

CONDENSED MATTER PHYSICS

Vortex phase diagram and the normal state of cuprates with charge and spin orders

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The phase diagram of underdoped cuprates in a magnetic field (H) is key to understanding the anomalous normal state of these high-temperature superconductors. However, the upper critical field (H_{c2}), the extent of superconducting (SC) phase with vortices, and the role of charge orders at high H remain controversial. Here we study stripe-ordered La-214, i.e., cuprates in which charge orders are most pronounced and zero-field SC transition temperatures T_c^0 are lowest. This enables us to explore the vortex phases in a previously inaccessible energy scale window. By combining linear and nonlinear transport techniques sensitive to vortex matter, we determine the $T - H$ phase diagram, directly detect H_{c2} , and reveal novel properties of the high-field ground state. Our results demonstrate that quantum fluctuations and disorder play a key role as $T \rightarrow 0$, while the high-field ground state is likely a metal, not an insulator, due to the presence of stripes.

INTRODUCTION

Cuprates are type II superconductors (1): Above the lower critical field H_{c1} , an external perpendicular magnetic field penetrates the material in the form of a solid lattice of vortices or quantized magnetic flux lines. Because this vortex lattice is set in motion by the application of a current, the pinning of vortices by disorder ensures the zero-resistivity property of a superconductor below $T_c(H)$. The disorder also turns the vortex lattice into a Bragg glass (1), i.e., a state that “looks” nearly as ordered as a perfect solid but with many metastable states and the dynamics of a glass. This phase melts into a vortex liquid (VL) when the temperature is high enough or into an amorphous vortex glass (VG) for strong enough disorder. The latter transition, in particular, can occur at low T as a function of H , which increases the density of vortices and the relative importance of disorder (1). In two-dimensional (2D) systems, the VG freezes at $T_g = 0$, and thus, the VG has zero resistivity only at $T_c = 0$; signatures of a glassy, viscous VL, however, can be observed at low enough T , i.e., above T_g . In general, the VL persists up to the crossover line $H_{c2}(T)$, i.e., up to the upper critical field $H_{c2} \equiv H_{c2}(T = 0)$ where the superconducting (SC) gap closes. Hence, the disorder suppresses the quantum melting field of the vortex lattice to be lower than H_{c2} . Because the presence of disorder plays a crucial role in the vortex physics and leads to glassy dynamics, a method of choice for probing the energy landscape of these systems is the response to a small external force. In particular, the key signatures of a Bragg glass and a glassy VL are nonlinear voltage-current ($V - I$) characteristics at low excitation currents: For $T < T_c(H)$, a vortex lattice or a Bragg glass has zero resistivity in the $I \rightarrow 0$ limit and a finite critical current; in contrast, the $I \rightarrow 0$ (i.e., linear) resistivity of a glassy VL is nonzero at all $T > 0$, but its $V - I$ remains non-ohmic for $I \neq 0$. At high enough T , the effects of disorder are no longer important, and the $V - I$ of a (nonglassy) VL becomes ohmic. Although the vortex matter in

cuprates has been extensively studied (1), the regime of high H and low T , in which disorder and quantum effects are expected to dominate, has remained largely unexplored; in particular, there have been no $V - I$ measurements. However, it is precisely this regime that is relevant for the determination of H_{c2} .

In cuprates, which have a quasi-2D nature, the value of H_{c2} continues to be of great interest because the strength of pairing correlations is an essential ingredient in understanding what controls the value of T_c^0 , the nature of the pairing mechanism, and the pseudogap regime (2). However, the interpretation of experimental data has been controversial and contradictory [(3–6) and references therein]. At least a part of the controversy lies in a disagreement on whether the VL regime vanishes (3) or persists (4) at $T = 0$, although it has been shown that the VL may survive up to surprisingly high fields (4, 7) at $T \ll T_c^0$. For example, in highly underdoped $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ (LSCO), in which charge order is at best very weak (8), the vortex phase diagram was proposed on the basis of the evidence (7) for quantum criticality of the linear resistivity associated with $T = 0$ transitions from the vortex lattice to VG and then from the VG to insulator, i.e., a 2D superconductor-insulator transition (SIT) (9), at higher H . Charge orders, however, are ubiquitous in all hole-doped cuprates in a range of dopings centered near $x = 1/8$, and their interplay with superconductivity at high H is one of the key open questions (10). To explore the possible effects of charge order on the phases of vortex matter and the nature of the normal state, we study the in-plane resistivity (ρ_{ab}) of other underdoped cuprates from the La-214 family because, at $H = 0$, they exhibit short-range charge orders with strongest correlations. Furthermore, they do not have the complication present in $\text{YBa}_2\text{Cu}_3\text{O}_{6+x}$ (YBCO), in which an additional, longer-range charge order emerges at high H (10). We also use nonlinear ($V - I$) transport as a direct probe of vortex matter. The measurements extend over an unusually large, more than three orders of magnitude wide range of T down to $T/T_c^0 \lesssim 0.003$ (Materials and Methods).

We focus on $\text{La}_{1.8-x}\text{Eu}_{0.2}\text{Sr}_x\text{CuO}_4$ (LESCO) and $\text{La}_{1.6-x}\text{Nd}_{0.4}\text{Sr}_x\text{CuO}_4$ (LNSCO), in which charge order coexists with the antiferromagnetic spin density wave order (2) at $T < T_{SO} < T_{CO}$; here, T_{SO} and T_{CO} are the onsets of static, short-range spin and charge orders or “stripes,” respectively, and $T_c^0(x)$ is suppressed for doping near $x = 1/8$ (Fig. 1, A and B). The low values of T_c^0 in this regime

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allow us to reveal and probe deep into the normal state by applying H up to 35 T, because we find $H_{c2} \sim 20$ T in LESCO with $x = 0.10$ and $H_{c2} \sim 25$ T in LNSCO with $x = 0.12$, as shown below. Fields perpendicular to CuO_2 planes, i.e., along the c axis, enhance both spin (11, 12) and charge orders (13, 14). These effects are observed only below T_c^0 and in samples away from $x = 1/8$, such as $x \sim 0.10$, where the stripe order is weaker. The emergence and enhancement of the charge order by H below T_c^0 , accompanying the suppression of high-temperature superconductivity, have been observed (15) also in YBCO. While there is no evidence of coincident static spin order in YBCO (2), it has been argued (16) that the charge order in YBCO is similar to that in La-based cuprates and, in fact, that charge density wave modulations persist in the $T = 0$ field-induced normal state in underdoped YBCO and in Hg- and La-based cuprates (16). Thus, the stripe order in LESCO and LNSCO is expected to persist even after $T_c(H)$ is suppressed to zero.

