Phonons become chiral in the pseudogap phase of cuprates

- G. Grissonnanche¹*, S. Thériault¹, A. Gourgout¹, M.-E. Boulanger¹, E. Lefrançois¹,
- A. Ataei¹, F. Laliberté¹, M. Dion¹, J.-S. Zhou², S. Pyon^{3,4}, T. Takayama^{3,5},
- H. Takagi^{3,5,6,7}, N. Doiron-Leyraud¹, and L. Taillefer^{1,8} *
- 1 Département de physique, Institut quantique, and RQMP, Université de Sherbrooke, Sherbrooke, Québec, Canada
- 2 Materials Science and Engineering Program, Department of Mechanical Engineering, University of Texas at Austin, Austin, TX, USA
- 3 Department of Advanced Materials Science, University of Tokyo, Kashiwa, Japan
- 4 Department of Applied Physics, University of Tokyo, Tokyo, Japan
- 5 Max Planck Institute for Solid State Research, Stuttgart, Germany
- 6 Department of Physics, University of Tokyo, Tokyo, Japan
- 7 Institute for Functional Matter and Quantum Technologies, University of Stuttgart, Stuttgart, Germany
- 8 Canadian Institute for Advanced Research, Toronto, Ontario, Canada

The nature of the pseudogap phase of cuprates remains a major puzzle^{1,2}. One of its new signatures is a large negative thermal Hall conductivity κ_{xy} , which appears for dopings p below the pseudogap critical doping p^* , but whose origin is as yet unknown³. Because this large κ_{xy} is observed even in the undoped Mott insulator La_2CuO_4 , it cannot come from charge carriers, these being localized at p=0. Here we show that the thermal Hall conductivity of La_2CuO_4 is roughly isotropic, being nearly the same for heat transport parallel and normal to the CuO_2 planes, *i.e.* $\kappa_{zy}(T) \approx \kappa_{xy}(T)$. This shows that the Hall response must come from phonons, these being the only heat carriers able to move as easily normal and parallel to the planes⁴. At $p > p^*$, in both $\text{La}_{1.6-x}\text{Nd}_{0.4}\text{Sr}_x\text{CuO}_4$ and $\text{La}_{1.8-x}\text{Eu}_{0.2}\text{Sr}_x\text{CuO}_4$ with

p=0.24, we observe no c-axis Hall signal, i.e. $\kappa_{zy}(T)=0$, showing that phonons have zero Hall response outside the pseudogap phase. The phonon Hall response appears immediately below $p^*=0.23$, as confirmed by the large κ_{zy} signal we find in La_{1.6-x}Nd_{0.4}Sr_xCuO₄ with p=0.21. The microscopic mechanism by which phonons become chiral in cuprates remains to be identified. This mechanism 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 p^* . This intrinsic phonon Hall effect provides a new window on quantum materials and it may explain the thermal Hall signal observed in other topologically nontrivial insulators 6,7 .

The thermal Hall effect has emerged as a new probe of insulators^{8,9}, materials in which the electrical Hall effect is zero because there are no mobile charge carriers. In the presence of a heat current J along the x axis and a magnetic field H along the z axis, a transverse temperature gradient ∇T (along the y axis) can develop even if the carriers of heat are neutral (chargeless), provided they have chirality¹⁰. In particular, carriers with a Berry curvature – whether fermions or bosons – will in general generate a nonzero thermal Hall conductivity κ_{xy} (refs. 11,12). So, potentially, a measurement of the thermal Hall effect can provide access to various topological excitations in quantum materials, for example Majorana edge modes in chiral spin liquids^{13,14,15}.

However, it turns out that phonons can also generate a nonzero thermal Hall conductivity, if some mechanism – intrinsic¹¹ or extrinsic¹⁶ – confers chirality to the phonons. (Here we use the term "chirality" to mean handedness in the presence of a magnetic field.) The phonon κ_{xy} signal can be large, as in multiferroic materials¹⁷ – where the mechanism is spin-phonon coupling – or in strontium titanate (SrTiO₃) (ref. 18) – where the mechanism seems to involve structural domain boundaries.

In cuprates, a large negative κ_{xy} signal was observed at low temperature inside the pseudogap phase, *i.e.* for dopings $p < p^*$ (ref. 3). Because it persists down to p = 0, in the Mott insulator state, this negative κ_{xy} cannot come from charge carriers. Therefore, it must come either from spin-related excitations (possibly topological, as in ref. 19) or from phonons. To distinguish between these two types of heat carriers, we adopt a simple approach: we measure the thermal Hall conductivity for a heat current along the c axis, normal to the CuO₂ planes, a direction in which only phonons move easily (see Methods).

