Chiral phonons in the pseudogap phase of cuprates

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The nature of the pseudogap phase of cuprates remains a major puzzle. One of its signatures is a large negative thermal Hall conductivity, whose origin is as yet unknown. This is observed even in the undoped Mott insulator La$_2$CuO$_4$, in which the charge carriers are localized and therefore cannot be responsible. Here, we show that the thermal Hall conductivity of La$_2$CuO$_4$ is roughly isotropic; that is, for doping levels higher than the critical doping level at which the pseudogap phase ends, both La$_{1.6}$Nd$_{0.4}$Sr$_{0.2}$CuO$_4$ and La$_{1.8}$Er$_{0.2}$Sr$_{0.2}$CuO$_4$ show no thermal Hall signal for a heat current normal to the planes, which establishes that phonons have zero Hall response outside the pseudogap phase. Inside the pseudogap phase, the phonons must become chiral to generate the Hall response, but the mechanism by which this happens remains to be identified. It must be intrinsic (from a coupling of phonons to their electronic environment) rather than extrinsic (from structural defects or impurities), as these are the same on both sides of critical doping.

The thermal Hall effect has emerged as a fruitful probe of insulators, which are materials in which the electrical Hall effect is zero because there are no mobile charge carriers. In the presence of a heat current $\mathbf{J}$ along the $x$ axis and a magnetic field $\mathbf{H}$ along the $z$ axis, a transverse temperature gradient $\nabla T$ along the $y$ axis can develop even if the carriers of heat are neutral (chargeless), provided that they have chirality. In particular, carriers with a Berry curvature, whether they are fermions or bosons, in general will generate a non-zero thermal Hall conductivity, $\kappa_{xy}$ (ref. 1). So, a measurement of the thermal Hall effect can potentially reveal various topological excitations in quantum materials; for example, Majorana edge modes in chiral spin liquids.

However, phonons in fact can also generate a non-zero thermal Hall conductivity if some mechanism, either intrinsic or extrinsic, confers chirality to the phonons. (Here, we use the term 'chirality' to mean handedness in the presence of a magnetic field.) The phonon $\kappa_{xy}$ signal can be large, as is the case for multiferroic materials and for strontium titanate (SrTiO$_3$; ref. 3). In multiferroic materials, the signal is caused by spin-phonon coupling, whereas in SrTiO$_3$, the cause appears to involve structural domain boundaries.

In cuprates, a large negative $\kappa_{xy}$ signal was observed at a low temperature inside the pseudogap phase, for doping levels $p < p^*$ (ref. 3). As this negative $\kappa_{xy}$ persists at levels as low as $p = 0$ in the Mott insulator state, it cannot come from charge carriers. Therefore, it must come from either spin-related excitations (which are possibly topological) or phonons. To distinguish between these two types of heat carrier, we adopt a simple approach: we measure the thermal Hall conductivity for a heat current along the $c$ axis, normal to the CuO$_2$ planes, a direction in which only phonons move easily (see Methods).

First, we look at the undoped cuprate La$_2$CuO$_4$, a Mott insulator with no mobile charge carriers. Here, phonons are the dominant heat carriers at low temperatures, and their longitudinal thermal conductivity $\kappa_{zz}(T)$ is nearly the same for $J \parallel a$ ($n = x$) and $J \parallel c$ ($n = z$) (ref. 4; see Methods). As shown in Fig. 1a, the in-plane thermal Hall conductivity $\kappa_{xy}$ of La$_2$CuO$_4$ ($J \parallel -x \perp c$, $H \parallel z$ and $\nabla T \parallel y$; Extended Data Fig. 1a) was found previously to be negative at all $T$, with $|\kappa_{xy}|/|\kappa_{zz}|$ growing steadily as temperature is decreased below 100 K, reaching one of the largest Hall conductivities of any insulator at $T = 10$ K (ref. 5). In a separate sample of La$_2$CuO$_4$, we measured $\kappa_{xy}(J \parallel z \parallel c, H \parallel x$ and $\nabla T \parallel y$; Extended Data Fig. 1b) and found that $|\kappa_{xy}|/|\kappa_{zz}|$ (all for $T$ (Fig. 1a). The fact that the thermal Hall conductivity is as large across the CuO$_2$ planes as it is along the planes is strong evidence that the carriers of heat responsible for the thermal Hall effect in La$_2$CuO$_4$ are phonons. Indeed, any excitation of electronic origin (that carries charge or spin) is expected to be much more mobile along the CuO$_2$ planes as opposed to across planes (see Methods).