We find that the vortex phase diagrams of La-214 underdoped cuprates are qualitatively the same regardless of the presence or strength of the charge orders: As $T \rightarrow 0$, the vortex lattice is separated from the high-field ground state by a wide range of fields where quantum phase fluctuations and disorder (i.e., a viscous VL) domi-

nate. On general grounds, the same conclusions should apply also to other cuprates below optimum doping. By establishing the $T-H$ phase diagram over an unprecedented range of parameters and demonstrating that measurements, such as nonlinear transport, are needed down to $T \ll T_c^0$ to determine H_{c2} , our work also resolves the lasting controversy in the cuprate research. Furthermore, we reveal novel properties of the high-field normal (non-SC) state in the presence of stripes: The insulating-like $\ln(1/T)$ dependence of the in-plane resistivity, the origin of which has been a long-standing puzzle, is suppressed by H , suggesting a metallic high-field ground state. This is in contrast to the early work (17) in the absence of static stripes, where H does not seem to affect the $\ln(1/T)$ behavior, and the high-field ground state is an insulator.

RESULTS

In-plane resistivity of LESCO and LNSCO

Our samples were single crystals with the nominal composition $\text{La}_{1.7}\text{Eu}_{0.2}\text{Sr}_{0.1}\text{CuO}_4$ and $\text{La}_{1.48}\text{Nd}_{0.4}\text{Sr}_{0.12}\text{CuO}_4$ (Materials and Methods). T_c^0 was defined as the temperature at which the linear resistance $R_{ab} \equiv \lim_{I_{dc} \rightarrow 0} V/I$ (i.e., ρ_{ab}) becomes zero. For $\text{La}_{1.7}\text{Eu}_{0.2}\text{Sr}_{0.1}\text{CuO}_4$,

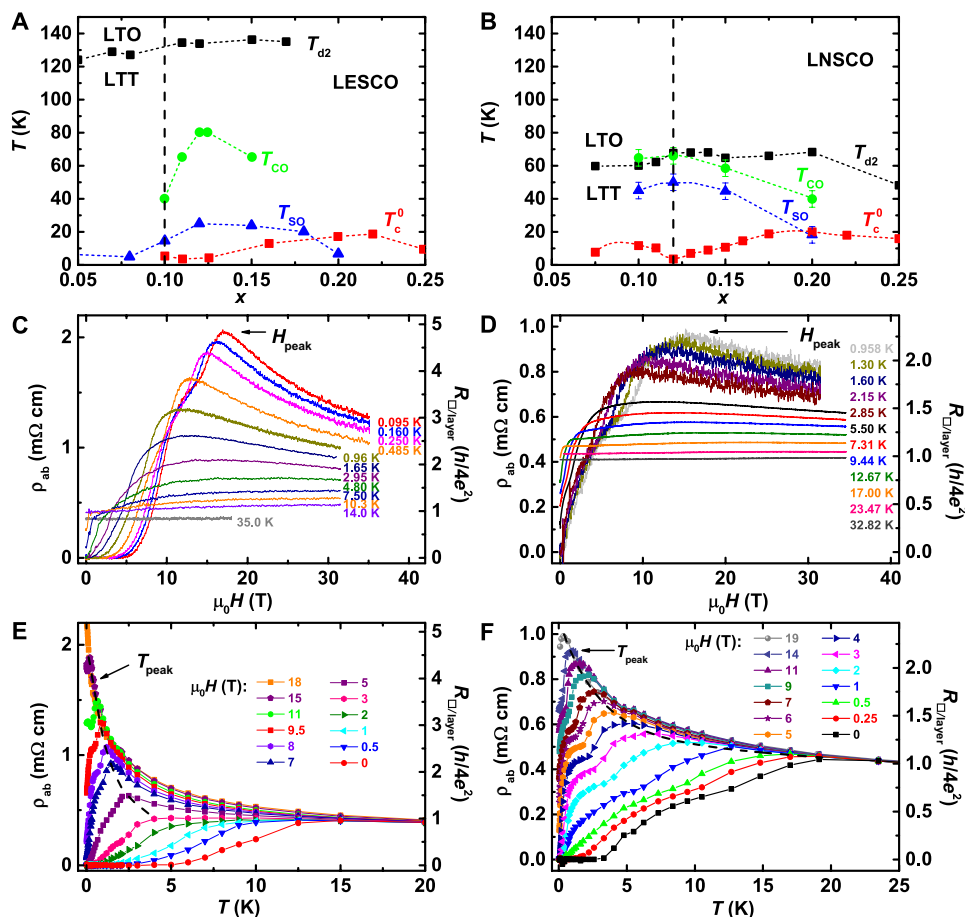


Fig. 1. In-plane transport properties of striped cuprates. (A and B) $T-x$ phase diagrams of LESCO and LNSCO, respectively, for $H = 0$; T_c^0 is the SC transition temperature, and T_{d2} is the transition temperature from the low-temperature orthorhombic (LTO) to a low-temperature tetragonal (LTT) structure. T_{CO} and T_{SO} are the onset temperatures for charge and spin orders, respectively. Dashed lines guide the eye. Vertical dashed lines show the doping of our single crystals. The data in (A) are reproduced from (59) and references therein, and those in (B) from (55, 59, 60) and references therein. (C and D) $\rho_{ab}(H)$ of $\text{La}_{1.7}\text{Eu}_{0.2}\text{Sr}_{0.1}\text{CuO}_4$ and $\text{La}_{1.48}\text{Nd}_{0.4}\text{Sr}_{0.12}\text{CuO}_4$, respectively, for several T . At low T , $\rho_{ab}(H)$ exhibits a strong peak at $H = H_{\text{peak}}(T)$. The right axes show the corresponding $R_{\square/\text{layer}}$ in units of quantum resistance for Cooper pairs, $R_Q = h/(2e)^2$. (E and F) $\rho_{ab}(T)$ of $\text{La}_{1.7}\text{Eu}_{0.2}\text{Sr}_{0.1}\text{CuO}_4$ and $\text{La}_{1.48}\text{Nd}_{0.4}\text{Sr}_{0.12}\text{CuO}_4$, respectively, for several $H \leq 19$ T. Solid lines guide the eye. The black dashed lines track the values of $T_{\text{peak}}(H)$.