We start by looking at the undoped cuprate La₂CuO₄, a Mott insulator with no mobile charge carriers. Here, phonons are the dominant heat carriers at low T and their longitudinal thermal conductivity $\kappa_{nn}(T)$ is nearly the same for J//a (n = x) and J//c (n = z) (ref. 4; see Methods). As reproduced in Fig. 1a, the in-plane thermal Hall conductivity κ_{xy} of La₂CuO₄ ($J//-x \perp c$, H//z and $\nabla T//y$; Extended Data Fig. 1a) was previously found to be negative at all T, with $|\kappa_{xy}/T|$ growing steadily as temperature is reduced below 100 K, reaching one of the largest Hall conductivities of any insulator, at T = 10 K (ref. 3). In a separate sample of La₂CuO₄, we measured κ_{zy} (J//z//c, H//x and $\nabla T//y$; Extended Data Fig. 1b) and found that $\kappa_{zy}(T) \approx \kappa_{xy}(T)$ at all T (Fig. 1a). The fact that the thermal Hall conductivity is as large across the CuO₂ planes as within is compelling evidence that the carriers of heat responsible for the thermal Hall effect in La₂CuO₄ are phonons. Indeed, any excitation of electronic origin (carrying charge or spin) is expected to be much more mobile within the CuO₂ planes as opposed to across planes (see Methods).

Next, we turn to the hole-doped cuprate $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$ (Nd-LSCO), whose phase diagram is shown in Fig. 2a. The pseudogap phase boundary $T^*(p)$ ends at

a T=0 critical point $p^*=0.23$, as determined by both transport²⁰ and photoemission (ARPES; ref. 21) measurements. At p=0.24, just above p^* , the in-plane thermal Hall conductivity κ_{xy} of Nd-LSCO was found to be positive at all T (Fig. 1b) and in good agreement with the Wiedemann-Franz law, namely $\kappa_{xy}/T=L_0\sigma_{xy}$ as $T\to 0$, where $L_0=(\pi^2/3)(k_{\rm B}/{\rm e})^2$ (ref. 3). Using a sample cut from the same large crystal, we measured κ_{zy} and found that $\kappa_{zy}(T)=0$ at all T, below 100 K (Fig. 1b). Combined with the fact that the Wiedemann-Franz law is satisfied for J//a, our data for J//c show that phonons in Nd-LSCO have no Hall effect at p=0.24, for any direction. (Note that the contribution of charge carriers to $\kappa_{zy}(T)$ is extremely small – see Methods.) In other words, phonons have no chirality outside the pseudogap phase.

In the related material La_{1.8-x}Eu_{0.2}Sr_xCuO₄ (Eu-LSCO), also with $p^* = 0.23$ (ref. 22), we again find that $\kappa_{zy}(T) = 0$ at $p = 0.24 > p^*$ (Fig. 1d). We stress that our data showing $\kappa_{zy}(T) = 0$ down to 10 K (on two separate samples) demonstrate that our measurement technique does not introduce any spurious background Hall signal (see Methods). In other words, any thermal Hall signal coming from the sample mount is negligible compared to the signal due to the samples.

Inside the pseudogap phase $(p < p^*)$, a large negative κ_{xy} was observed at low T in La_{2-x}Sr_xCuO₄ (LSCO) with p = 0.06, Eu-LSCO with p = 0.08, Bi₂Sr_{2-x}La_xCuO_{6+δ} with x = 0.2, and Nd-LSCO with p = 0.20, 0.21 and 0.22 (ref. 3). In Fig. 1c, we reproduce the published κ_{xy} data for Nd-LSCO with p = 0.21, seen to go negative below 25 K – in contrast to σ_{xy} , which remains positive down to $T \rightarrow 0$ (refs. 3,20). In the same figure, we report our data for κ_{zy} measured in Nd-LSCO with p = 0.21. We see that in striking contrast with p = 0.24, we now have a sizable (negative) κ_{zy} signal.

We summarize our κ_{zy} measurements in Fig. 2b. At p = 0.24, just outside the

pseudogap phase $(p > p^*; \text{Fig. 2a})$, $\kappa_{zy}(T) = 0$ and phonons have no chirality. At p = 0.21, just inside the pseudogap phase $(p < p^*; \text{Fig. 2a})$, $\kappa_{zy}(T) << 0$ and phonons have suddenly acquired chirality. This new phonon Hall effect grows in strength with decreasing doping, being largest at p = 0, in La₂CuO₄. We therefore 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 smallness of two expected signatures: a field dependence of κ_{xx} and a drop in κ_{xx} below p^* . These quantitative considerations now have to be understood. See Methods.)

The question then becomes this: what special property of the pseudogap phase confers chirality to phonons? One possibility is that phonons acquire Berry curvature¹¹ from their interaction with the special electronic properties of that phase. A rather universal consequence of Berry curvature is to produce a thermal Hall response that varies as $\kappa_{xy}/T \sim \exp(-T/T_0)$ at intermediate temperatures (ref. 12). In Fig. 3, we show a fit of our κ_{zy} data to the relation $\kappa_{zy}/T = A \exp(-T/T_0) + C$, for La₂CuO₄ and Nd-LSCO with p = 0.21. We see that the fits are excellent, down to $T \sim T_0 \sim 15$ K. This supports the scenario of phonons with 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, while skew scattering of phonons by magnetic impurities can produce a thermal Hall effect 16,23 , typically very small (orders of magnitude smaller than that found in La₂CuO₄), this extrinsic impurity-related mechanism cannot apply here since 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-v-x}RE_vSr_xCuO₄

(RE=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. Interestingly, a recent ARPES study in the cuprate Bi₂Sr₂CaCu₂O_{8+ δ} saw a rapid increase in the coupling of phonons to electrons upon crossing below p^* (ref. 24).

