Colossal transverse magnetoresistance due to nematic superconducting phase fluctuations in a copper oxide

Jonatan Wårdh\textsuperscript{a,}, Mats Granath\textsuperscript{b,*,}, Jie Wu\textsuperscript{b,e}, Anthony T. Bollinger\textsuperscript{b}, Xi He\textsuperscript{c,d} and Ivan Božovic\textsuperscript{d,b,c,*}

\textsuperscript{a}Department of Physics, University of Gothenburg, SE-41296 Gothenburg, Sweden
\textsuperscript{b}Brookhaven National Laboratory, Upton, NY 11973, USA
\textsuperscript{c}Department of Chemistry, Yale University, New Haven, CT 06520, USA
\textsuperscript{d}Energy Sciences Institute, Yale University, West Haven, CT 06516, USA
\textsuperscript{e}Present address: School of Science, Westlake University, Hangzhou, China
*To whom correspondence may be addressed: Email: bozovic@bnl.gov, mats.granath@physics.gu.se

Abstract

Electronic anisotropy ("nematicity") has been detected in cuprate superconductors by various experimental techniques. Using angle-resolved transverse resistance (ARTR) measurements, a very sensitive and background-free technique that can detect 0.5% anisotropy in transport, we have observed it also in La\textsubscript{2-x}Sr\textsubscript{x}CuO\textsubscript{4} (LSCO) for 0.02 \textless x \textless 0.25. A central enigma in LSCO is the rotation of the nematic director (orientation of the largest longitudinal resistance) with temperature; this has not been seen before in any material. Here, we address this puzzle by measuring the angle-resolved transverse magnetoresistance (ARTMR) in LSCO. We report the discovery of colossal transverse magnetoresistance (CTMR)—an order-of-magnitude drop in the transverse resistivity in the magnetic field of 6 T. We show that the apparent rotation of the nematic director is caused by anisotropic superconducting fluctuations, which are not aligned with the normal electron fluid, consistent with coexisting bond-aligned and diagonal nematic orders. We quantify this by modeling the (magneto-)conductivity as a sum of normal (Drude) and paraconducting (Aslamazov–Larkin) channels but extended to contain anisotropic Drude and Cooper-pair effective mass tensors. Strikingly, the anisotropy of Cooper-pair stiffness is much larger than that of the normal electrons. It grows dramatically on the underdoped side, where the fluctuations become quasi-one-dimensional. Our analysis is general rather than model dependent. Still, we discuss some candidate microscopic models, including coupled strongly-correlated ladders where the transverse (interladder) phase stiffness is low compared with the longitudinal intraladder stiffness, as well as the anisotropic superconducting fluctuations expected close to the transition to a pair-density wave state.

Significance Statement

The electrical conductivity of standard metals is understood using the model of a gas of free electrons with an "effective" mass. However, in cuprate superconductors, the electrical conductivity shows an anisotropy that is absent in the crystal lattice, the so-called electronic nematic order. Even more enigmatic, in some cuprates, the direction of the highest conductivity rotates at the temperature approaches the superconducting transition temperature. Here, we report new experiments that show that this rotation is due to fluctuations of quasi-one-dimensional Cooper pairs, with an effective mass tensor that is not aligned with that of the normal electrons. The phenomenology bears resemblance to that of a striped superconductor, but the understanding of the nematic state remains a challenge.

Introduction

Apart from a high superconducting critical temperature (\(T_c\)), copper oxides show other striking features (1). Unlike in standard metals, in the normal state, the rotational symmetry of electron fluid is spontaneously broken ("electronic nematicity") (2–12). Unlike that in conventional superconductors, \(T_c\) is set by the phase ordering temperature rather than by the pairing energy scale inferred from the measured single-particle response; consequently, above \(T_c\), superconducting phase fluctuations abound (13–21). The fact that nematicity is strongly enhanced in underdoped cuprates implies that there may be interesting, yet to be revealed, connections with other unusual properties such as the pseudo-gap, antiferromagnetic fluctuations, and charge-, spin-, or pair-density waves. Indeed, nematic order, or fluctuations near a nematic quantum critical point, has been suggested to be intimately related to high-temperature superconductivity in both cuprate and iron-based superconductors (22–27) and possibly associated with strange metal physics in the cuprates (28).