Next, we examine the hole-doped cuprate La$_{1.8}$Nd$_{0.2}$Sr$_{0.2}$CuO$_4$ (Nd-LSCO; see phase diagram in Fig. 2a). The pseudogap phase boundary $T^*(p)$ ends at a $T = 0$ critical point $p^* = 0.23$, as determined by both transport and photoemission (ARPES; ref. 21) measurements. At $p = 0.24$, just above $p^*$, the in-plane thermal Hall conductivity $\kappa_{xy}$ of Nd-LSCO was found to be positive at all $T$ (Fig. 1b) and in good agreement with the Wiedemann–Franz law, which states $\kappa_{xy} = T = L_{\text{ph}} \sigma_{xy}$ as $T \to 0$ K, where $L_{\text{ph}} = (\pi^2/3)(k_B/e)^2$ (ref. 22). Using a sample cut from the same large crystal, we measured $\kappa_{xy}$ and found that $\kappa_{xy}(T) = 0$ at all $T$, below 100 K (Fig. 1b). Not only is the Wiedemann–Franz law satisfied for $J \parallel a$, our data for $J \parallel c$ show...
that phonons in Nd-LSCO have no Hall effect at $p = 0.24$ for any direction of motion. (Note that the contribution of charge carriers to $\kappa_\text{xy}(T)$ is extremely small; see Methods.) In other words, phonons have no chirality outside of the pseudogap phase.

In the related material $\text{La}_{0.66}\text{Eu}_{0.34}\text{Sr}_{0.3}\text{CuO}_4$ (Eu-LSCO), which also has $p^* = 0.23$ (ref. 19), we find again that $\kappa_\text{xy}(T) = 0$ at $p = 0.24 > p^*$ (Fig. 1d). The fact that $\kappa_\text{xy}(T) = 0$ down to 10 K (on two separate samples) shows that our measurement technique does not introduce any spurious background Hall signal (see Methods). That is, any thermal Hall signal coming from the sample mount is negligible compared to the signal from the samples.

Inside the pseudogap phase ($p < p^*$), a large negative $\kappa_\text{xy}$ was observed at low $T$ in $\text{La}_{0.84}\text{Sr}_{0.16}\text{CuO}_4$ (LSCO) with $p = 0.06$, Eu-LSCO with $p = 0.08$, $\text{Bi}_{2}\text{Sr}_{2-x}\text{La}_x\text{CuO}_4$, with $x = 0.2$ and Nd-LSCO with $p = 0.20$, 0.21 and 0.22 (ref. 1). In Fig. 1c, we show the published $\kappa_\text{xy}$ data for Nd-LSCO with $p = 0.21$, which become negative below 25 K. This is in contrast to $\sigma_\text{xy}$, which remains positive as $T \to 0$ (refs. 1,20). In the same figure, we report our data for $\kappa_\text{xy}$ as measured in Nd-LSCO with $p = 0.21$. We see that there is now a sizeable (negative) $\kappa_\text{xy}$ signal, in contrast to that at $p = 0.24$.

We summarize our $\kappa_\text{xy}$ measurements in Fig. 2b. At $p = 0.24$, just outside the pseudogap phase ($p > p^*$; Fig. 2a), $\kappa_\text{xy}(T) = 0$ and phonons have no chirality. At $p = 0.21$, just inside the pseudogap phase ($p < p^*$; Fig. 2a), $\kappa_\text{xy}(T) < 0$ and phonons have suddenly acquired chirality. This new phonon Hall effect is of comparable magnitude throughout the pseudogap phase, from $p^*$ down to $p = 0$, when measured relative to $\kappa_\text{xx}$ ($\kappa_\text{xy} / \kappa_\text{xx} \approx 0.3$–0.5 at $H = 15$ T and $T = 20$ K). Therefore, we have two key findings: the large negative thermal Hall signal in cuprates is carried by phonons, and the phonons become chiral only once they enter the pseudogap phase. (In ref. 3, a phonon scenario was considered unlikely because of the small size of two expected signatures, a field dependence of $\kappa_\text{xx}$ and a drop in $\kappa_\text{xx}$ below $p^*$; see Methods.)