A large κ_{xy} signal due to phonons was recently observed in SrTiO₃, but not in the related material KTaO₃, where $\kappa_{xy}(T)\approx 0$ below 100 K (ref. 18). This striking difference was attributed to the presence of structural domains in SrTiO₃, absent in KTaO₃. Exactly how structural domains can generate a Hall effect is still unclear²⁵, 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 – both are in the so-called LTT phase (see Methods).

A large κ_{xy} signal due to phonons was observed in multiferroic materials like $Fe_2Mo_3O_8$ (ref. 17), where 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 model²⁶. It may be that the topological character of this unusual state of correlated spins²⁷ confers chirality to phonons. Note that slow antiferromagnetic correlations (quasi-static moments) are indeed observed for dopings up to p^* in Nd-LSCO (ref. 28) and LSCO (ref. 29), and not above.

The broad implication of our finding that phonons in insulators can generate large thermal Hall signals is to impose a re-examination of previous studies where the thermal Hall effect was attributed to heat carriers other than electrons or phonons, for example to Majorana edge modes in the 2D insulator α -RuCl₃ (ref. 30).

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Author information. The authors declare no competing financial interest.

Correspondence and requests for materials should be addressed to

G.G. (gael.grissonnance@usherbrooke.ca) or L.T. (louis.taillefer@usherbrooke.ca).

MAIN FIGURE CAPTIONS

Fig. 1 | Thermal Hall conductivity of cuprates at three different dopings.

Thermal Hall conductivity versus temperature in a field of magnitude H = 15 T, plotted as κ_{ny}/T vs T for two heat current directions, J//a (n = x; blue) and J//c (n = z; red) in **a)** La₂CuO₄ (p = 0), **b)** Nd-LSCO with p = 0.24, **c)** Nd-LSCO with p = 0.21, and **d)** Eu-LSCO with p = 0.21. All lines are a guide to the eye. The κ_{xy} data are from ref. 3; in Nd-LSCO, they were taken in 18 T, and so are multiplied here by a factor 15/18.

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-LSCO (refs. 2, 20) and Eu-LSCO (ref. 22). The orange circles indicate the temperature below which the in-plane resistivity deviates upwards from its T-linear dependence at high temperature (refs. 20, 31). The orange square marks the onset temperature for the opening of the anti-nodal pseudogap in Nd-LSCO at p = 0.20 detected by ARPES (ref. 21). The two vertical bands indicate the two dopings on either side of p^* at which we measured $\kappa_{zy}(T)$, the c-axis thermal Hall conductivity shown in panel b (blue for p = 0.21, green for p = 0.24). b) Thermal Hall conductivity κ_{zy} , for a heat current normal to the CuO₂ planes (J // c // z) and a magnetic field of 15 T applied parallel to the planes (H // a // x), plotted as κ_{zy} / T vs T, in La₂CuO₄ (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.

Fit of the thermal Hall conductivity $\kappa_{zy}(T)$ in **a)** La₂CuO₄ and **b)** Nd-LSCO at p = 0.21 to the phenomenological expression κ_{zy} / $T = A \exp(-T/T_0) + C$, derived from a theory that links the thermal Hall effect to the Berry curvature of the heat carriers¹². The fit interval is from 15 K to 100 K. The resulting fit parameters are: a) $A = -4.9 \text{ mW/K}^2\text{cm}$, $C = -0.02 \text{ mW/K}^2\text{cm}$, $T_0 = 17.5 \text{ K}$; b) $A = -2.4 \text{ mW/K}^2\text{cm}$, $C = -0.04 \text{ mW/K}^2\text{cm}$, $T_0 = 15.8 \text{ K}$. The fact that the theoretical expression fits the data well in the temperature range above T_0 supports the hypothesis that phonons in those cuprates have a non-zero Berry curvature.

METHODS

SAMPLES

Nd-LSCO. Single crystals of La_{2-y-x}Nd_ySr_xCuO₄ (Nd-LSCO) were grown at the University of Texas at Austin using a travelling-float-zone technique, with a Nd content y = 0.4 and nominal Sr concentrations x = 0.21 and 0.25. The hole concentration p is given by p = x, with an error bar ± 0.003 , except for the x = 0.25 sample, for which the doping is $p = 0.24 \pm 0.005$ (for details, see ref. 20). The value of T_c , defined as the point of zero resistance, is: $T_c = 15$ 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. 20). The a-axis (J // a) and c-axis (J // c) samples were both cut out of the same large single crystal. The orientation and cutting of the samples were performed in Sherbrooke.

Eu-LSCO. The single crystal of La_{2-y-x}Eu_ySr_xCuO₄ (Eu-LSCO) was grown at the University of Tokyo using a travelling-float-zone technique, with a 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 ± 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. 22). The a-axis (J // a) and c-axis (J // c) samples were both cut out of the same large single crystal. The orientation and cutting of the samples were performed in Sherbrooke.

La₂CuO₄. Our two single crystals of La₂CuO₄ came from the same batch, grown at the University of Tokyo using a travelling-float-zone technique. The a-axis (J // a) and c-axis (J // c) samples were each cut out of these two single crystals, respectively. The orientation and cutting of the samples were performed in Sherbrooke.