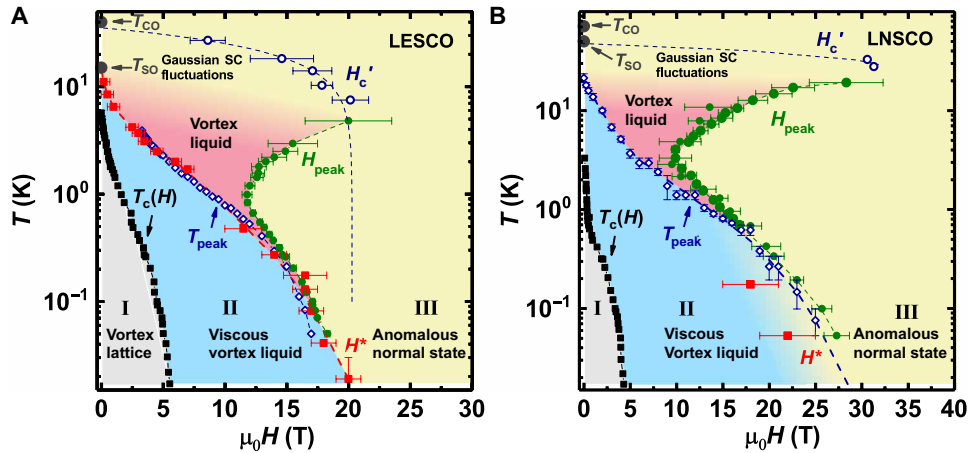


Fig. 2. In-plane transport T - H phase diagram of striped cuprates with $H \parallel c$ axis. (A) $\text{La}_{1.7}\text{Eu}_{0.2}\text{Sr}_{0.1}\text{CuO}_4$. (B) $\text{La}_{1.48}\text{Nd}_{0.4}\text{Sr}_{0.12}\text{CuO}_4$. $T_c(H)$ (black squares) mark the boundary of the pinned vortex lattice, which is a superconductor with $\rho_{\text{ab}} = 0$ for all $T < T_c(H)$ [region I; $T_c(H) > 0$]. $H^*(T)$ symbols mark the boundary of the viscous VL, in which dV/dI is non-ohmic [for $H < H^*(T)$] and freezes into a VG at $T = T_c = 0$. Dashed red line guides the eye. Ohmic behavior is found at $H > H^*(T)$. $H^*(T = 0)$ thus corresponds to the upper critical field H_{c2} . $H_{\text{peak}}(T)$ (green dots) represent fields above which the MR changes from positive to negative. The region $H^* < H < H_{\text{peak}}$, in which the MR is positive but transport is ohmic, is identified as the VL. $T_{\text{peak}}(H)$ (open blue diamonds) tracks the positions of the peak in $\rho_{\text{ab}}(T)$. $H'_c(T)$ is the field above which SC fluctuations are not observed. Gaussian fluctuations of the SC amplitude and phase are expected at the highest T and $H < H'_c(T)$. The highest field region (III) corresponds to the H -induced normal state. The dashed line in (A) is a fit with $\mu_0 H'_c [T] = 20.3 [1 - (T[K]/35.4)^2]$, and the error bars indicate the uncertainty in H'_c that corresponds to 1 SD in the slopes of the linear fits in fig. S5. In (B), SC fluctuations vanish between 33 and 48 K for $H = 0$, and the dashed line is a guide to the eye. Zero-field values of T_{SO} and T_{CO} are also shown; both spin and charge stripes are known to be enhanced by H (see the main text). Except for $T_c(H)$, lines do not represent phase boundaries but finite-temperature crossovers.

$T_c^0 = (5.7 \pm 0.3)$ K, $T_{\text{SO}} \sim 15$ K, $T_{\text{CO}} \sim 40$ K (Fig. 1A), and the pseudogap temperature $T_{\text{pseudogap}} \sim 175$ K (5). For $\text{La}_{1.48}\text{Nd}_{0.4}\text{Sr}_{0.12}\text{CuO}_4$, $T_c^0 = (3.6 \pm 0.4)$ K, $T_{\text{SO}} \sim 50$ K, $T_{\text{CO}} \sim 70$ K (Fig. 1B), and $T_{\text{pseudogap}} \sim 150$ K (5).

Figure 1 (C and D) shows the in-plane magnetoresistance (MR) measurements at fixed T for $\text{La}_{1.7}\text{Eu}_{0.2}\text{Sr}_{0.1}\text{CuO}_4$ and $\text{La}_{1.48}\text{Nd}_{0.4}\text{Sr}_{0.12}\text{CuO}_4$, respectively. The positive MR, indicative of the suppression of superconductivity, appears below ~ 35 to 40 K. However, as T decreases further, a negative MR develops at the highest fields, resulting in a peak in $\rho_{\text{ab}}(H)$ at $H = H_{\text{peak}}(T)$ for $T < T_c^0$. In cuprates, only positive MR has been discussed so far, with the exception of a broad MR maximum (17) in underdoped LSCO. Its similarities to that in 2D films of conventional superconductors near a field-tuned SIT have led to the suggestion (18) that, in both cases, H_{peak} represents the field scale above which the SC gap, a measure of the pairing strength between electrons that form Cooper pairs, vanishes.

Figure 1E shows the $\rho_{\text{ab}}(T)$ curves for LESCO extracted from the MR measurements for $H \leq 18$ T (i.e., Fig. 1F for LNSCO up to $H \leq 19$ T); the MR data at higher H are discussed further below. When the normal state sheet resistance, $R_{\square/\text{layer}}$, is close to the quantum resistance for Cooper pairs, $R_Q = h/(2e)^2$, which occurs for $T \approx 15$ K, the $\rho_{\text{ab}}(T)$ curves start to separate from each other: Lower $H\rho_{\text{ab}}(T)$ curves exhibit a metallic-like drop associated with superconductivity, while higher H curves show a tendency toward insulating behavior. This is also remarkably reminiscent of the behavior of 2D films of many materials at $T = 0$ SIT (19), where the critical resistance is close to R_Q . Such a transition is generally attributed to quantum fluctuations of the SC phase and, hence, loss of phase coherence; cooper pairs that form the SC condensate thus survive the transition to the insulator. Although underdoped cuprates are highly anisotropic, layered materials, and thus behave effectively as 2D systems (7, 20, 21), these similarities between bulk systems, LESCO and LNSCO, and 2D films are striking: It took only specially engineered,

double-layer transistors to observe (22) the critical resistance of R_Q for the $H = 0$ electric field-driven SIT in LESCO. These similarities thus suggest the importance of phase fluctuations in LESCO and LNSCO at low T . Figure 1 (E and F) shows that the increase of H leads to the suppression of $T_c(H)$ and, just like in highly underdoped LSCO (7), to a peak in $\rho_{\text{ab}}(T)$ that shifts to lower $T = T_{\text{peak}}(H)$. In LSCO, $T_{\text{peak}}(H)$ was attributed (7) to the onset of the viscous VL regime. The values of $T_c(H)$ (see also fig. S1), $H_{\text{peak}}(T)$, and $T_{\text{peak}}(H)$ are shown in Fig. 2 over a wide range of T and H for both materials.