The question then becomes what special property of the pseudogap phase confers chirality to phonons. One possibility is that phonons acquire Berry curvature from their interaction with the special electronic properties of that phase. A rather universal consequence of Berry curvature is the production of a thermal Hall response that varies as $\kappa_\text{xy} / T \propto \exp(-T/T_\text{A})$ at intermediate temperatures 33. In Fig. 3, we show a fit of our $\kappa_\text{xy}$ data to the relation $\kappa_\text{xy} / T = A \exp(-T/T_\text{A}) + C$, for La$_2$CuO$_4$ and Nd-LSCO with $p = 0.21$. We see that the fits are excellent, down to $T \approx T_\text{A} \approx 15$ K. This supports the scenario in which phonons have Berry curvature below $p^*$.

Further experimental and theoretical work is needed to identify the microscopic mechanism responsible for the chirality of phonons in the pseudogap phase. Note that it cannot simply be the skew scattering of phonons from impurities. Indeed, although skew scattering of phonons by rare-earth impurities can produce a thermal Hall effect123, this extrinsic impurity-related mechanism cannot apply here, as for the same Nd-LSCO material (with the same impurities) we find zero thermal Hall effect when $p > p^*$. Also, changing non-magnetic Eu ions for magnetic Nd ions in La$_2$Cu$_{0.8} \text{RE}_{0.2}\text{CuO}_4$ ($\text{RE} = \text{Eu, Nd}$), at $p = 0.24$, still yields zero phonon Hall signal. What is needed is a qualitative change below $p^*$ in the intrinsic coupling of phonons to their environment. A recent ARPES study 24 in the cuprate $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ saw a rapid increase in the coupling of phonons to electrons upon crossing below $p^*$.

A large $\kappa_\text{xy}$ signal due to phonons was recently observed in $\text{SrTiO}_3$, but not in the related material $\text{KTaO}_3$, for which $\kappa_\text{xy}(T) \approx 0$ below 100 K (ref. 1). This difference was attributed to the presence of structural domains in $\text{SrTiO}_3$ that are absent in $\text{KTaO}_3$. Exactly how structural domains can generate a Hall effect is still unclear 15.
but this mechanism cannot be responsible for the phonon Hall effect in Nd-LSCO. Indeed, there is no change in the crystal structure of Nd-LSCO between \( p = 0.21 \) and \( p = 0.24 \), two dopings that are both located in the so-called low-temperature tetragonal (LTT) phase (see Methods).

A large \( \kappa_v \) signal due to phonons was observed in multiferroic materials such as Fe\(_8\)MoO\(_6\) (ref. 10), in which it was attributed to a coupling of phonons to spins. A spin-phonon coupling could be relevant in the case of cuprates, given that the pseudogap phase is characterized by short-range antiferromagnetic correlations and spin singlet formation, according to numerical solutions of the Hubbard model13. It may be that the topological character of this unusual state of correlated spins16 confers chirality to phonons. Note that slow antiferromagnetic correlations (quasi-static moments) are indeed observed for dopings up to \( p^* \) in Nd-LSCO17 and LSCO18, but not above.

Fig. 2 | Evolution of the \( c \)-axis thermal Hall conductivity across the phase diagram. a, Temperature-doping phase diagram of Nd-LSCO, showing the superconducting transition temperature \( T_c \) (black line; zero field) and the pseudogap phase below \( T^* \) (PG; orange region), which ends at the critical doping \( p^* \) = 0.23 (diamond) for both Nd-LSCO19–21 and \( \text{La}_2\text{CuO}_4\) \( \text{Eu}_x\text{Sr}_y\text{CuO}_4 \) (ref. 22). The orange circles indicate the temperature below which the in-plane resistivity deviates upwards from its linear \( T \) dependence at high temperature (refs. 20,22; the error bars, taken from ref. 22, reflect the uncertainty in pinpointing the start of that gradual upturn). The orange square marks the onset temperature for the opening of the anti-nodal pseudogap in Nd-LSCO at \( p = 0.20 \) as detected by ARPES (ref. 23); the error bar is given by the temperature spacing of the ARPES data. The two vertical bands indicate the two dopings on either side of \( T^* \) at which we measured \( \kappa_v(T) \), the \( c \)-axis thermal Hall conductivity shown in part b (blue for \( p = 0.21 \), green for \( p = 0.24 \)). b, Thermal Hall conductivity \( \kappa_v \) for a heat current normal to the CuO\(_2\) planes (\( J \parallel c \parallel z \)) and a magnetic field of 15 T applied parallel to the planes (\( J \parallel c \parallel z \)), plotted as \( \kappa_v(T) / T \) versus \( T \), in \( \text{La}_2\text{CuO}_4 \) (\( p = 0; \) red), Nd-LSCO with \( p = 0.21 \) (blue) and Nd-LSCO with \( p = 0.24 \) (green).