THERMAL HALL MEASUREMENT

Our measurements of the *c*-axis thermal Hall conductivity κ_{zy} were performed on four samples: La₂CuO₄ (p = 0); Nd-LSCO with p = 0.21; Nd-LSCO with p = 0.24; Eu-LSCO with p = 0.24. In the same three materials, with the same four dopings, the in-plane thermal Hall conductivity κ_{xy} was previously reported, in ref. 3. Those κ_{xy} data are reproduced in the four panels of Fig. 1 (blue curves).

Experimental Procedure. For our measurements, six contacts were made on the sample using silver epoxy Dupont H20E diffused by annealing at high temperature in

oxygen – two contacts for the heat current, two for the longitudinal temperature difference $\Delta T_{\rm n}$ (n=x or z) and two for the transverse temperature difference $\Delta T_{\rm y}$ (Extended Data Fig. 1). The sample was glued on a copper heat sink (Extended Data Fig. 1) with Dupont silver paint. Sample temperatures T+ and T- are measured with one absolute type-E (chromel-constantan) thermocouple connected to T- and one differential type-E thermocouple connected to T+ and T- (which measures the temperature difference $\Delta T_{\rm n} = T+$ – T-). Another differential type-E thermocouple measures the transverse temperature difference $\Delta T_{\rm n}$ (Extended Data Fig. 1). A finite temperature difference $\Delta T_{\rm n}$ is created by applying heat to the free end of the sample (Extended Data Fig. 1), using a 5 k Ω resistor whose resistance is well known and does not vary with temperature or field. Thermocouples and heater are connected to the sample with silver wires (25 and 50 μ m in diameter, respectively).

The experiment is performed in a fixed magnetic field. A positive field H = +15 T is applied at T = 100 K and the sample is then cooled down to $T \sim 5$ K. At fixed field, the temperature is increased in steps, and the system is stabilized at each temperature point. For each point, the background voltages across all thermocouples in the absence of applied heat are carefully measured. Then heat is applied and, once the sample has reached thermal equilibrium, the thermocouple voltages are measured again. By subtracting the background voltages from the corresponding heat-on voltages, we can reliably extract the intrinsic response of the sample. We repeat this procedure at each temperature point from ~ 5 K to 100 K. Once the entire temperature range is covered at positive field, the field is inverted at T = 100 K, to its negative value H = -15 T, and the system is cooled down to ~ 5 K. We then repeat the whole procedure, under otherwise identical conditions. As always in a Hall measurement, the pure transverse signal (here ΔT_y) is obtained by anti-symmetrization: $\Delta T_y = [\Delta T_y(+15\text{T}) - \Delta T_y(-15\text{T})] / 2$.

To determine the sign of the (transverse) thermal Hall conductivity, *i.e.* the sign of ΔT_y , we use reference samples for which the sign of the thermal Hall conductivity is unambiguous, for example overdoped $\text{Tl}_2\text{Ba}_2\text{CuO}_{6+\delta}$ (positive sign), measured using the very same set-up (and thermocouple connections). For further details, see ref. 32.

For all the κ_{zy} data reported here, the magnetic field strength was H=15 T. Because $H \perp c$ in this case, superconductivity is only weakly suppressed, so in order to report only normal-state data we limit the data in Figs. 1, 2 and 3 to $T > T_c$. For the κ_{xy} data

reproduced in Fig. 1 (blue curves), the field strength was either H = 15 T (for La₂CuO₄ and Eu-LSCO) or H = 18 T (for Nd-LSCO) (ref. 3). In Figs. 1b and 1c, we have multiplied the κ_{xy} data taken at 18 T by a factor 15/18, to enable a comparison at 15 T.

ORIENTATION OF HEAT CURRENT AND MAGNETIC FIELD

In-plane heat current $(J \perp c)$. For our prior measurements of κ_{xy} (ref. 3), the heat current J was sent in the basal plane of the single crystal (along -x), so parallel to the CuO₂ planes, generating a longitudinal temperature difference $\Delta T_x = T + -T$ - (Extended Data Fig. 1a). The longitudinal thermal conductivity along the x axis is given by $\kappa_{xx} = (J/\Delta T_x) (L_x/w_y t_z)$, where L_x is the separation (along x) between the two points at which T+ and T- are measured, w_y is the width of the sample (along y) and t_z its thickness (along z // c). By applying a magnetic field H along the c axis of the crystal (along z), normal to the CuO₂ planes, one generates a transverse temperature difference ΔT_y (Extended Data Fig. 1a). The in-plane thermal Hall conductivity is defined as $\kappa_{xy} = -\kappa_{yy} (\Delta T_y/\Delta T_x) (L_x/w_y)$, where κ_{yy} is the longitudinal thermal conductivity along the y axis. Here, we can take $\kappa_{yy} = \kappa_{xx}$, as all samples are either twinned or tetragonal.

