Electrons with Planckian scattering obey standard orbital motion in a magnetic field

In various so-called strange metals, electrons undergo Planckian dissipation\textsuperscript{1,2}, a strong and anomalous scattering that grows linearly with temperature\textsuperscript{3}, in contrast to the quadratic temperature dependence expected from the standard theory of metals. In some cuprates\textsuperscript{4,5} and pnictides\textsuperscript{6}, a linear dependence of resistivity on a magnetic field has also been considered anomalous—possibly an additional facet of Planckian dissipation. Here we show that the resistivity of the cuprate strange metals \( \text{Nd}_{0.4}\text{La}_{1.6-x}\text{Sr}_x\text{CuO}_4 \) (ref. 7) and \( \text{La}_{2-x}\text{Sr}_x\text{CuO}_4 \) (ref. 8) is quantitatively consistent with the standard Boltzmann theory of electron motion in a magnetic field, in all aspects—field strength, field direction, temperature and disorder level. The linear field dependence is found to be simply the consequence of scattering rate anisotropy. We conclude that Planckian dissipation is anomalous in its temperature dependence, but not in its field dependence. The scattering rate in these cuprates does not depend on field, which means that their Planckian dissipation is robust against fields up to at least 85 T.

The hallmark of strange metals is a perfectly linear temperature dependence of the electrical resistivity as temperature \( T \) goes to zero, in contrast to the \( T^2 \) dependence expected from the standard Fermi-liquid theory of metals. This behaviour is observed in a wide range of metals, typically close to a quantum critical point, as in heavy-fermion metals\textsuperscript{9}, hole-doped cuprates\textsuperscript{10,11}, electron-doped cuprates\textsuperscript{12,13}, organic superconductors\textsuperscript{14,15} and iron-based superconductors\textsuperscript{16,17}, even though the nature of the critical point may be different\textsuperscript{18}. The phenomenon is called Planckian dissipation, because in all cases an estimate\textsuperscript{1,2} or a measurement\textsuperscript{3} of the inelastic scattering time \( \tau \) yields \( \tau \approx \hbar / k_B T \), where \( \hbar \) is Planck’s constant and \( k_B \) is Boltzmann’s constant. The microscopic mechanism that underlies Planckian dissipation remains unknown, but the simplicity and universal character of the phenomenon point to a fundamental quantum principle.

It has been suggested that the dependence of resistivity on magnetic field \( B \) is another facet of Planckian dissipation in strange metals. Specifically, the scattering rate would have not only an anomalous \( T \)-linear dependence, but also an anomalous \( B \)-linear dependence. This suggestion was inspired by the observation of \( B \)-linear resistivity in cuprates such as \( \text{La}_{2-x}\text{Sr}_x\text{CuO}_4 \) (LSCO)\textsuperscript{4}, \( \text{Bi}_2\text{Sr}_2\text{CuO}_6 \) (Bi2201)\textsuperscript{5}, and pnictides such as \( \text{BaFe}_2(\text{As}_{1-x}\text{P}_x)_2 \) (ref. 6) ---a behaviour that contrasts with the usual \( B^2 \) dependence observed in simple metals. In one proposal, \( T \) and \( B \) would be linked via a scattering rate of the form \( \sqrt{(a k_B T)^2 + (\gamma \mu_B B)^2} \), where \( \mu_B \) is the Bohr magneton, and \( a \) and \( \gamma \) are coefficients of comparable magnitude\textsuperscript{6}.

To determine whether the linear magnetoresistance is anomalous, we must compare it to what is expected from the standard Boltzmann...
Magnetism 21 (Fig. 1a). Its superconductivity can be entirely suppressed by applying a magnetic field in excess of 20 T. Its resistivity is perfectly $T$-linear down to the lowest temperature ($T \approx 1$ K) 7.

Thermal conductivity measurements down to 50 mK have shown this $T$-linearity to persist down to $T = 0$ (ref. 22). Nd-LSCO is an archetypal strange metal, with a simple quasi-two-dimensional (2D) single-band theory of electron motion in a magnetic field providing all electronic parameters are known. Here we carry out such a comparison in detail for two closely related strange metals: the cuprates La$_{1.6-x}$Nd$_x$Sr$_x$CuO$_4$ (Nd-LSCO) and LSCO, at a hole concentration (doping) of $p = 0.24$.

At that doping, Nd-LSCO is in its purely metallic phase, without pseudogap 16–18, charge-density wave modulations 19,20 or static magnetism 21 (Fig. 1a). Its superconductivity can be entirely suppressed by applying a magnetic field in excess of 20 T. Its resistivity is perfectly $T$-linear down to the lowest temperature ($T = 1$ K). Thermal conductivity measurements down to 50 mK have shown this $T$-linearity to persist down to $T = 0$ (ref. 22). Nd-LSCO is an archetypal strange metal, with a simple quasi-two-dimensional (2D) single-band...
Fermi surface, as mapped out by angle-resolved photoemission spectroscopy (ARPES) measurements. A first test of Boltzmann theory was recently carried out on Nd-LSCO in a fixed field by measuring its angle-dependent magnetoresistance (ADMR). Changes in the c-axis resistivity $\rho_c$, as a function of the field angle relative to the c axis ($\theta$) and a axis ($\phi$) were used to extract the detailed shape and size of the Fermi surface, using the standard Chambers formalism. The resulting Fermi surface was in good agreement with that seen by ARPES, thereby validating Boltzmann theory in a fixed field.