Fig. 3 | Phenomenological fit to the phonon thermal Hall conductivity. a, Fit of the thermal Hall conductivity \( \kappa_v(T) \) in \( \text{La}_2\text{CuO}_4 \) (a) and Nd-LSCO at \( p = 0.21 \) (b). The resulting fit parameters are \( A = -4.9 \) mW K\(^{-2}\) m, \( C = -0.02 \) mW K\(^{-2}\) m, \( T_c = 15.8 \) K (for a), and \( A = -2.4 \) mW K\(^{-2}\) m, \( C = -0.04 \) mW K\(^{-2}\) m, \( T_c = 15.8 \) K (for b). The fact that the theoretical expression fits the data well in the temperature range above \( T_c \) supports the hypothesis that phonons in these cuprates have a non-zero Berry curvature.

The broad implication of our findings in cuprates is that phonons in insulators can generate large thermal Hall signals. All possible mechanisms for phonon chirality should be explored (for example, refs. 9,15,26,30). Also, the possible role of phonons in causing the thermal Hall effect observed in materials such as the two-dimensional Kitaev insulator \( \alpha\text{-RuCl}_3 \) (refs. 31,32) or the frustrated magnet \( \text{Tb}_2\text{Ti}_2\text{O}_7 \) (refs. 7,30) should be considered.

**Online content**

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Methods

Samples. Nd-LSCO. Single crystals of La$_{2-x}$Nd$_x$Sr$_{1.5}$Cu$_{2.5}$O$_{y}$ (Nd-LSCO) were grown at the University of Texas at Austin, USA using a travelling-float-zone technique, with an Nd content $y=0.4$ and nominal Sr concentrations $x=0.21$ and 0.23. The hole concentrations were defined by $p=x$, with an error bar $\pm 0.003$, except for the $x=0.25$ sample, for which the doping is $p=0.24 \pm 0.005$ (for details, see ref. 1). The error bars on the doping values come from the uncertainty in the Sr content $x$, refined with the measured values of $T_c$ and the Hall coefficient $R_h$ (ref. 2). The value of $T_c$ defined as the point of zero resistance, is $T_c = 15$ K and 11 K for samples with $p=0.21$ and 0.24, respectively. The pseudogap critical point in Nd-LSCO is at $p=0.23 \pm 0.005$ (ref. 2). The $a$-axis ($L_a$) and $c$-axis ($L_c$) samples were both cut out of the same large single crystal.

Eu-LSCO. The single crystal of La$_{2-x}$Eu$_x$Sr$_{1.5}$Cu$_{2.5}$O$_{y}$ (Eu-LSCO) was grown at the University of Tokyo, Japan using a travelling-float-zone technique, with an Eu content $y=0.2$ and nominal Sr concentration $x=0.24$. The hole concentration $p$ is given by $p=x$, with an error bar of $\pm 0.005$. The value of $T_c$, defined as the point of zero resistance, is $T_c = 9$ K. The pseudogap critical point in Eu-LSCO is at $p^* = 0.23 \pm 0.005$ (ref. 2). The $a$-axis ($L_a$) and $c$-axis ($L_c$) samples were both cut out of the same large single crystal.

La$_2$CuO$_4$. Our two single crystals of La$_2$CuO$_4$ came from the same batch, grown at the University of Tokyo, Japan using a travelling-Float technique. The $a$-axis ($L_a$) and $c$-axis ($L_c$) samples were each cut out of these two single crystals, respectively.

Thermal Hall measurement. Our measurements of the $c$-axis thermal Hall conductivity $\kappa_C$ were performed on four samples: La$_2$CuO$_4$, (p = 0); Nd-LSCO with $p=0.21$; Nd-LSCO with $p=0.24$; and Eu-LSCO with $p=0.24$. The in-plane thermal Hall conductivity $\kappa_C$ was previously reported for La$_2$CuO$_4$, Nd-LSCO, and Eu-LSCO at the same doping levels as used in this work. Those $\kappa_C$ data are shown in the four parts of Fig. 1 for comparison (blue curves).