Out-of-plane heat current (J//c). For the measurements of κ_{zy} presented here, the heat current J was sent along the c axis of the single crystal (along z), so perpendicular to the CuO₂ planes, generating a longitudinal temperature difference $\Delta T_z = T + -T$ - (Extended Data Fig. 1b). By applying a magnetic field H along the a axis of the crystal (along x), so parallel to the CuO₂ planes, one generates a transverse temperature difference ΔT_y (Extended Data Fig. 1b). The longitudinal thermal conductivity along the z axis is given by $\kappa_{zz} = (J/\Delta T_z) (L_z/w_y t_x)$, where L_z is the separation (along z) between the two points at which T+ and T- are measured, w_y is the width of the sample (along y) and t_x its thickness (along x // a). The out-of-plane thermal Hall conductivity is defined as $\kappa_{zy} = -\kappa_{yy} (\Delta T_y/\Delta T_z) (L_z/w_y)$, where κ_{yy} is the longitudinal thermal conductivity along the y axis (again taken to be equal to κ_{xx}).

LONGITUDINAL THERMAL CONDUCTIVITY

As reported previously⁴, we find that La₂CuO₄ has a nearly isotropic longitudinal thermal conductivity at low temperature (Extended Data Fig. 2). Indeed, $\kappa_{xx} / \kappa_{zz} = \kappa_a / \kappa_c \sim 0.8$ at T = 25 K. At higher temperature, thermally excited magnons

contribute to heat transport in La₂CuO₄, but only within the plane, and κ_a grows to exceed κ_c (ref. 4). So at low temperature, where phonons dominate the heat transport, the conductivity of phonons is nearly isotropic.

In Nd-LSCO, we also find that the phonon conductivity is nearly isotropic, as can be deduced from the data in Extended Data Fig. 3. Once we remove the contribution of mobile charge carriers, as done in panels 3b and 3d using the Wiedemann-Franz law, we have $\kappa_{xx}/\kappa_{zz} = \kappa_a/\kappa_c \sim 1.2$ and 1.3 at T = 25 K, for p = 0.21 and p = 0.24, respectively.

Note that the electrical conductivity, and therefore also the electronic thermal conductivity from charge carriers, is highly anisotropic, with $\sigma_{xx} / \sigma_{zz} = \rho_{zz} / \rho_{xx} \sim 250$ in Nd-LSCO at p = 0.24 (from ref. 33).

ANISOTROPY OF THE ELECTRONIC HALL CONDUCTIVITY

In Extended Data Fig. 4, we show the anisotropy of the electrical Hall conductivity in Nd-LSCO at p = 0.24, plotted as $L_0 \sigma_{ny}$ vs T, for n = x (blue) and n = z (red). We see that there is an anisotropy comparable to that found in the longitudinal conductivity, namely $\sigma_{xy} / \sigma_{zy} \sim 250$. 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 that reason, we attribute the nearly isotropic thermal Hall conductivity found in La₂CuO₄ to phonons.

WIEDEMANN-FRANZ LAW FOR CURRENTS NORMAL TO THE PLANES

In Nd-LSCO with p=0.24, the maximal contribution of charge carriers to $\kappa_{zy}(T)$ can be estimated using the Wiedemann-Franz law, namely κ_{zy} / $T \le L_0 \sigma_{zy}$, where $\sigma_{zy} \le \rho_{zy}$ / $(\rho_{zz}\rho_{yy})$. The data for ρ_{zz} and ρ_{zy} are displayed in Extended Data Figs. 5a and 5b, respectively. The ρ_{xx} data for the a-axis sample cut from the same crystal was reported in ref. 20. The resulting curve for $L_0 \sigma_{zy}$ (using $\rho_{yy} = \rho_{xx}$) is displayed in Extended Data Figs. 5c. Because ρ_{zz} / $\rho_{xx} \sim 250$ in Nd-LSCO at p=0.24, we have a correspondingly very small electrical Hall conductivity σ_{zy} . The maximal value of the electronic thermal Hall conductivity along the c axis is about κ_{zy} / $T \sim 0.01$ mW / K^2 m, at T=10 K – a value 200 times smaller than the electronic thermal Hall conductivity measured in the plane (Fig. 1b). In Extended Data Fig. 5d, we see that this maximal electronic κ_{zy} is within the noise of our measured κ_{zy} . Any phonon contribution to κ_{zy} in

Nd-LSCO at p=0.24 must therefore be smaller than $|\kappa_{zy}|/T \sim 0.01$ mW / K² m, at T=10 K. This is smaller than the measured $|\kappa_{zy}|/T = 10$ in Nd-LSCO at p=0.21 by a factor ~ 100 . 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

In Extended Data Fig. 6, we show how κ_{zz} and κ_{zy} vary with the strength of the applied field, for three of our samples, by plotting : 1) κ_{zz} vs T at H = 0, 10 and 15 T; 2) $\kappa_{zy} / (TH)$ vs T at H = 10 and 15 T. In all cases, the field dependence of the thermal conductivity κ_{zz} is very small, and the thermal Hall conductivity κ_{zy} is essentially linear in H.

BACKGROUND SIGNAL FROM THE SAMPLE MOUNT

Because in our experimental set-up the sample was attached to a block of copper serving as the heat sink (Extended Data Fig. 1), one might expect a thermal Hall signal to come from Cu. However, in all the data reported here and published in ref. 3, all obtained using the same set-up, this background signal from Cu was negligible, as demonstrated in three ways.

First, the fact that the Wiedemann-Franz law is satisfied for in-plane transport in Nd-LSCO p = 0.24 (ref. 3) rules out any significant contamination of the κ_{xy} data in that measurement.