The quantum melting of the vortex lattice, in which $\rho_{\text{ab}} = 0$ as the vortices are pinned by disorder (1), occurs when $T_c(H) \rightarrow 0$, e.g., for ~ 5.5 T in LESCO (Fig. 2A). On general grounds, in type II superconductors, the vortex lattice melts into a VL or glass, i.e., a regime of strong phase fluctuations. At the lowest T in the intermediate H regime, the data are described best with the power-law fits $\rho_{\text{ab}}(H, T) = \rho_0(H)T^{\alpha(H)}$ in both materials (fig. S2), suggesting a true SC state ($\rho_{\text{ab}} = 0$) only at $T = 0$ when the vortices are frozen. This finding is similar to that in highly underdoped LSCO ($x = 0.06, 0.07$) and consistent with the expectations for a viscous VL above its glass freezing temperature $T_g = 0$ [(7) and references therein]. Here, we also use nonlinear transport measurements to directly probe the vortex matter.

Nonlinear transport and SC correlations

The second technique, therefore, involves measurements of $V - I$ characteristics at fixed H and T (Materials and Methods), in addition to the linear resistance R_{ab} discussed above. When $T < T_c$, dV/dI is zero, as expected in a superconductor (Fig. 3A), because small values of I_{dc} are not able to cause the depinning of the vortex lattice. However, at higher H , where T_c is suppressed to zero, a zero-resistance state is not observed even at $I_{\text{dc}} = 0$ (Fig. 3A), down to the lowest T (Fig. 3B), but the $V - I$ characteristic remains non-ohmic and dV/dI increases with I_{dc} . This type of behavior is expected

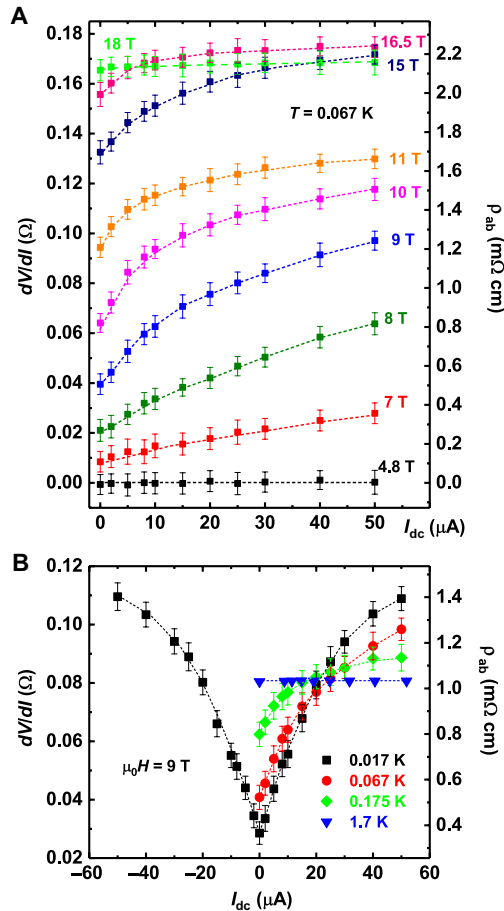


Fig. 3. Nonlinear in-plane transport in $\text{La}_{1.7}\text{Eu}_{0.2}\text{Sr}_{0.1}\text{CuO}_4$. (A) Differential resistance dV/dI as a function of dc current I_{dc} for several $H \leq 18$ T at $T = 0.067$ K. In the bottom trace, for which $T < T_c(H = 4.8 \text{ T}) \approx 0.08$ K, dV/dI is zero as expected in a superconductor. (B) dV/dI versus I_{dc} for several T at $H = 9$ T. The linear resistance (dV/dI for $I_{dc} \rightarrow 0$) has a metallic-like temperature dependence, but at higher $I_{dc} > 20 \mu\text{A}$, the temperature dependence of dV/dI is insulating-like. Dashed lines guide the eye.

from the motion of vortices in the presence of disorder, i.e., it is a signature of a glassy, viscous VL (1). At higher H and T , the non-ohmic response vanishes (Fig. 3).

A comprehensive study of nonlinear transport (see, e.g., fig. S3) over the entire range of T and H was performed on $\text{La}_{1.7}\text{Eu}_{0.2}\text{Sr}_{0.1}\text{CuO}_4$. The non-ohmic behavior was established for all $H < H^*(T)$ and ohmic behavior for $H > H^*(T)$ in Fig. 2A; as $T \rightarrow 0$, H^* extrapolates to ~ 20 T. We note the quantitative agreement between $H^*(T)$, the boundary of the viscous VL obtained from nonlinear transport, with the values of $T_{\text{peak}}(H)$ obtained from the linear resistivity measurements. Thus, $T_{\text{peak}}(H)$ can be used to identify the extent of the viscous VL. Moreover, at $T < 0.4$ K, both $H^*(T)$ and $T_{\text{peak}}(H)$ agree, within the error, with $H_{\text{peak}}(T)$, suggesting that, for $T \ll T_c^0$, H_{peak} may be interpreted as the field scale corresponding to the closing of the SC gap (18). In $\text{La}_{1.48}\text{Nd}_{0.4}\text{Sr}_{0.12}\text{CuO}_4$, $T_{\text{peak}}(H)$ and $H_{\text{peak}}(T)$ are also found to be the same, within the error, at low enough $T < 0.7$ K (Fig. 2B); $V - I$ measurements at low T (fig. S4) confirm that transport remains non-ohmic, for example, up to $H^* = (22 \pm 3)$ T at $T \sim$

0.05 K, comparable to $H_{\text{peak}}(T \sim 0.05 \text{ K}) \sim 27$ T, and well beyond the quantum melting field of the vortex lattice (~ 4 T).

The extent of SC fluctuations observed in linear transport was determined from the positive MR at high T (Fig. 1, C and D) as the field $H'_c(T)$ above which the MR increases as H^2 (fig. S5), as expected in the high- T normal state. As in other studies on cuprates [e.g., (7, 21, 23, 24)], the result can be fitted with $H'_c = H'_0[1 - (T/T_2)^2]$ (Fig. 2A). As $T \rightarrow 0$, both H'_c and H^* extrapolate to ~ 20 T in $\text{La}_{1.7}\text{Eu}_{0.2}\text{Sr}_{0.1}\text{CuO}_4$, consistent with $H^*(T = 0)$ being the depairing field, i.e., H_{c2} . Region III in Fig. 2 ($H > H^*$, H'_c) then corresponds to the H -induced normal state. Similar, albeit fewer, measurements of H'_c in $\text{La}_{1.48}\text{Nd}_{0.4}\text{Sr}_{0.12}\text{CuO}_4$ (Fig. 2B) are consistent with this picture.