The possibility of electronic nematicity was first envisioned theoretically (29–34). It was subsequently detected in several materials—two-dimensional electron gas in high magnetic fields, copper oxides, Fe-based superconductors, strontium ruthenates,
and twisted bilayer graphene (35–41). Nematicity is unambiguously detected by measurements of various electronic properties — electron transport, thermal conductivity, Nernst effect, THz dichroism, magnetic torque, scanning tunneling microscopy/spectroscopy maps, angle-resolved photoemission, electronic Raman scattering in the off-diagonal (crossed-polarization) geometry, second-harmonic generation, and angle-resolved transverse resistivity (ARTR) (2–12). Note that all these effects are observed in the normal state, so these materials are nematic metals.

Rotational symmetry could also be broken in the superconducting state, a nematic superconductor. A prominent candidate is Bi$_2$Se$_3$ doped by Cu, Sr, or Nb, where, as judged by the observed in-plane anisotropy of the critical magnetic field, a multicomponent superconducting order parameter breaks both the U(1) gauge symmetry and the point group symmetry of the lattice (42, 43). In addition, in the normal state, such a superconductor can give rise to the vestigial nematic order by breaking only the point group symmetry without breaking the gauge symmetry. In the copper oxides, superconductivity is single component ($d_{x^2-y^2}$) and does not break the crystal symmetry at the mean-field level. Nevertheless, in the presence of nematic order, because of the reduced symmetry, a subleading $s$-wave component will be induced in the superconducting state, shifting the gap nodes (44). In contrast, in the normal state, nematicity would make superconducting fluctuations anisotropic.

Here, we investigate this interplay between nematicity and superconducting fluctuations in La$_{2-x}$Sr$_x$CuO$_4$ (LSCO) by studying the temperature and magnetic field dependence of the conductivity tensor in the normal state. As is well established, superconducting fluctuations are essential to describe the conductivity in the transition region through the paraconductance due to finite-lifetime Cooper pairs (45–48). We synthesize single-crystal LSCO films using atomic-layer-by-layer molecular beam epitaxy (ALL-MBE) on tetragonal LaSrAlO$_4$ (LSAO) substrates. For ARTR measurements, we lithographically pattern the films into a sunbeam arrangement of LSCO bars with different orientations with respect to the crystallographic axes; see Fig. 1A. This allows for a complete mapping of the conductivity tensor and, by applying an external magnetic field, of the magnetoconductivity. As shown in our earlier work, the nematic signature is strongly enhanced close to the superconducting transition, in the form of sharp peaks in the transverse resistivity that are systematically modulated in sign and magnitude according to the orientation of the bars (11).

We now show that this signal is rapidly suppressed by a magnetic field, the colossal transverse magnetoresistance (CTMR), which provides explicit evidence for the importance of superconducting fluctuations. The observation is consistent with the broadening of the transition region observed in the longitudinal conductance and a more gradual decrease of paraconductivity with increasing temperature, thus confirming the superconducting origin of the peaks. The principal axes of the conductivity are not aligned with the high-symmetry directions of the tetragonal crystal, which indicates a general in-plane nematic order with independent $x^2-y^2$ ($B_{1g}$) and $xy$ ($B_{2g}$) Ising ($Z_2$) nematic fields. This observation of two symmetry-breaking nematic orders is consistent with observations in bulk LSCO from neutron scattering of both bond-aligned and diagonal spin-density wave fluctuations (49, 50), and both types of nematic orders have also been observed in the iron-based superconductors (51, 52).

Even more unexpected, the anisotropy of the Cooper-pair mass, deduced by analyzing the conductivity tensor, greatly exceeds, and is not aligned with, that of the effective mass of normal electrons. The first result follows from a simple two-fluid model of normal-electron Drude conductivity and Aslamazov–Larkin paraconductivity, which accounts for the sharp peaks observed in the transverse resistance. The second result follows directly from the observation that the principal axes of the conductivity rotate back to the high-temperature orientation when a magnetic field suppresses the paraconductivity.

The conclusion that the Drude and Cooper-pair mass tensors are independent gives new insights into the nature of superconductivity in the cuprate superconductors, as the anisotropy of phase stiffness would normally be expected to reflect the anisotropy of the constituent electrons. The observed anisotropy of the superconducting fluctuations is very large, even quasi-1D in the underdoped samples, giving additional evidence of an exotic state. The findings are broadly reminiscent of models for high-temperature superconductivity based on coupled, strongly correlated (Hubbard or t-J) ladders with low transverse interladder stiffness due to pair hopping between ladders and a large intraladder pairing (pseudo-) gap (53–55).