Secondly, the fact that our *c*-axis data on Nd-LSCO and Eu-LSCO with p = 0.24 yield $|\kappa_{zy}/T| < 0.01$ mW / K² m for all temperatures up to at least 100 K (red, Figs. 1b and 1d) shows that the signal from Cu is smaller than the noise in our measurement.

Thirdly, we have carried out a test study whereby a cuprate sample was measured first in the usual way, using a Cu block to which the sample was glued with Ag paste, and then re-measured using a block of LiF (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, *i.e.* $\kappa_{xy}(T)$ was fully reproduced all the way from 10 K to 100 K. This test data will be reported in a separate paper (M.-E. Boulanger *et al.*, in preparation). The smallness of the contamination from the Cu block is largely due to the mounting geometry whereby the main (longitudinal) temperature gradient in the Cu 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 κ_{xy} found in cuprates based on two observations. First, the longitudinal phonon thermal conductivity κ_{xx} couples very weakly to the magnetic field. Specifically, κ_{xx} changes at most by 0.5 % in 15 T, and the maximal ratio κ_{xy}/κ_{xx} is also about 0.5 %. This is much smaller than in multiferroics¹⁷, for example, where phonons are thought to be responsible for the thermal Hall effect. This weak field dependence of κ_{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 κ_{xx} increases upon crossing below p^* (ref. 3), as opposed to the decrease one might expect if some new scattering mechanism of phonons (causing the chirality) appears in the pseudogap phase. An increase in κ_{xx} is natural in view of the large drop in the charge carrier density of Nd-LSCO below p^* (ref. 20), which means that phonons become less scattered by electrons. So 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 κ_{xx} .

CRYSTAL STRUCTURE OF Nd-LSCO

At low temperature, the material La_{1.6-x}Nd_{0.4}Sr_xCuO₄ adopts the so-called low-temperature tetragonal (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. 34). At x = 0.20 and x = 0.25, x-ray diffraction detects the structural transition into the LTT phase upon cooling at $T_{\rm LTT} \sim 70$ K and 50 K (ref. 34), respectively (Extended Data Fig. 7a).

At temperatures above $T_{\rm LTT}$, the structural phase is labeled LTO1 (low-temperature orthorhombic), with transitions at $T_{\rm LT01} \sim 250$ K and 150 K, for x = 0.20 and x = 0.25, respectively.

So 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 $p = 0.24 \pm 0.005$, are both expected to have the same crystal structure below 150 K. We have confirmed this by performing dilatometry measurements of the sample length L vs temperature T in Nd-LSCO samples with p = 0.21 (the actual sample in which κ_{zy} was measured) and p = 0.24 (a sample cut immediately next to the sample in which κ_{zy} was measured). The data are shown in Extended Data Fig. 7b, plotted as dL / dT vs T. A clear anomaly is observed in both samples at the structural transition, with transition temperatures $T_{LTT} \sim 82 \pm 5$ K at p = 0.21 and $T_{LTT} \sim 45 \pm 10$ 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, completely absent at p = 0.24, is due to structural domain boundaries that scatter phonons, as proposed for SrTiO₃ (ref. 18), or to any other structural feature.

Data availability. The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

EXTENDED DATA FIGURE CAPTIONS

Extended Data Fig. 1 | Current and field orientation for κ_{xy} and κ_{zy} measurements.

Sketch of the thermal Hall measurement setup for **a)** J // a // -x and **b)** J // c // z. The Cartesian coordinate system is defined in the same way for the two samples.

Extended Data Fig. 2 | Longitudinal thermal conductivities κ_{xx} and κ_{zz} in La₂CuO₄.

Thermal conductivity versus temperature in a field of magnitude H = 15 T for La₂CuO₄ (p = 0), plotted as **a**) κ_{nn} vs T and **b**) κ_{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 κ_{xx} and κ_{zz} in Nd-LSCO.

Extended Data Fig. 4 | Anisotropy of electrical Hall conductivity in Nd-LSCO.

Electrical Hall conductivity σ_{ny} versus temperature in a field of magnitude H=15 T, plotted as L_0 σ_{ny} vs T, for Nd-LSCO with p=0.24, for heat current directions J // a (n=x; blue) and J // c (n=z; red). The data for σ_{zy} are multiplied by a factor 250. We use the approximate relation $\sigma_{zy} = \rho_{zy}$ / (ρ_{zz} ρ_{xx}), with ρ_{zz} and ρ_{xx} data taken from ref. 33. The σ_{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 σ_{zy} , namely κ_{zy} / $T \le L_0 \sigma_{zy}$, where $\sigma_{zy} \le \rho_{zy}$ / $(\rho_{zz} \rho_{yy})$. a) Electrical resistivity for J // c, ρ_{zz} vs T (from ref. 33); b) electrical Hall

resistivity for J//c and H//a, ρ_{zy} vs T; **c**) maximal electrical Hall conductivity for J//c and H//a, defined as $\sigma_{zy} = \rho_{zy} / (\rho_{zz} \rho_{xx})$ (with ρ_{xx} data from ref. 33), plotted as $L_0 \sigma_{zy}$ (multiplied by 60) vs T; **d**) comparison of the measured electrical (σ_{zy}) and thermal (κ_{zy}) Hall conductivities, plotted as $L_0 \sigma_{zy}$ (blue) and κ_{zy} / T (red; Fig. 1b) vs T.