Experimental procedure. For our measurements, six contacts are made on the sample using silver epoxy Dupont H202E by annealing at high temperature in oxygen: two contacts for the heat current, two for the longitudinal temperature difference $\Delta T$, and two for the transverse temperature difference $\Delta T_x$ (see Extended Data Fig. 1). The sample is glued onto a copper heat sink (Extended Data Fig. 1). The sample is taken to be equal to $\kappa_T$.)

Longitudinal thermal conductivity. As reported previously, we find that La$_2$CuO$_4$ has a highly isotropic longitudinal thermal conductivity at low temperatures (Extended Data Fig. 2). Indeed, $\kappa_L/\kappa_T \approx 1$ at $T = 25$ K. At higher temperatures, thermally excited magnons contribute to heat transport in La$_2$CuO$_4$, but only along the plane, and $\kappa_L$ grows to several $\kappa_T$ (ref. 3). For phonons dominate the heat transport at lower temperatures, the conductivity of phonons is nearly isotropic.

In Nd-LSCO, we also find that the phonon conductivity is nearly isotropic (determined from the data in Extended Data Fig. 3). Once we remove the contribution of mobile charge carriers using the Wiedemann–Franz law, we have $\kappa_L/\kappa_T \approx 1.2$ at $T = 25$ K, for $p=0.21$ and $p=0.24$, respectively.

Note that the electrical conductivity, and therefore also the electronic thermal Hall conductivity from charge carriers, is highly anisotropic, with $\sigma_C / \sigma_T \approx 250$ in Nd-LSCO at $p=0.24$ (ref. 4).

Anisotropy of the electronic Hall conductivity. The anisotropy of the electrical Hall conductivity in Nd-LSCO at $p=0.24$ is plotted as $\sigma_L$, $\sigma_T$, versus $T$ for $n=x$ and $n=2$ (Extended Data Fig. 4). We see that there is an anisotropy comparable to that found in the longitudinal conductivity, namely $\sigma_L / \sigma_T \approx 250$. We expect that any excitation of electronic origin, arising from either charge or spin degrees of freedom, would yield a similarly strong anisotropy in both its longitudinal and transverse thermal conductivities. For this reason, we attribute the nearly isotropic thermal Hall conductivity found in La$_2$CuO$_4$ to phonons.

Wiedemann–Franz law for currents normal to the planes. In Nd-LSCO with $p=0.24$, the maximum contribution of charge carriers to $\kappa_L$ can be estimated using the Wiedemann–Franz law: $\kappa_L \approx T S \rho_L$, where $\rho_L$ is the resistivity of the sample at temperature $T$ (Extended Data Fig. 5a). As $p_L = \rho_L / \rho_T$ the data for $\rho_L$ and $\rho_T$ are displayed in Extended Data Fig. 5b, respectively. The $\rho_L$ data for the $c$-axis sample cut from the same crystal was reported in ref. 1. The resulting curve for $\rho_L$ in Nd-LSCO at $p=0.24$ is a correspondingly very small electrical Hall conductivity $\sigma_L$. The maximum value of the electronic thermal Hall conductivity along the $c$ axis is roughly $\kappa_L / T \approx 0.01$ mW K$^{-1}$ m$^{-1}$ at $T = 10$ K, a value 200 times smaller than the electronic thermal Hall conductivity measured in the plane (Fig. 1). In Extended Data Fig. 5d, we see that this maximum electronic $\kappa_L$ is within the noise of the measured $\kappa_L$. Any phonon contribution to $\kappa_L$ in Nd-LSCO at $p=0.24$ must therefore be smaller than $\kappa_L / T \approx 0.01$ mW K$^{-1}$ m$^{-1}$ at $T = 10$ K. This is smaller than the measured $\kappa_L / T$ in Nd-LSCO at $p=0.21$ by a factor of 10. In other words, the thermal Hall response of phonons in Nd-LSCO undergoes an increase of at least 100-fold immediately upon crossing below $p^*$.

Field dependence of the conductivities. We show how $\kappa_L$ and $\kappa_C$ vary with the strength of the applied field for three of our samples by plotting $\kappa_C$ versus $T$ at $H=0$, 10 and 15 T; and $\kappa_L / T$ versus $T$ at $H=10$ and 15 T (Extended Data Fig. 6). In all cases, the field dependence of the thermal conductivity $\kappa_L$ is very small, and the thermal Hall conductivity $\kappa_H$ is essentially linear in $H$.