Another possible interpretation is that we observe fluctuations of a unidirectional pair-density wave order (56–59), for which a difference in transverse and longitudinal stiffness would be expected. However, neither of these models seems to capture complete physics. In the “ladder” scenario, it may be expected that the normal transport would also be quite anisotropic. In the PDW scenario, the divergence of superconducting fluctuations approaching $T_c$ may require fine-tuning the finite momentum and homogenous components. In addition, the existence of bond-aligned and diagonal nematic fields would have to be considered.

It should be emphasized that the large stiffness anisotropy that we have observed does not imply a large gap anisotropy. In cuprates, the stiffness is generally very low and not directly related to the superconducting gap. The stiffness quantifies slow deformations of the order parameter and describes the dynamic properties. The superconducting gap quantifies local pair-breaking excitations and is a static (mean-field) property. Assuming that the pseudogap is related to pairing, this dichotomy is consistent with our observation of small normal-electron anisotropy and large pair-fluctuation anisotropy in the pseudogap regime. This crucial distinction between probing static and dynamic properties and the sensitive nature of the nematic order may explain why these critical observations have not been made previously.

Results and discussion

To provide context, we begin with a summary of the general properties of the in-plane conductivity, with or without a magnetic field. The conductivity takes the form of a 2D tensor which can be decomposed by its transformation under rotation:

$$\rho = \begin{bmatrix} \rho_{xx} & \rho_{yx} \\ \rho_{yx} & \rho_{yy} \end{bmatrix} \equiv \begin{bmatrix} \sigma_{00} + \sigma_{01} + \sigma_{02} & -\sigma_{11} \sigma_{02} - \sigma_{12} \\ -\sigma_{12} \sigma_{02} - \sigma_{11} & \sigma_{00} + \sigma_{01} + \sigma_{02} \end{bmatrix},$$

(1)

here expressed in the $a$, $b$ crystal frame (the [100] and [010] directions). The trace $2\sigma_{00}$ and the Hall conductivity $\sigma_{11}$ are left invariant under rotation, while $\sigma_5 = \begin{bmatrix} \sigma_{00} - \sigma_{01} - \sigma_{02} \\ -\sigma_{02} - \sigma_{01} + \sigma_{00} \end{bmatrix}$ transforms as a traceless symmetric tensor. A current $J$ running at an angle $\phi$ (with respect to the crystal axis $a$) will in general yield both a longitudinal resistivity $\rho_L(\phi) = |E|/|J|^2$ and a transverse resistivity $\rho_T(\phi) = z \cdot E \times J/|J|^2$, given by

$$\rho_T(\phi) = \frac{\sigma_{00} + \sqrt{\det(\sigma_5)} \sin(2\phi - a)}{\sigma_{00} + \sigma_{01} + \sigma_{02} + \sqrt{\det(\sigma_5)}},$$

$$\rho_L(\phi) = \frac{\sigma_{00} + \sqrt{\det(\sigma_5)} \cos(2\phi - a)}{\sigma_{00} + \sigma_{01} + \sigma_{02} + \sqrt{\det(\sigma_5)}}.$$
Here, $\alpha = 1/2 \arctan(\sigma_{S1}^{(2)} / \sigma_{S2}^{(2)})$ is the angle, measured from the crystal $a$-axis, along which the longitudinal resistivity is maximal.

Given that the crystal is tetragonal, $\sigma_{S1}^{(1)}$ and $\sigma_{S2}^{(1)}$ are order parameters for $B_{1g}$ (bond-aligned) and $B_{2g}$ (diagonal) nematic orders, respectively. In the absence of a magnetic field ($\sigma_{0} = 0$), the appearance of a nonzero transverse voltage in a zero magnetic field is thus coincident with the development of nematic order. An out-of-plane magnetic field induces an antisymmetric Hall component $\sigma_{H}$ in Eq. (2). It will give rise to a transverse resistance even without $\sigma_{0}$. However, since $\sigma_{0}$ is rotationally invariant, the Hall resistivity $\rho_{H}(B)$ can generally be distinguished from the traceless symmetric part of the total $\rho_{S}(2\alpha)$ angular dependence is measured and resolved. We use the term “nematic director” to denote the orientation $\alpha$ of the conductivity tensor, even though it is not a continuous rotational symmetry that is broken, which implies that different physical quantities may have different orientations depending on how strongly they couple to the two nematic order parameters (see Sections S2 and S3).