Extended Data Fig. 6 | Field dependence of κ_{zz} and κ_{zv} in La₂CuO₄ and Nd-LSCO.

Upper panels: thermal conductivity κ_{zz} measured at H=0 T (purple), 10 T (green) and 15 T (red), plotted as κ_{zz}/T vs T, for **a)** La₂CuO₄, **b)** Nd-LSCO with p=0.21 and **c)** Nd-LSCO with p=0.24. Lower panels: thermal Hall conductivity κ_{zy} measured at H=10 T (green) and 15 T (red), plotted as $\kappa_{zy}/(TH)$ vs T, for **d)** La₂CuO₄, **e)** Nd-LSCO with p=0.21 and **f)** Nd-LSCO with p=0.24. We see that κ_{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 $T_{\rm LTT}$, as measured by x-ray diffraction³⁴. The squares mark $T_{\rm LTT}$ 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 $T_{\rm LTT}$, where $T_{\rm LTT}=82\pm5$ K at p=0.21 and $T_{\rm LTT}=45\pm10$ K at p=0.24. 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 κ_{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 $p^*=0.23$.

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MAIN FIGURES

Fig. 1 | Thermal Hall conductivity of cuprates at three different dopings.

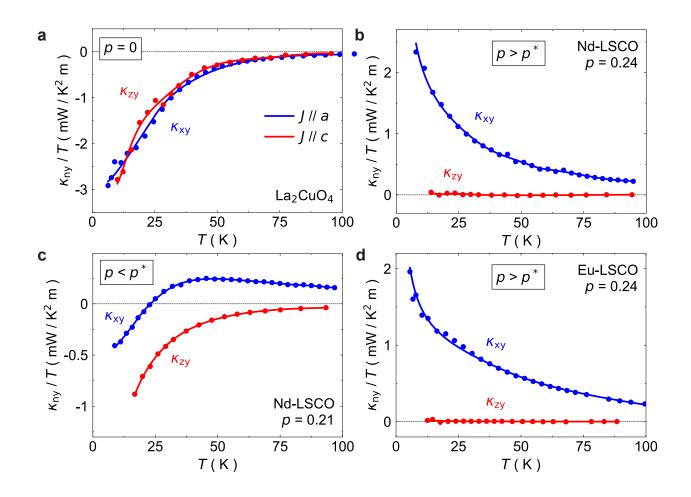


Fig. 2 | Evolution of the c-axis thermal Hall conductivity across the phase diagram.

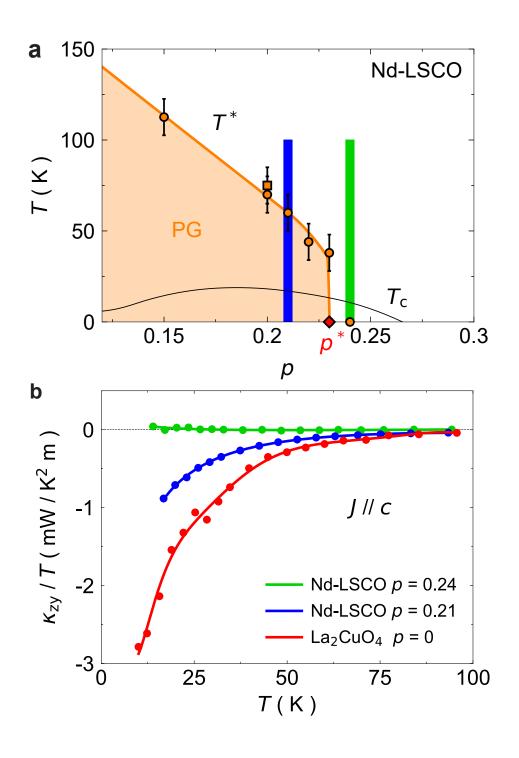
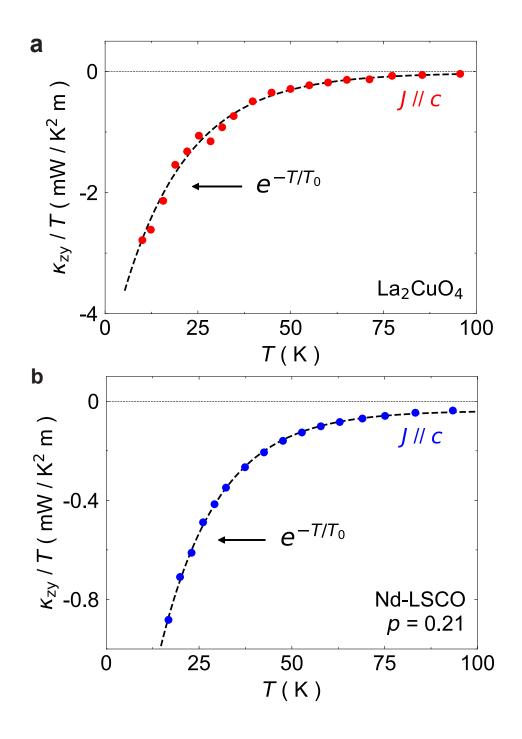
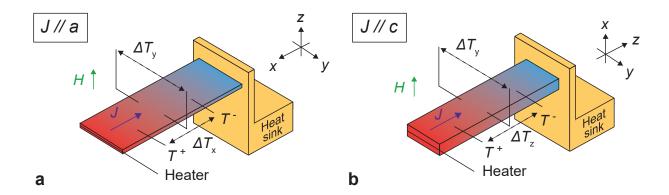


Fig. 3 | Phenomenological fit to the phonon thermal Hall conductivity.