Background signal from the sample mount. As the sample is attached to a block of copper that serves as the heat sink in our experimental set-up (Extended Data Fig. 1), it might expected that a thermal Hall signal would come from copper. However, for all of the data reported here and those published in ref. 1, which were obtained using the same set-up, this background signal from copper was negligible, as demonstrated in three ways.

First, the fact that the Wiedemann–Franz law is satisfied for in-plane transport in Nd-LSCO at $p=0.24$ (ref. 4) rules out any substantial contamination of the $\kappa_L$ data in that measurement.
Second, the fact that our $\epsilon_x$-axis data for Nd-LSCO and Eu-LSCO with $p=0.24$ yield $|\kappa_{xx}| / T < 0.01 \text{ mW K}^{-2} \text{ m}$ for all temperatures of up to at least 100 K (Fig. 1b,d) shows that the signal from copper is smaller than the noise in our measurement.

Third, we have carried out a test study whereby a cuprate sample was measured first in the usual way, using a copper block to which the sample was glued with silver paste, and then re-measured using a block of lithium fluoride (an insulator known to generate no thermal Hall signal) to which the sample was glued with GE varnish. All other aspects of the experiment were kept the same in the two measurements (contacts, wires, heater, thermometers, electronics). The thermal Hall signal obtained in the two separate ways was identical within error bars; that is, $\kappa_{xy}(T)$ was fully reproduced at all temperatures from 10 K to 100 K. These test data will be reported in a separate paper. The small level of contamination from the copper block is largely due to the mounting geometry such that the main (longitudinal) temperature gradient in the block is perpendicular to the main (longitudinal) temperature gradient in the sample (Extended Data Fig. 1).

Prior arguments against a phonon scenario. In ref. 3, it was considered unlikely that phonons could be responsible for the large negative thermal Hall signal $\kappa_{xy}$ found in cuprates on the basis of two observations. First, the longitudinal phonon thermal conductivity $\kappa_{xx}$ couples very weakly to the magnetic field. Specifically, $\kappa_{xx}$ changes at most by 0.5% in fields of strength 15 T, and the maximal ratio $\kappa_{xy}/\kappa_{xx}$ is also about 0.5% is much smaller than in multiferroics, for example, in which phonons are thought to be responsible for the thermal Hall effect. This weak field dependence of $\kappa_{xx}$ in cuprates is now one aspect of the phenomenology that needs to be understood.

The second observation is that the phonon part of the longitudinal thermal conductivity $\kappa_{xx}$ increases upon crossing below $p^*$ (ref. 3), as opposed to the decrease expected if some new scattering mechanism of phonons (causing the chirality) appears in the pseudogap phase. An increase in $\kappa_{xx}$ is natural in view of the large drop in the charge carrier density of Nd-LSCO below $p^*$ (ref. 3), which means that phonons become less scattered by electrons. Therefore, a putative extra scattering mechanism would have to overcompensate for the electron-phonon effect. At this stage, the quantitative aspects of these two scattering mechanisms are unknown. Also, it may be that a scattering mechanism is not really what confers chirality to phonons in the pseudogap phase. They may instead acquire a Berry curvature, for example, which may not have a large effect on $\kappa_{xx}$.

Crystal structure of Nd-LSCO. At low temperatures, the material La$_{1-x}$Nd$_x$Sr$_2$CuO$_4$ adopts the so-called LTT crystal structure for a range of Sr concentrations that extends down to at least $x=0.10$ and up to at least $x=0.25$ (ref. 36). At $x=0.20$ and $x=0.25$, X-ray diffraction detects the structural transition into the LTT phase upon cooling at $T_{\text{LTT}}=70$ K and 50 K (ref. 36), respectively (Extended Data Fig. 7a). At temperatures above $T_{\text{LTT}}$, the structural phase is labelled LTO1 (low-temperature orthorhombic), with transitions at $T_{\text{LTO1}}=250$ K and 150 K, for $x=0.20$ and $x=0.25$, respectively (ref. 36).