High-field normal state

The highest field $\rho_{ab}(T)$ data are shown in Fig. 4. In $\text{La}_{1.7}\text{Eu}_{0.2}\text{Sr}_{0.1}\text{CuO}_4$, $\rho_{ab} \propto \ln(1/T)$ is observed in this regime over a temperature range of one and a half decades, without any sign of saturation down to at least ~ 0.07 K or $T/T_c^0 \sim 10^{-2}$ (Fig. 4A). The $\ln(1/T)$ behavior was first reported (17) in underdoped LSCO; it was not dependent on H , and its origin is still not well understood (7). Nevertheless, experiments suggest that the high- H normal state in underdoped LSCO is an insulator (7, 17, 25). In contrast, a clear weakening of the insulating-like $\ln(1/T)$ behavior with H is observed in $\text{La}_{1.7}\text{Eu}_{0.2}\text{Sr}_{0.1}\text{CuO}_4$ (Fig. 4A), strongly suggesting that ρ_{ab} becomes independent of T , i.e., metallic, at much higher fields of ≥ 55 T (Fig. 4A, inset).

Similar $\rho_{ab} \propto \ln(1/T)$ behavior is found in $\text{La}_{1.48}\text{Nd}_{0.4}\text{Sr}_{0.12}\text{CuO}_4$ (Fig. 4B), in agreement with earlier experiments (26) performed up to 15 T and down to 1.5 K. However, while that work reported (26) that ρ_{ab} became independent of the field strength for $H \geq 11$ T, lower T and higher H have allowed us to reveal the weakening of the $\ln(1/T)$ behavior by H also in $\text{La}_{1.48}\text{Nd}_{0.4}\text{Sr}_{0.12}\text{CuO}_4$ (Fig. 4B). The apparent saturation at low T is attributed to the presence of $T_{\text{peak}}(H)$, which moves to lower T with increasing H . The onset of metallic behavior is anticipated at ~ 70 T (Fig. 4B, inset). The results thus strongly suggest that the high-field ground state of striped cuprates is a metal.

We note that the possibility that SC fluctuations persist in the $H > H^*$ regime (e.g., beyond $H^* \sim 20$ T as $T \rightarrow 0$ in $\text{La}_{1.7}\text{Eu}_{0.2}\text{Sr}_{0.1}\text{CuO}_4$) cannot be completely ruled out based on these measurements, as $H'_c(T)$ may acquire a “tail” at low T such that the fitted $H'_0 < H'_c(T = 0)$ (7). However, magnetotransport studies that also use parallel magnetic fields do confirm the absence of any observable remnants of superconductivity for $H > H^*(T \rightarrow 0)$; those results will be presented elsewhere. In any case, it would be interesting to perform additional studies of this peculiar high-field normal state that is characterized by the $\ln(1/T)$ temperature dependence and the negative MR, as well as to extend the measurements to $H > 55$ T to probe the properties of the anticipated high-field metal phase.

Vortex phase diagram

Figure 2 shows that, in $H = 0$, phase fluctuations become dominant at $T \lesssim 15$ K $\sim (2$ to $3) T_c^0$ in $\text{La}_{1.7}\text{Eu}_{0.2}\text{Sr}_{0.1}\text{CuO}_4$ and at $T \lesssim 20$ K $\sim 6 T_c^0$ in $\text{La}_{1.48}\text{Nd}_{0.4}\text{Sr}_{0.12}\text{CuO}_4$, i.e., about an order of magnitude below $T_{\text{pseudogap}}$. Gaussian fluctuations of amplitude and phase become observable below ~ 35 K in $\text{La}_{1.7}\text{Eu}_{0.2}\text{Sr}_{0.1}\text{CuO}_4$, i.e., $\sim (33$ to $48)$ K in $\text{La}_{1.48}\text{Nd}_{0.4}\text{Sr}_{0.12}\text{CuO}_4$ as in previous work (26). Therefore, we find no evidence for pairing at temperatures comparable to $T_{\text{pseudogap}}$, similar to the conclusions of other recent studies (5, 21). Measurements

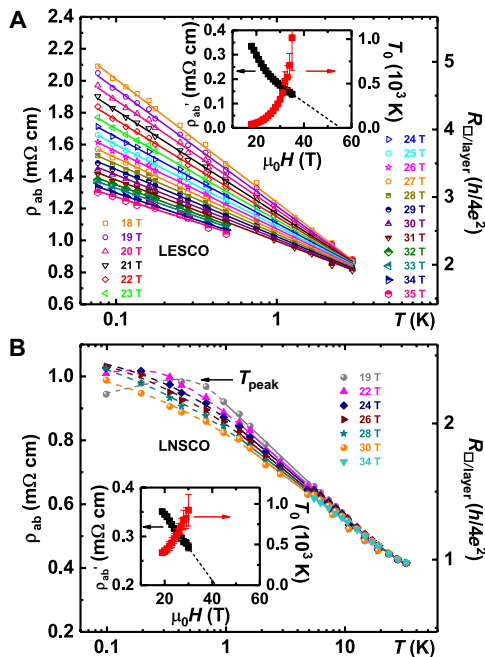


Fig. 4. Temperature dependence of the in-plane resistivity ρ_{ab} at the highest H , i.e., in the normal state. (A) $\text{La}_{1.7}\text{Eu}_{0.2}\text{Sr}_{0.1}\text{CuO}_4$. (B) $\text{La}_{1.48}\text{Nd}_{0.4}\text{Sr}_{0.12}\text{CuO}_4$. Solid lines are fits to $\rho_{ab} = \rho'_{ab}(H) \ln(T_0(H)/T)$, and dashed lines guide the eye. The arrow in (B) shows $T_{\text{peak}}(H=19\text{ T})$. Insets: Fitting parameters $\rho'_{ab}(H)$ and $T_0(H)$. The decrease of the slopes ρ'_{ab} (black squares) with H indicates the weakening of the insulating-like $\ln(1/T)$ dependence with H . The linear extrapolation of ρ'_{ab} to zero (dashed line) provides a rough estimate of the field $\sim 55\text{ T}$ in $\text{La}_{1.7}\text{Eu}_{0.2}\text{Sr}_{0.1}\text{CuO}_4$, i.e., $\sim 71\text{ T}$ in $\text{La}_{1.48}\text{Nd}_{0.4}\text{Sr}_{0.12}\text{CuO}_4$, where insulating-like behavior vanishes.