A series of experiments consisted of measuring the longitudinal and transverse voltage versus current in mesoscopic Hall bar structures manufactured from single-crystal LSCO films synthesized by ALL-MBE on tetragonal LSAO substrates. In the zero field, the data coincide with those in (11) but the experimental set-up is now upgraded to allow an out-of-plane magnetic field, up to 9 T, to be applied, enabling us to suppress superconductivity. The crucial aspect of the experiment is the sunbeam arrangement of Hall bars, with an orientation that varies sequentially with respect to the crystal axes, allowing for angle-resolved measurements; see Fig. 1A.

Figure 1 summarizes the experimental findings near the optimal doping ($x = 0.16$). [Data for additional doping levels are presented in SI.] The Hall resistance has been identified from symmetry and subtracted from the data. The polar color plots represent the magnitude and sign of the transverse resistivity as a function of temperature (radial) and orientation of the bar. The plots are based on interpolating high-resolution temperature data from some bars and discrete fixed temperature data for all bars (see Fig. S1A). There is evident $\sin(2(\varphi - \alpha))$ periodicity (Fig. 1B and Figs. S1B and S3) with respect to the azimuth angle $\varphi$ consistent with nematic order. Most notable are the sharp peaks close to $T_{c}$ in the zero-field data, which also show the $\sin(2(\varphi - \alpha))$ dependence. The orientation of principal axes of conductivity (identified as the directions along which $\rho_{2g}(\varphi)$ changes sign) is temperature dependent, with a rapid twist close to $T_{c}$, which coincides with the onset of the peaks. A magnetic field of 9 T broadens the superconducting transition and eliminates the peaks in transverse resistivity. Notably, this also unwinds the twist of the nematic director, which now shows just a single, fixed (i.e. temperature-independent) orientation, the same as the high-temperature orientation in the zero field, from room temperature.
down to $T = 25$ K, which is the lowest temperature for which we can resolve the angular dependence.

Figures 1D and E show data along one azimuthal direction for the same sample, for a range of magnetic fields. As the field is increased, in copper oxides, the superconducting transition broadens and fans out. To illustrate in Fig. 1D. The critical new experimental observation here is that, concomitantly, the sharp peak in transverse resistivity is suppressed and broadened with an increasing field. As shown in Fig. 1E, in the magnetic field of 6 T or higher, the transverse resistivity drops by order of magnitude. This is comparable to the colossal magnetoresistance (CMR) effect seen in the longitudinal resistivity channel in La$_{0.7}$Sr$_{0.3}$MnO$_3$, the canonical CMR material (61). The main novelty here is that the "colossal" drop is seen in the transverse resistivity channel, with the maximal effect near $T = 41$ K, while at the same temperature, there is hardly any change in the longitudinal resistivity. Hence, this new effect can be called CTMR.

To gain some deeper insights from these experimental observations, we have modeled the conductivity using a standard "two-fluid" model consisting of a normal-electron Drude conductivity and a Cooper-pair paraconductivity:

$$\sigma = \sigma_n + \sigma_p,$$  

adapted to account for in-plane anisotropy. The normal component is given by an anisotropic Drude conductivity:

$$\sigma_n = ne^2 \tau \hat{m}_n^{-1} = \frac{1}{2\pi \hbar} \frac{1}{\rho_{\text{princ.}}} ne^2 \tau \begin{bmatrix} 1 & 0 \\ 0 & \frac{1}{\rho_{\phi \phi}} \end{bmatrix},$$

where $n$ is the density of normal electrons, $\tau$ is the (temperature-dependent) relaxation time, and $\hat{m}_n$ is the single-particle mass tensor, in its principal frame. We choose to model the anisotropy through the mass. Whether all or part of the anisotropy derives from an anisotropic scattering rate is irrelevant to the analysis in this paper. To describe the contribution from fluctuating superconductivity, the paraconductivity, we consider a generalized Aslamazov-Larkin (AL) expression (45) obtained by considering an anisotropic 2D Ginzburg-Landau free energy:

$$\int d^2 x (T - T_c)|\Delta|^2 + \frac{1}{2m_p} (D|\Delta|^2)(D|\Delta|).$$

Here, $D_i = \partial_i - (2e/\hbar)A_i$ is the gauge-invariant derivative which includes the vector potential $\mathbf{A}$, $\hbar$ is the Planck constant, $m_p$ is the Cooper-pair mass tensor, and $\partial$ is a constant with the dimension energy/K. The last term describes the electromagnetic response and represents the stiffness to deformation. Given Eq. (5), we find the (generalized) AL contribution to paraconductivity (see SI):

$$\sigma_p = \sigma_{p,0} \frac{T_c}{T - T_c} \sqrt{\text{det}(\hat{m}_p)} \hat{m}_p^{-1} = \frac{1}{\rho_{\text{princ.}}} \sigma_{p,0} \frac{T_c}{T - T_c} \begin{bmatrix} \frac{m_{p,x}}{m_{p,x}} & 0 \\ 0 & \frac{m_{p,y}}{m_{p,y}} \end{bmatrix},$$

where $\sigma_{p,0} = e^2/16\hbar d$ and $d$ is the layer thickness. The last expression holds in the principal frame of the Cooper-pair mass tensor. The basic physics behind this paraconductivity is that the electric field induces a nonequilibrium distribution of Cooper pairs, with a relaxation time that diverges as $T_c$ being approached. The Drude part will dominate the conductivity, except very close to $T_c$, where the diverging paraconducting contribution gives the characteristic rapid drop in the longitudinal resistivity. This in-plane paraconductivity of cuprate superconductors has been studied earlier (46–48), but not in terms of the transverse conductance, which is our main focus here. Although there is evidence in earlier studies for the more complex behavior of the paraconductivity, we will only consider the dominant $1/(T - T_c)$ temperature dependence of the 2D AL term.

In tetragonal cuprates, there are two distinct symmetry-allowed nematic fields: a bond-nematic ($\mathbf{B}_{\text{b}}$) field transforming as $x^2-y^2$ and a diagonal-nematic ($\mathbf{B}_{\text{d}}$) field transforming as $xy$. These fields break the tetragonal symmetry, and if only one of them is present, it introduces a preferred direction, either along a crystal axis or a diagonal one. If both fields are present, they couple independently to different tensorial physical quantities, and hence, their principal axes need not be aligned with each other or with high-symmetry crystal directions. The fact that the experimentally observed conductivity is generally not aligned with a high-symmetry tetragonal direction implies that both nematic fields are present. The relevant tensorial objects in the two-fluid model are the Drude and Cooper-pair mass tensors that are quantified by their mass anisotropies and principal axes' orientations. Specifically, $m_n$ and $m_p$ are assumed to be aligned with the measured $\rho_{\phi \phi}$ at the high-temperature tail and just above $T_c$, respectively. In their respective principal frames of reference, the mass anisotropies are denoted $m_{n,x}/m_{n,y}$ and $m_{p,x}/m_{p,y}$. We will assume these tensors to be fixed, in magnitude and orientation, such that the only temperature dependence is built into the Drude relaxation time (to fit the high-temperature tail) and the intrinsic $1/(T - T_c)$ temperature dependence of the AL expression. In addition, we will assume that prefactor $\sigma_{p,0}$ may deviate from the universal expression, possibly reflecting non-BCS Cooper-pair relaxation. The details of the modeling are presented in Supplementary Information. We have made several independent fits of the key quantities described there, all pointing to the same conclusion of effective decoupling of superconducting fluctuations from the normal electrons.

Figure 2 exemplifies the main results of the modeling of the zero-field conductivity. The deduced Cooper-pair mass anisotropy roughly follows the superconducting transition temperature. At low doping, $x = 0.10$, the estimated anisotropy is at least ten times larger, indicating that superconducting fluctuations are effectively quasi-one dimensional. Near the optimal doping, $x = 0.16$, Drude and Cooper-pair mass tensors are not aligned, which causes a rapid rotation of the principal axis of conductivity that corresponds to $\rho_{\phi \phi} = 0$ (white in Fig. 2C). Figure 3 exemplifies how the model, when extended to include the effects of the magnetic field on the paraconductivity and a phenomenological description of the broadened transition region (see Fig. S2), qualitatively reproduces the characteristic experimental observations, including the suppression of the peak in transverse resistivity and the unwinding of the sharp twist of the principal axes of conductivity.