Therefore, our two Nd-LSCO samples with nominal Sr concentrations $x=0.21$ and $x=0.25$, refined to $p=0.21 \pm 0.003$ and $p=0.24 \pm 0.005$, respectively, are expected to have the same crystal structure below 150 K. We have confirmed this by performing dilatometry measurements of the sample length $L$ versus temperature in Nd-LSCO samples with $p=0.21$ (the actual sample in which $\kappa_{xx}$ was measured) and $p=0.24$ (a sample cut immediately next to the sample in which $\kappa_{xx}$ was measured). The data are shown in Extended Data Fig. 7b, plotted as $dL/dT$ versus $T$. A clear anomaly is observed in both samples at the structural transition, with transition temperatures $T_{\text{LTT}}=82 \pm 5$ K at $p=0.21$ and $T_{\text{LTT}}=45 \pm 10$ K at $p=0.24$. This confirms that there is no structural difference between our two Nd-LSCO samples with $p=0.21$ and $p=0.24$. Therefore, this rules out the possibility that the large phonon Hall effect observed at $p=0.21$ but absent at $p=0.24$ is due to structural domain boundaries that scatter phonons, as has been proposed for SrTiO$_3$ (ref. 33), or to any other structural feature.

Data availability

All of the data that support the plots in this paper and other findings of this study are available from the corresponding author upon reasonable request. Source data are provided with this paper.

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Author contributions

G.G., S.T., M.-E.B. and E.L. performed the thermal Hall conductivity measurements. A.G., A.A., F.L., M.D. and N.D.-L. prepared and characterized the samples. J.-S.Z. grew the Nd-LSCO single crystals. P.P., T.T. and H.T. grew the Eu-LSCO and La$_2$CuO$_4$ single crystals. G.G. and L.T. wrote the manuscript, in consultation with all of the authors. L.T. supervised the project.

Competing interests

The authors declare no competing interests.

Additional information

Extended data is available for this paper at https://doi.org/10.1038/s41567-020-0965-γ. Correspondence and requests for materials should be addressed to G.G. or L.T.

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Extended Data Fig. 1 | Current and field orientation for κ_xy and κ_y measurements. Sketch of the thermal Hall measurement setup for a) $J \parallel a \parallel \hat{x}$ and b) $J \parallel c \parallel \hat{z}$. The Cartesian coordinate system is defined in the same way for the two samples.
Extended Data Fig. 2 | Longitudinal thermal conductivities $\kappa_{xx}$ and $\kappa_{zz}$ in La$_2$CuO$_4$. Thermal conductivity versus temperature in a field of magnitude $H = 15$ T for La$_2$CuO$_4$ ($p = 0$), plotted as a) $\kappa_{nn}$ vs $T$ and b) $\kappa_{nn}/T$ vs $T$, for heat current directions $J$ // $a$ ($n = x$; blue) and $J$ // $c$ ($n = z$; red). The longitudinal thermal conductivity of phonons at low temperature is nearly isotropic, with $\kappa_{xx}/\kappa_{zz} = \kappa_a/\kappa_c \sim 0.8$ at $T = 25$ K.
Extended Data Fig. 3 | Longitudinal thermal conductivities $\kappa_{xx}$ and $\kappa_{zz}$ in Nd-LSCO. Thermal conductivity $\kappa_{nn}$ versus temperature in a field of magnitude $H = 15$ T, plotted as $\kappa_{nn} / T$ vs $T$, for a) Nd-LSCO with $p = 0.21$ and b) Nd-LSCO with $p = 0.24$, for heat current directions $J \parallel a$ ($n = x$; blue) and $J \parallel c$ ($n = z$; red). In panels c) and d), the thermal conductivity of charge carriers is subtracted, using the Wiedemann-Franz law to estimate its magnitude (see ref. 3). The longitudinal thermal conductivity of phonons at low temperature is nearly isotropic, with $\kappa_{xx} / \kappa_{zz} = \kappa_{a} / \kappa_{c} \approx 1.2$ and 1.3 at $T = 25$ K, for $p = 0.21$ and $p = 0.24$, respectively.
Extended Data Fig. 4 | Anisotropy of electrical Hall conductivity in Nd-LSCO. Electrical Hall conductivity $\sigma_{xy}$ versus temperature in a field of magnitude $H = 15$ T, plotted as $L_0 \sigma_{ny}$ vs $T$, for Nd-LSCO with $p = 0.24$, for heat current directions $J \parallel a$ ($n = x$; blue) and $J \parallel c$ ($n = z$; red). The data for $\sigma_{xy}$ are multiplied by a factor 250. We use the approximate relation $\sigma_{xy} = \rho_{xy} / (\rho_{zz} \rho_{xx})$, with $\rho_{zz}$ and $\rho_{xx}$ data taken from ref. 35. The $\sigma_{xy}$ data are taken from ref. 3.
Extended Data Fig. 5 | Electronic thermal Hall conductivity in Nd-LSCO $p = 0.24$. Estimate of the maximal c-axis thermal Hall conductivity from charge carriers in our sample of Nd-LSCO with $p = 0.24$, obtained by applying the Wiedemann-Franz law to the measured electrical Hall conductivity $\sigma_{zy}$, namely $\kappa_{zy} / T \leq L_0 \sigma_{zy}$, where $\sigma_{zy} \leq \rho_{zy} / (\rho_{zz} \rho_{yy})$. 