at relatively high $T < T_c$ suggest low values of H^* needed to close the gap (Fig. 2), consistent with some reports (5, 27) of low values of H_{c2} . For example, it was reported (27) that $H_{c2} \sim 8\text{ T}$ on $\text{La}_{1.7}\text{Eu}_{0.2}\text{Sr}_{0.1}\text{CuO}_4$ with a similar T_c^0 , but those experiments were performed at fairly high T (see fig. S6). Figure 2A shows that $H^* \sim 8\text{ T}$ at a comparably high $T \sim 1\text{ K}$. By extrapolating to $T \rightarrow 0$ in different cuprate families, it was then argued (3) that there is no VL at $T = 0$. However, as our study demonstrates, it is only by systematically tracking the evolution of SC correlations with H and T down to $T/T_c^0 \ll 1$ that reliable $T \rightarrow 0$ extrapolations can be made. Figure 2 shows that the regime of viscous VL broadens markedly as T is reduced. The VL thus survives up to fields $H_{c2} = H^* \sim 20\text{ T}$ in $\text{La}_{1.7}\text{Eu}_{0.2}\text{Sr}_{0.1}\text{CuO}_4$ ($\sim 25\text{ T}$ in $\text{La}_{1.48}\text{Nd}_{0.4}\text{Sr}_{0.12}\text{CuO}_4$) as $T \rightarrow 0$, i.e., well beyond the quantum melting field of the vortex lattice ($H_m \sim 5.5\text{ T}$ and $H_m \sim 4\text{ T}$, respectively, for $\text{La}_{1.7}\text{Eu}_{0.2}\text{Sr}_{0.1}\text{CuO}_4$ and $\text{La}_{1.48}\text{Nd}_{0.4}\text{Sr}_{0.12}\text{CuO}_4$). The relatively high values of H_{c2} are consistent with the $H = 0$ opening of the SC gap at T several times higher than T_c^0 (albeit $\ll T_{\text{pseudogap}}$).

The existence of a broad phase fluctuation regime in $H = 0$ can be attributed to several factors. The first one is the effective 2D nature of the materials, which leads to the Berezinskii-Kosterlitz-Thouless transition and broadening of $\rho_{ab}(T)$ close to T_c^0 (21). The second one is the presence of stripes, i.e., the intrinsic nanoscale phase separation or intrinsic electronic inhomogeneity, which can result from competing interactions even in the absence of disorder (28, 29): The presence of stripes in cuprates has been suggested to lead to an intrinsically granular SC state (30). In contrast to highly underdoped LSCO (7), the $\rho_{ab}(T)$ curves of striped LESCO

and LNSCO exhibit a two-step development of superconductivity (Fig. 1F and figs. S1, S2, and S7B) similar to novel hybrid structures with engineered nanoscale phase separation [e.g., (31–33)], granular films of conventional superconductors (19, 34), relatively clean heavy fermion (35), iron-based superconductors (36) in the presence of competing orders, and some novel 2D materials (37). Last, even homogeneous disorder may lead to the inhomogeneity of the pairing amplitude (38) on the scale of the coherence length, forming SC islands weakly coupled by the Josephson effect; although inhomogeneous, the pairing amplitude is finite throughout the system, and the SC transition occurs at T_c^0 because of the loss of phase coherence. Spatially inhomogeneous pairing gaps persisting above T_c^0 have been observed in cuprates, such as $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ [e.g., (39)], and in films of conventional superconductors (40), including on both sides of the SIT (41).

In films with weak and homogeneous disorder, the application of H itself can lead to the emergent granularity of the SC state (42). Generally speaking, because increasing H increases the effective disorder (1), as $T \rightarrow 0$, it also leads to the suppression of $T_c(H)$, i.e., the suppression of the ordered vortex lattice phase (region I in Fig. 2) to fields below H_{c2} . This results in an intermediate regime characterized by large quantum phase fluctuations, i.e., a viscous VL in Fig. 2, which extends up to H_{c2} . Therefore, consistent with general expectations (1, 34), $H^*(T \rightarrow 0) = H_{c2}$ in Fig. 2 corresponds to the upper critical field of the clean system, i.e., in the absence of disorder.

Our results (Fig. 2) indicate that, in analogy to 2D SC films near the H -tuned SIT (19, 34), the MR peak in LESCO and LNSCO allows access to both bosonic (positive MR) and fermionic (negative MR) regimes. While $H_{\text{peak}}(T)$ tracks $H^*(T)$ and $T_{\text{peak}}(H)$ at low temperatures, there is a clear bifurcation at higher T . This results in the $H^*(T) < H < H_{\text{peak}}(T)$ bosonic regime in which, in contrast to the viscous VL, the transport is ohmic. Therefore, we identify this regime as the (ohmic) VL. This is consistent with the finding, based on other types of probes, that a line similar to $T_{\text{peak}}(H)$ separates the VL from the viscous VL in the high-temperature ($T < T_c^0$), low- H regime of several cuprate families (1). It is still an open question whether that line represents a true second-order glass transition or just a crossover energy scale. The nonmonotonic behavior of $H_{\text{peak}}(T)$ observed at low T , however, is a new and unexpected finding. It suggests that, for certain H , the system can pass from a regime dominated by SC phase fluctuations (i.e., a VL) to a normal, albeit very unusual, state and then again to a phase fluctuations dominated regime (i.e., a viscous VL) as T is lowered. Although the understanding of this intriguing behavior is beyond the scope of this study, we note its strong resemblance to the solid-liquid melting line in the T -pressure phase diagram of He^3 that was predicted by Pomeranchuk, thus strongly suggesting that the striped normal state (the “solid”) carries a higher entropy than the viscous VL.

DISCUSSION

Our key results are summarized in the T - H phase diagrams (Fig. 2) of striped LESCO and LNSCO, which have been mapped out over more than three orders of magnitude of T and deep into the H -induced normal state using two different complementary techniques that are sensitive to global phase coherence. In particular, by relying only on transport techniques, we have been able to obtain a self-consistent set of data points and achieve quantitative agreement of

our results, allowing us to compare different energy scales. Furthermore, by using cuprates with a very low T_c^0 , we have been able to access a much larger energy scale window to explore the vortex phases compared to previous studies. Figure S6 shows that our measurements extend to effectively much lower T and higher H compared to previous studies of H_{c2} on these and other underdoped cuprates. For example, our lowest T/T_c^0 is an order of magnitude lower than that in the study of YBCO in a similar part of the T - x phase diagram (3). This has allowed us to probe the previously inaccessible regimes, including deep into the normal state. We have revealed that the unusual, insulating-like behavior [$\rho_{ab} \propto \ln(1/T)$] of the normal state is suppressed by even higher H , leading to a metallic high-field ground state in striped cuprates.