**Conclusions and outlook**

We have shown that detailed measurements of longitudinal and transverse resistivity in the normal state of LSCO indicate that the electronic nematicity can be explained within a two-fluid model of normal electrons and finite-lifetime Cooper pairs. The fact that the observed nematic director (the direction of largest longitudinal resistivity) is not generally aligned with the crystal axes, and may even rotate with temperature, is explained by the presence of both...
We emphasize that this unexpected behavior follows from even the simplest model of normal conductivity and Aslamazov–Larkin pair conductivity (Fig. S4); for a peak in transverse resistivity to appear, it is necessary that the pair anisotropy is substantially larger than the normal anisotropy. This is further supported by extracting the mass anisotropies from the asymptotic behavior (Fig. S5) and by more elaborate fits to the data over the entire experimentally accessible temperature range (Figs. S6–S7 and Tables S3–S4), which all independently turn out similar estimates of the mass anisotropies (Table S2).

The nature of the underlying nematicity is unknown, but we stress that it is manifested primarily via the collective response of the superconductor. The latter points to some highly anisotropic superconducting state without global phase coherence, a “phase-stiffness nematic”, which is possibly even quasi-one dimensional. Such a dichotomy between single-particle and pair response is expected neither in the standard BCS nor in common Bose–Einstein condensation scenarios, for which the phase stiffness anisotropy should reflect the anisotropy of the effective mass of constituent electrons. This is an important new insight into the nature of cuprate superconductivity. Our data, and notably the facts that the crystal structure of the films (and the substrates they are epitaxially anchored to) is tetragonal, that the director is bond-aligned and diagonal Ising nematic orders that couple differently to the two channels of conductivity. A sharp peak in the transverse resistivity close to $T_c$ is a signature of the divergence of the relaxation time of the Cooper pairs as $T \to T_c$. This explanation of the peak origin is supported by our measurements which show that the peak in transverse resistivity is rapidly suppressed by a relatively small ($6 \, \text{T}$) out-of-plane magnetic field that has little effect on the longitudinal resistivity, an effect that we have dubbed CTMR. The concomitant reorientation of the nematic director is also consistent with the suppression of the contribution from superconducting fluctuations. The systematic angular dependence of the peak (see Figs. S1 and S3) is consistent with an underlying nematic order, and it rules out the possibility that the peak could originate from the sample inhomogeneity.  

The most striking result of the study is that the Cooper-pair mass anisotropy (or phase stiffness) is very large (more than 10, in underdoped LSCO with $x = 0.10$) and decoupled from a much smaller anisotropy of the mass of normal electrons. We emphasize (for details, see SI) that this unexpected behavior follows from even the simplest model of normal conductivity and Aslamazov–Larkin pair conductivity (Fig. S4); for a peak in transverse resistivity to appear, it is necessary that the pair anisotropy is substantially larger than the normal anisotropy. This is further supported by extracting the mass anisotropies from the asymptotic behavior (Fig. S5) and by more elaborate fits to the $T$-dependence of the data over the entire experimentally accessible temperature range (Figs. S6–S7 and Tables S3–S4), which all independently turn out similar estimates of the mass anisotropies (Table S2).

In theory, this decoupling of single-particle and collective pair response has already been contemplated. A rare tractable model is a coupled array of strongly correlated ladders (29, 53–55, 64–66). In the simplest scenario, each ladder is a Luther–Emery liquid (67) with a spin gap corresponding to singlet pairing but no charge gap and the susceptibilities to superconducting and charge-density-wave orders that both diverge with temperature. Single-particle tunneling between ladders can be neglected, but Josephson pair hopping may stabilize a 2D superconductor at the temperature scale of...
phase ordering between ladders. In this model, the pairing (pseudo) gap, due to the breaking of local singlet pairs, can indeed be isotropic (except for the form factor, which could be d-wave). In contrast, the phase stiffness can be very anisotropic since the intrinsic stiffness of deformations within a strongly correlated ladder can be quite different from the stiffness due to Josephson coupling between ladders (68). This anisotropic phase stiffness would manifest itself in the pseudogap phase of the model as highly anisotropic superconducting fluctuations. Related models have also found that the nodal “Fermi arc” electrons can be largely unaffected by quasi-1D charge- and spin-orders as well as superconducting fluctuations (69–72). Although the model of coupled ladders cannot capture the complex physics of the cuprate superconductors, unidirectional spin- and charge-density-wave orders as well as the nematic order (1, 5, 6, 73, 74), corresponding to broken translational and/or rotational invariance (29, 75, 76), appear to be a ubiquitous phenomenon in cuprates and may be linked to the pseudogap (25, 77, 78).