- **a)** Electrical resistivity for $J \parallel c$, $\rho_{zz}$ vs $T$ (from ref. 35);
- **b)** Electrical Hall resistivity for $J \parallel c$ and $H \parallel a$, $\rho_{zy}$ vs $T$;
- **c)** Maximal electrical Hall conductivity for $J \parallel c$ and $H \parallel a$, defined as $\sigma_{zy} = \rho_{zy} / (\rho_{zz} \rho_{xx})$ (with $\rho_{xx}$ data from ref. 35), plotted as $L_0 \sigma_{zy}$ (multiplied by 60) vs $T$;
- **d)** Comparison of the measured electrical ($\sigma_{zy}$) and thermal ($\kappa_{zy}$) Hall conductivities, plotted as $L_0 \sigma_{zy}$ (blue) and $\kappa_{zy} / T$ (red; Fig. 1b) vs $T$. 

Nd-LSCO

$\rho_{zz}$ (m$\Omega$cm)

$T$ (K)

$\rho_{zy}$ (m$\Omega$cm)

$T$ (K)

Nd-LSCO $p = 0.24$

$\rho_{zy}$

H = 15 T

Nd-LSCO $p = 0.24$

$\kappa_{zy} / T$

H = 15 T
Extended Data Fig. 6 | Field dependence of $\kappa_{zz}$ and $\kappa_{zy}$ in La$_2$CuO$_4$ and Nd-LSCO. Upper panels: thermal conductivity $\kappa_{zz}$ measured at $H = 0$ T (purple), 10 T (green) and 15 T (red), plotted as $\kappa_{zz} / T$ vs $T$, for a) La$_2$CuO$_4$, b) Nd-LSCO with $p = 0.21$ and c) Nd-LSCO with $p = 0.24$. Lower panels: thermal Hall conductivity $\kappa_{zy}$ measured at $H = 10$ T (purple) and 15 T (red), plotted as $\kappa_{zy} / (T H)$ vs $T$, for d) La$_2$CuO$_4$, e) Nd-LSCO with $p = 0.21$ and f) Nd-LSCO with $p = 0.24$. We see that $\kappa_{zy}$ is approximately linear in $H$. 
Extended Data Fig. 7 | Structural transition in Nd-LSCO. a) Structural phase diagram of Nd-LSCO as a function of doping. The black dots and black line mark the structural transition from the LTO1 phase to the LTT phase at low temperature, at $T_{LT}$, as measured by x-ray diffraction. The squares mark $T_{LT}$ in our samples with $p = 0.21$ (blue) and $p = 0.24$ (green), as detected by dilatometry measurements (see panel b). b) Change in sample length $L$ as a function of temperature, plotted as its derivative $dL/dT$ vs $T$, measured in our c-axis sample of Nd-LSCO with $p = 0.21$ (blue) and in a sample of Nd-LSCO cut from the same large single crystal as, and next to, our c-axis sample of Nd-LSCO with $p = 0.24$ (green). The dip in the curves marks the structural phase transition from the LTO1 phase above to the LTT phase below the transition temperature $T_{LT}$, where $T_{LT} = 82 \pm 5$ K at $p = 0.21$ and $T_{LT} = 45 \pm 10$ K at $p = 0.24$. The error bars on the two values of $T_{LT}$ correspond to the full width of each corresponding dip. These data confirm that our two Nd-LSCO samples, with $p = 0.21$ and $p = 0.24$, have the same crystal structure. This shows that all the differences observed in their properties, in particular the dramatic difference in their thermal Hall conductivity $\kappa_{zy}$ (Fig. 1), are not due to a difference in structural properties. Instead, these differences are linked with the onset of the pseudogap phase at $p^* = 0.23$. 