 'wipe-out') fraction of the NQR intensity present at 100 K tracks the increase in the intensity of superlattice peaks detected with X-rays[9]. For $p = 0.20$, the onset of charge order occurs at $T_{CO} = 40 \pm 6$ K (ref. 9). **b**–**d**, Transport coefficients in two samples of Nd-LSCO, respectively with $p = 0.20$ (red) and $p = 0.24$ (blue): in-plane electrical resistivity, ρ_{xx}, in magnetic fields $B = 0$ (open symbols) and 15 T (filled symbols) (**b**; from ref. 6); Hall coefficient, R_H, for $B = 15$ T (**c**; from ref. 6); Nernst coefficient, ν, for $B = 10$ T (**d**; this work). In both samples, $T_c \approx 20$ K in zero field (see **b**). We note how for $p = 0.20$ all coefficients show a pronounced and simultaneous upturn starting at a temperature that coincides with the onset of charge order; this is strong evidence of Fermi surface reconstruction by stripe order being the cause of the large, positive Nernst signal. By contrast, for $p = 0.24$, $\nu(T)$ remains small and negative, unaffected by the onset of superconductivity. **e**, Charge stripe ordering in Eu-LSCO with $p = 0.125$ measured by diffraction using hard (filled symbols; this work) and soft (open symbols; ref. 10) X-rays. Error bars on filled symbols represent the standard error in the height of the Gaussian in a Gaussian-plus-background fit to the momentum scan at each temperature. Error bars on open symbols are from ref. 10. The onset of charge order is identified by both to be $T_{CO} = 80 \pm 10$ K. a.u., arbitrary units. **f**–**h**, Transport coefficients measured on a sample of Eu-LSCO with $p = 0.125$: in-plane electrical resistivity, ρ_{xx}, in magnetic fields $B = 0$ (open symbols) and 15 T (filled symbols) (**f**); Hall coefficient, R_H, for $B = 10$ T (**g**); Nernst coefficient, ν, for $B = 10$ T (**h**). The onset of charge order is seen to coincide with anomalies in transport (marked by arrows): the minimum in $\rho(T)$, the decrease in $R_H(T)$ and the sign change in $\nu(T)$, all at ~100 K. As for Nd-LSCO with $p = 0.20$, this again argues for a Fermi surface reconstruction caused by stripe order.

modification of the Fermi surface[6]. In Fig. 1a, we reproduce the NQR wipe-out fraction measured on Nd-LSCO with $x = 0.20$ (ref. 7). The precipitous loss of NQR intensity below 40 K is caused by the onset of stripe order[7] (see also ref. 9). The crucial fact that the upturn in all coefficients matches with this onset strongly suggests that stripe order is the cause of the Fermi surface reconstruction[5].

In a second experiment, we investigated the more underdoped regime in $La_{1.8-x}Eu_{0.2}Sr_xCuO_4$ (Eu-LSCO). In Fig. 1e, we show X-ray diffraction data on Eu-LSCO with $p = 0.125$. The intensity of scattering at the incommensurate stripe wavevector is seen to vanish at $T_{CO} = 80 \pm 10$ K. In Fig. 1f–h, we show transport data taken from one sample with $p = 0.125$. It is clear that the pronounced changes in $\rho(T)$, $R_H(T)$ and $\nu(T)$ all coincide with the onset of stripe order, as in Nd-LSCO with $p = 0.20$. We note that stripe ordering for $p = 0.125$ now causes $R_H(T)$ to decrease below T_{CO}, by contrast with the increase seen for $p = 0.20$. This evolution in the behaviour of $R_H(T)$ is consistent with calculations[16] based on a theory of the Fermi surface reconstruction by stripe order[17].

In Supplementary Fig. 2, we define T_ν, the onset of the upturn in $\nu(T)$, whose doping dependence is plotted in the inset of Fig. 2. Because of the wide separation between $T_\nu \approx 140$ K and $T_c \approx 10$ K in Eu-LSCO with $p = 0.125$, we see that $\nu(T)$ consists of two separate peaks. The evolution of this two-peak structure with doping is shown in Fig. 2. The low-temperature peak, which is due to superconducting fluctuations, is suppressed by a magnetic field, whereas the high-temperature peak, which is due to quasiparticles, is not (Supplementary Figs 3 and 4). A similar situation prevails in the electron-doped copper oxide $Pr_{2-x}Ce_xCuO_4$, for which the Nernst signal separates clearly into a quasiparticle peak at high temperature and a superconducting peak near T_c (ref. 18). In that case, Fermi surface reconstruction is attributed to antiferromagnetic order[18,19]. A comparison between Eu-LSCO and LSCO shows that the onset of the increase in $\nu(T)$ occurs at very similar values of T_ν in both materials (Supplementary Figs 3 and 5), suggesting a common mechanism of Fermi surface reconstruction.

To conclude, we have resolved two contributions to the Nernst signal in the hole-doped copper oxide LSCO doped with Nd or Eu: one at low temperature, caused by superconducting fluctuations, and the other at high temperature, caused by a change in the Fermi surface.

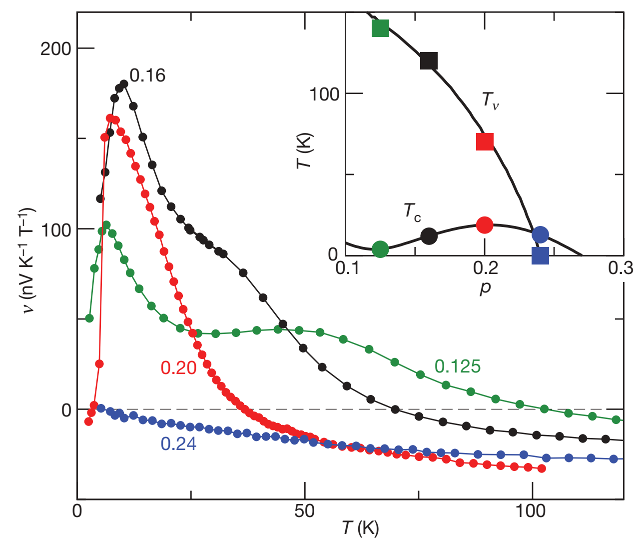

Figure 2 | Doping evolution of the Nernst coefficient and T_ν. Temperature dependence of the Nernst coefficient, $\nu(T)$, for different dopings in Eu-LSCO (green, $p = 0.125$; black, $p = 0.16$) and Nd-LSCO (red, $p = 0.20$; blue, $p = 0.24$) for $B = 10$ T. This shows the doping evolution of the two contributions to $\nu(T)$, respectively from superconducting fluctuations at low temperature and quasiparticles on a reconstructed Fermi surface at high temperature. The gradual convergence of the two peaks in $\nu(T)$ is a consequence of the fact that T_ν, which marks the onset of the high-temperature peak (Supplementary Fig. 2), and T_c, which controls the location of the low-temperature peak, come together as they approach p^*, the quantum critical point for the onset of stripe order[6] (see inset).

In this case, the change in Fermi surface is clearly caused by the onset of stripe order at T_{CO} (ref. 6). The fact that $v(T)$ starts to rise at $T_v \approx 2T_{CO}$ suggests that stripe fluctuations are sufficient to cause $v(T)$ to increase[5]. It will be interesting to investigate whether the same mechanism is also involved in other hole-doped high-T_c superconductors.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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