Recently, the pair-density wave (PDW) order of spatially modulated superconductivity has also emerged as a critical new concept in high-$T_c$ and strongly correlated superconductivity (56–59, 79–85). A unidirectional (striped) PDW would naturally be expected to have an anisotropic stiffness if it breaks the rotational symmetry of the crystal. Nevertheless, to explain our observation of the nematic peak in the transverse resistance in terms of fluctuating PDW, order would require fine-tuning the PDW ordering temperature to match the observed $T_c$ very closely. An alternative interpretation, presently being investigated, instead invokes a vestigial PDW state (87, 88), accounting all at once for the nematicity, how this couples to superconducting fluctuations, and the increase of anisotropy as the underdoped critical point is approached (89).

Methods

For film synthesis, we have used atomic-layer-by-layer molecular beam epitaxy (ALL-MBE) (90). LSCO thin films were synthesized on LSAO substrates by sequentially depositing La, Sr, and Cu. The atomic fluxes were measured using a quartz crystal monitor, and the shuttering times were computer controlled. The substrate temperature was kept at 650°C and the ozone partial pressure at $5 \times 10^{-6}$ Torr. Reflection high-energy electron diffraction (RHEED) was used to monitor the crystal structure and morphology of the film in real time. The RHEED patterns showed single-crystal LSCO films growing epitaxially on LSAO. The film thickness was controlled digitally by counting the RHEED intensity oscillations. After the growth, the ozone partial pressure was increased to $2 \times 10^{-5}$ Torr and the film was annealed for 30 minutes (to fill in oxygen vacancies) and cooled down at the same pressure. Subsequently, the films were characterized by ex situ mutual inductance measurements (91). The real component of inductance showed the Meissner effect with a very sharp onset at $T_c$, indicating remarkable film homogeneity and uniformity. The peak in the imaginary component of inductance, which measures the rise and fall of the ac (40 kHz) conductance, was an order of magnitude sharper than the resistive transition because superconducting fluctuations and vortex flow broaden the latter.

We have verified by high-resolution X-ray diffraction measurements that our LSCO films are almost perfectly tetragonal. The
films are very thin (20 nm thick) and epitaxially anchored to the tetragonal LSAO substrates, so the orthorhombic distortions are suppressed compared with the bulk samples of the same composition.

To study the angular dependence of longitudinal and transverse resistivity, we patterned the films into devices for transport measurements, using a well-established lithographic process that includes dry etching by ion bombardment. A 500-nm-thick layer of gold was deposited on the contact pads, ensuring low-resistance Ohmic contacts. A “sun-beam” lithography pattern shown in Fig. 1A consists of 36 current-carrying Hall bars, with the angle $\phi_0 = 10^\circ$ between every two consecutive bars. The strips are 100-μm wide, and the voltage contacts spaced 300 μm apart. This pattern enables us to determine the dependence of $\rho$ and $\rho_T$ on the azimuthal angle $\phi$, measured from the [100] crystallographic directions of LSAO and LSCO, with $\pm 5^\circ$ resolution.

Transport measurements were made using two experimental setups, based on Helium-4 and Helium-3, reaching temperatures down to $T = 4.2$ K and $T = 0.3$ K, respectively. The sample is placed in a He exchange gas in both setups, ensuring the temperature stability is better than $\pm 1$ mK. The He-3 setup is equipped with a superconducting solenoid magnet capable of reaching the dc field of 9 T. The measurements were made with the magnetic field perpendicular to the film surface.

By extensive experimentation that encompassed several thousand devices, we ruled out all extrinsic factors; and indicate that the observed behavior is intrinsic to LSCO (11, 92).

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Supplementary material
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Data availability
All data are included in the manuscript and/or supporting information.

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