Our findings have important implications for other cuprates, especially YBCO, which is considered the cleanest cuprate, but, just like any other real material, it does contain some disorder (6, 43). Even if the disorder is weak, its effects will be amplified at low T with increasing H , leading to the quantum melting of the vortex lattice into a VL below H_{c2} . Therefore, probes sensitive to vortex matter, used over a wide range of T and H , and studying the response of the system to a small external force, are needed to determine H_{c2} . For transport measurements, for example, Fig. 3 demonstrates that, due to the intrinsically nonlinear nature of the V - I characteristics of the vortex matter, using high excitations I_{dc} would yield much higher measured values of ρ_{ab} and even change the sign of its temperature dependence (Fig. 3B). As a result, the observation of $T_{peak}(H)$ and the identification of the viscous VL regime would not be possible. In YBCO, low- T magnetization measurements have reported (4) the melting of the vortex lattice into a “second vortex solid” with a much weaker shear modulus, somewhat reminiscent of the viscous VL regime in Fig. 2, but H_{c2} was not reached with the accessible fields. Conflicting MR results, i.e., both a positive MR only (44) and a peak (45), have been reported for the same material and doping, leaving the question of H_{c2} in YBCO open. A quantitative comparison of the typical current densities ($\sim 10^{-3}$ A/cm²) used to measure linear ρ_{ab} in our study (Materials and Methods) to those used in the studies of H_{c2} in YBCO [e.g., (3)] is difficult, because the latter information is missing. However, the related literature (46) suggests current excitations of ~ 1 mA and the corresponding current densities of >1 A/cm² in YBCO. In any case, nonlinear transport studies at low excitations of YBCO with a very low T_c^0 , comparable to that in our striped LESCO and LNSCO crystals or in highly underdoped LSCO (7), are needed to identify the vortex phases, determine H_{c2} , and probe the normal state.

A comparison of spectroscopic data on a variety of hole-doped cuprates, in which the La-214 family was not considered, has established (47) that the SC gap $\sim 5 k_B T_c^0$ with the value of ~ 40 meV at optimal doping. This suggests inaccessibly high H_{c2} (~ 100 T), although this same relationship yields an order of magnitude lower gap of ~ 2 to 3 meV for $T_c^0 \approx 4$ to 6 K that are comparable to those in our LESCO and LNSCO crystals. Similarly, in the La-214 family at optimal doping, where $T_c^0 \sim 40$ K, it was found (48–50) that the SC energy scales ~ 20 meV. It is thus reasonable to expect an SC gap of ~ 2 meV when $T_c^0 \approx 4$ to 6 K, i.e., of the same order as H_{c2} found in our study.

In $\text{La}_{1.7}\text{Eu}_{0.2}\text{Sr}_{0.1}\text{CuO}_4$ and $\text{La}_{1.48}\text{Nd}_{0.4}\text{Sr}_{0.12}\text{CuO}_4$, which have different strengths of stripe correlations, we have qualitatively established the same vortex phase diagrams as in highly underdoped LSCO (7), in which there is no clear evidence of charge order (8).

The LSCO study (7) was performed using a different method, as described above, and on samples grown by two different techniques. Therefore, the qualitative agreement between the vortex phase diagrams obtained on three different materials confirms that our findings are robust and that the presence of different phases of vortex matter in underdoped La-214 cuprates is not very sensitive to the details of the competing charge orders. Our data also highlight the key role of disorder in understanding the $T \rightarrow 0$ behavior of underdoped cuprates and demonstrate that the SC phase with vortices persists up to much higher fields H_{c2} than those argued previously. Even in conventional superconductors, the interplay of vortex matter physics, disorder, and quantum fluctuations leads to the enhancement of H_{c2} as $T \rightarrow 0$, a long-standing puzzle in the field (51). It should thus come as no surprise that the precise values of H_{c2} may also be affected by the presence of stripes. In particular, stronger stripe correlations in $\text{La}_{1.48}\text{Nd}_{0.4}\text{Sr}_{0.12}\text{CuO}_4$ than in $\text{La}_{1.7}\text{Eu}_{0.2}\text{Sr}_{0.1}\text{CuO}_4$ seem to enhance the VL regime as $T \rightarrow 0$, but this issue is beyond the scope of this work. On the other hand, because strong stripe correlations have not altered the vortex phase diagrams, there is no reason to expect that much weaker, at least in $H = 0$, charge orders in other cuprates will qualitatively modify the vortex phase diagrams. Our results thus strongly suggest that our conclusions should apply to all underdoped cuprates, as supported by the agreement with the spectroscopic data on other cuprates, including the La-214 family. However, whether the VL regime extends out to overdoped regions of the cuprate phase diagram where the (normal state) pseudogap closes remains an open question for future study.

MATERIALS AND METHODS

Samples

Several single crystal samples of LESCO (Fig. 1A) with a nominal $x = 0.10$ and LNSCO (Fig. 1B) with a nominal $x = 0.12$ were grown by the traveling-solvent floating-zone technique (52). From the x-ray fluorescence analysis using an x-ray analytical and imaging microscope (HORIBA XGT-5100), it was confirmed that the chemical compositions were close to the nominal values within the experimental error and spatially homogeneous with the SD less than 0.003 for $a \sim 1$ mm² area mapping with ~ 10 - μm resolution. This is supported by the fact that the structural phase transition from the low-temperature orthorhombic to low-temperature tetragonal phase, which reflects the global chemical composition, was very sharp as observed in the temperature dependence of the c -axis resistivity, measured (53) on a bar-shaped $\text{La}_{1.48}\text{Nd}_{0.4}\text{Sr}_{0.12}\text{CuO}_4$ sample with dimensions of 0.24 mm \times 0.41 mm \times 1.46 mm ($a \times b \times c$) and $T_c^0 = (3.51 \pm 0.06)$ K. SQUID and torque magnetometry measurements were performed on a bar-shaped $\text{La}_{1.7}\text{Eu}_{0.2}\text{Sr}_{0.1}\text{CuO}_4$ crystal with dimensions of 1.19 mm \times 0.24 mm \times 0.78 mm ($a \times b \times c$). Detailed transport measurements were performed on two crystals, shaped as rectangular bars suitable for direct measurements of the in-plane resistance, with dimensions of 3.06 mm \times 0.53 mm \times 0.37 mm and 3.82 mm \times 1.19 mm \times 0.49 mm ($a \times b \times c$) for $\text{La}_{1.7}\text{Eu}_{0.2}\text{Sr}_{0.1}\text{CuO}_4$ and $\text{La}_{1.48}\text{Nd}_{0.4}\text{Sr}_{0.12}\text{CuO}_4$, respectively. Gold contacts were evaporated on polished crystal surfaces and annealed in air at 700°C . The current contacts were made by covering the whole area of the two opposing sides with gold to ensure uniform current flow, and the voltage contacts were made narrow to minimize the uncertainty in the absolute values of the resistance. Multiple voltage contacts on opposite sides of the crystals were prepared. The distance between

the voltage contacts for which the data are shown is 1.53 mm for LESCO and 2.00 mm for LNSCO. Gold leads ($\approx 25 \mu\text{m}$ thick) were attached to the samples using the DuPont 6838 silver paste, followed by the heat treatment at 450°C in the flow of oxygen for 15 min. The resulting contact resistances were less than 0.1Ω for LESCO (0.5Ω for LNSCO) at room temperature.