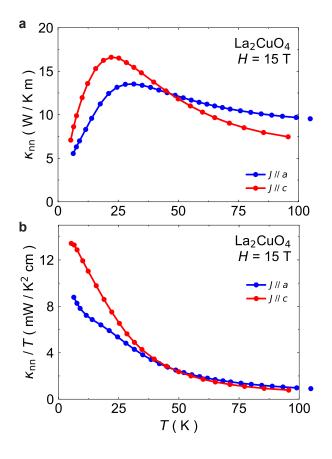


EXTENDED DATA FIGURES

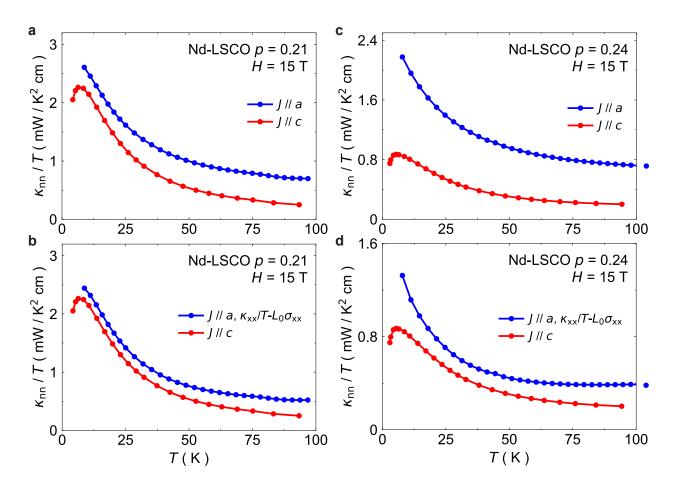
Extended Data Fig. 1 | Current and field orientation for κ_{xy} and κ_{zy} measurements.



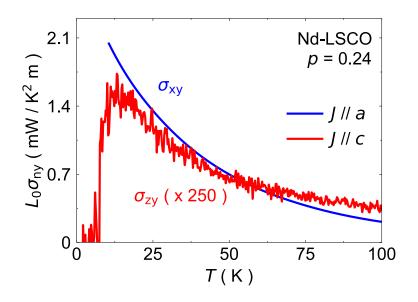
Extended Data Fig. 2 | Longitudinal thermal conductivities κ_{xx} and κ_{zz} in $La_2CuO_4.$



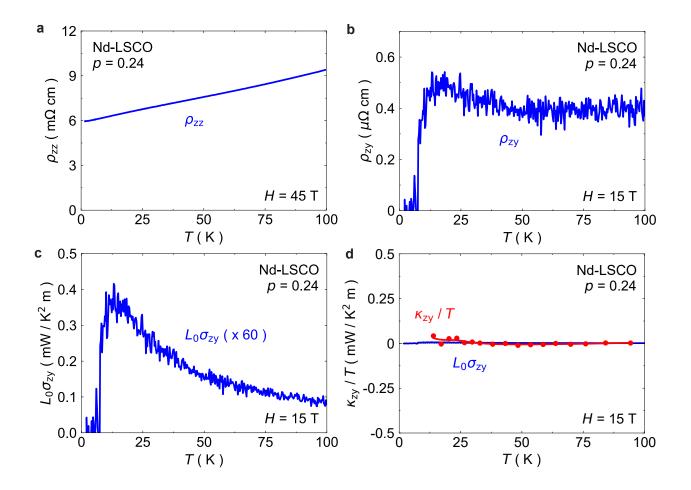
Extended Data Fig. 3 | Longitudinal thermal conductivities κ_{xx} and κ_{zz} in Nd-LSCO.



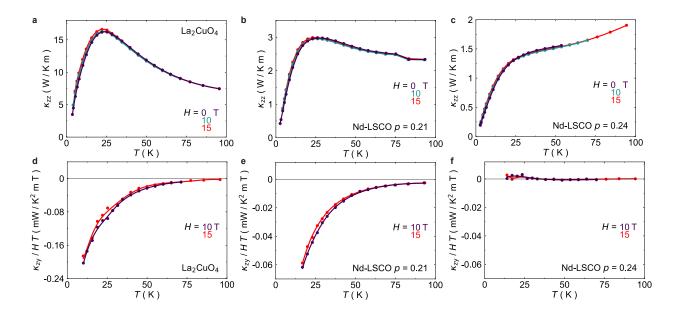
Extended Data Fig. 4 | Anisotropy of electrical Hall conductivity in Nd-LSCO.



Extended Data Fig. 5 | Electronic thermal Hall conductivity in Nd-LSCO p = 0.24.



Extended Data Fig. 6 | Field dependence of κ_{zz} and κ_{zy} in La_2CuO_4 and Nd-LSCO.



Extended Data Fig. 7 | Structural transition in Nd-LSCO.