The values of T_c^0 and the behavior of the samples did not depend on which voltage contacts were used in the measurements, reflecting the absence of extrinsic (e.g., compositional) inhomogeneity in these crystals. Furthermore, both T_c^0 and the sample behavior remained astonishingly stable with time (see, e.g., fig. S1), without which it would have not been possible to conduct such an extensive and systematic study that requires matching data obtained using different cryostats and magnets (see below) over the period of 2 to 3 years during which this study was performed, thus further attesting to the high quality of the crystals. Even the value of $T_c^0 = (3.6 \pm 0.4)$ K in $\text{La}_{1.48}\text{NdSr}_{0.12}\text{CuO}_4$ indicates high sample homogeneity: First, it agrees with the value (~ 4 K) obtained (54) from magnetic susceptibility, a bulk probe, and second, it is lower than the values of T_c^0 away from this doping at which the superconductivity is most suppressed [(55) and references therein; see also Fig. 1B]. In contrast, some of the other transport studies of $\text{La}_{1.48}\text{Nd}_{0.4}\text{Sr}_{0.12}\text{CuO}_4$ have found $T_c^0 \sim 6$ K (26) and $T_c^0 \sim 7$ K (27), pointing to either a different effective doping or inhomogeneity in their samples. Likewise, $T_c^0 \approx 5.7$ K of our $\text{La}_{1.7}\text{Eu}_{0.2}\text{Sr}_{0.1}\text{CuO}_4$ crystal agrees with the bulk susceptibility measurements (fig. S7A), while its high- T resistivity (fig. S7B) is about five times, i.e., significantly lower than in some studies (27) of the same material. Similarly, the high- T resistivity of our $\text{La}_{1.48}\text{Nd}_{0.4}\text{Sr}_{0.12}\text{CuO}_4$ crystal is at least $\sim 30\%$ lower than previously published values (26), indicating that our samples are at least as homogeneous. The agreement between the resistive $T_c(H)$ and the irreversibility field $H_{\text{irr}}(T)$ obtained from torque magnetometry in LESCO (fig. S8) further confirms the absence of extrinsic inhomogeneity and high crystal quality. It is probably because of the relatively low level of disorder that our striped LESCO and LNSCO crystals exhibit a two-step $\rho_{\text{ab}}(T)$ (Fig. 1F and figs. S1 and S2), known to reflect the onset of local and global superconductivity in various 2D systems (19, 31–34), as discussed above. A similar two-step $\rho_{\text{ab}}(T)$ is also observed (26, 27, 56–58) in other La-214 cuprates near $x = 1/8$.

Measurements

The standard four-probe ac method (~ 13 Hz) was used for measurements of the sample resistance, with the excitation current (density) of $10 \mu\text{A}$ ($\sim 5 \times 10^{-3}$ and $\sim 2 \times 10^{-3}$ A cm^{-2} for LESCO and LNSCO, respectively). The Lakeshore 372 AC resistance bridge, which minimizes power dissipation at low temperatures, was used for linear resistivity measurements. dV/dI measurements were performed by applying a dc current bias (density) down to $2 \mu\text{A}$ ($\sim 1 \times 10^{-3}$ and $\sim 4 \times 10^{-4}$ A cm^{-2} for LESCO and LNSCO, respectively) and a small ac current excitation $I_{\text{ac}} \approx 1 \mu\text{A}$ (~ 13 Hz) through the sample while measuring the ac voltage across the sample. For each value of I_{dc} , the ac voltage was monitored for 300 s, and the average value was recorded. The data that were affected by Joule heating at large dc bias were not considered. In the high-field normal state, for example, the dc current bias where Joule heating becomes relevant, identified as the current above which the V - I characteristic changes from ohmic to non-ohmic, was $I_{\text{dc}} > 100 \mu\text{A}$ at the lowest T ; at higher T , such as 1.7 K, that current was $I_{\text{dc}} \gtrsim 10$ mA. In all measurements,

a π filter was connected at the room temperature end of the cryostat to provide a 5-dB (60 dB) noise reduction at 10 MHz (1 GHz).

The experiments were conducted in several different magnets at the National High Magnetic Field Laboratory: a dilution refrigerator ($0.016 \text{ K} \leq T \leq 0.7 \text{ K}$), a ^3He system ($0.3 \text{ K} \leq T \leq 35 \text{ K}$), and a variable-temperature insert ($1.7 \text{ K} \leq T \leq 200 \text{ K}$) in SC magnets (H up to 18 T) using 0.1 to 0.2 T/min sweep rates; a portable dilution refrigerator ($0.02 \text{ K} \leq T \leq 0.7 \text{ K}$) in a 35-T resistive magnet using a 1 T/min sweep rate; and a ^3He system ($0.3 \text{ K} \leq T \leq 20 \text{ K}$) in a 31-T resistive magnet using 1 to 2 T/min sweep rates. Below ~ 0.06 K, it was not possible to achieve sufficient cooling of the electronic degrees of freedom to the bath temperature, a common difficulty with electrical measurements in the millikelvin range. This results in a slight weakening of the $\rho_{\text{ab}}(T)$ curves below ~ 0.06 K for all fields. We note that this does not make any qualitative difference to the phase diagram (Fig. 2). The fields, applied perpendicular to the CuO_2 planes, were swept at constant temperatures. The sweep rates were low enough to avoid eddy current heating of the samples. The resistance per square per CuO_2 layer $R_{\square/\text{layer}} = \rho_{\text{ab}}/l$, where $l = 6.6 \text{ \AA}$ is the thickness of each layer.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at <http://advances.sciencemag.org/cgi/content/full/6/7/eaay8946/DC1>

Fig. S1. Determination of the zero-resistance $T_c(H)$.

Fig. S2. The dependence of the in-plane resistivity on T at intermediate fields.

Fig. S3. Nonlinear in-plane transport in $\text{La}_{1.7}\text{Eu}_{0.2}\text{Sr}_{0.1}\text{CuO}_4$.

Fig. S4. Nonlinear in-plane transport in $\text{La}_{1.48}\text{Nd}_{0.4}\text{Sr}_{0.12}\text{CuO}_4$.

Fig. S5. In-plane MR of $\text{La}_{1.7}\text{Eu}_{0.2}\text{Sr}_{0.1}\text{CuO}_4$ versus H^2 for several $T > T_c^0$.

Fig. S6. Comparison of studies of upper critical field in various underdoped cuprates at different hole concentrations (p).

Fig. S7. Temperature dependence of the magnetic susceptibility and in-plane resistivity.

Fig. S8. Comparison of the irreversibility fields $H_{\text{irr}}(T)$ with the resistive $T_c(H)$ in $\text{La}_{1.7}\text{Eu}_{0.2}\text{Sr}_{0.1}\text{CuO}_4$.

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