The ADMR data were also used to extract the scattering rate $1/\tau$. Its $T$ dependence was found to be linear, with a Planckian slope, namely $1/\tau = ak_B T/\hbar$ with $a = 1.2 \pm 0.4$ (specifically, $a = 1.2 \pm 0.4$). Moreover, and crucially, this $T$-linear inelastic scattering rate was found to be isotropic (independent of $\phi$), thereby explaining how a perfect $T$-linear resistivity is possible in a metal whose Fermi surface, density of states and Fermi velocity are strongly anisotropic. The scattering rate is the sum of an elastic ($T$-independent) term and an inelastic ($T$-dependent) term:

$$\frac{1}{\tau(\phi, T)} = c \left( \frac{1}{\tau_0} + \frac{1}{\tau_{\text{iso}}} \cos^2(2\phi) \right) + ak_BT/\hbar. \quad (1)$$

Fits to the ADMR data in Nd-LSCO $\rho = 0.24$ (ref. 1) yielded the parameters $a = 1.2$ and, the exponent, $\nu = 12$ (Extended Data Table 1), with $c = 1.0$ by construction.

The strongly anisotropic elastic term in Nd-LSCO is attributed to the nearby van Hove singularity (together with small-angle scattering), which causes the angle-dependent density of states to be strongly anisotropic, with a maximum in the antinodal directions.

Given the Fermi surface and the scattering rate, we can now use Boltzmann theory to predict how the resistivity of Nd-LSCO should evolve as a function of field strength, disorder level and field direction, at various temperatures. As shown below, we will find that all predictions are precisely confirmed by our data on Nd-LSCO and on the closely related material LSCO. In other words, the behaviour of electrons in a magnetic field in these strange metals is entirely the result of their orbital motion, and there is no evidence that the scattering rate has any field dependence.

The in-plane resistivity of the three samples considered here is displayed in Fig. 1b. It is perfectly $T$-linear below 70 K in all cases, with similar slopes. The only difference is the residual resistivity (at $T = 0$), which reflects the different levels of disorder (elastic scattering); $\rho_0 = 28, 12$ and 48 $\mu\Omega \cdot cm$ for Nd-LSCO, LSCO sample S1 and LSCO sample S2, respectively.

In Fig. 2a, we display the field dependence of the in-plane resistivity $\rho$ for Nd-LSCO, plotted as $\rho(B)/\rho(0)$, the relative magnetoresistance (MR), obtained by applying a pulsed field up to 85 T, at various constant temperatures (the full set of isotherms is provided in Extended Data Fig. 1). In Fig. 2b, we show the corresponding prediction of Boltzmann theory, based on the parameters established by ADMR in Nd-LSCO. We see that the data and calculation are in quantitative agreement: the MR values at 4 K and 80 T are $\rho(B)/\rho(0) = 1.35$ and 1.30, respectively. Qualitatively, we find that the MR increases with decreasing $T$ and it evolves from a $B^2$ dependence at high $T$ to $B$-linear at low $T$—an evolution that is nicely reproduced by the calculation.

The $B$-linear dependence at low $T$, hailed as anomalous in previous studies, is in fact entirely accounted for by Boltzmann theory, given the strongly anisotropic elastic scattering rate of Nd-LSCO. Indeed, if we remove the anisotropic part of the scattering (by setting $1/\tau_{\text{iso}} = 0$ in equation (1)), we then lose the $B$-linear character of the MR (Fig. 2d).

The fact that the MR becomes quadratic at high $T$ (MR $\sim B^2$ at 100 K) is also accounted for by the calculation (Fig. 2b), and this is due to the loss of anisotropy as the isotropic inelastic scattering dominates more and more with increasing temperature. We conclude that in overdoped Nd-LSCO and LSCO, there is no need for $1/\tau$ to depend on the field to explain quantitatively the $B$-linearity, because it is simply due to the orbital motion of electrons in the presence of anisotropic impurity scattering. In other words, Planckian dissipation in these cuprates is insensitive to field, up to at least 85 T. Note that the $B$-linear MR observed in iron-based superconductors has also been linked to an anisotropy of the Fermi surface in these materials.

To directly compare with earlier work on LSCO, we also measured the field dependence of $\rho$ in LSCO at $\rho = 0.24$, in our two samples, S1 and S2. In those two samples, $\rho$ is $T$-linear below $T = 70$ K, exactly as in Nd-LSCO, with a very similar slope (Fig. 1b). In a previous study on LSCO at $\rho = 0.23$ (ref. 2), in which a field of 48 T was applied to suppress superconductivity, the $T$-linear dependence of $\rho$ was found to extend down to at least $T = 1$ K. Note that the Fermi surface of LSCO is very similar to that of Nd-LSCO, namely it is electron-like, because the Fermi level has crossed the van Hove singularity.

In Fig. 2c, we display our high-field data on LSCO S1. The behaviour of the MR at various temperatures is seen to be very similar to that found in Nd-LSCO and in the calculations, namely $B$-linear at 4 K, evolving to $B^2$ at 100 K. (Note that our MR data on LSCO are also consistent with prior MR data on LSCO $\rho = 0.19$ (refs. 3, 4); Extended Data Fig. 2.) The only difference is the magnitude of the MR, equal to 1.65 in LSCO S1 versus 1.3 in Nd-LSCO, at 4 K and 60 T. This quantitative difference is expected, given the lower $\rho_0$ values in the former sample.

In Fig. 3a, we compare the MR in our three samples, at $T = 30$ K. In Fig. 3b, we show the predicted dependence of the MR on the disorder level. The calculation is performed using all the same ADMR-determined parameters, but now varying the multiplicative factor $c$ in front of the elastic term in equation (1). By definition, $c = 1.0$ is the value determined by the ADMR study for an Nd-LSCO sample with a very similar $\rho_0$ value to our own Nd-LSCO sample (from the same source and batch). We see that by decreasing the strength of
Anisotropic Planckian scattering rate in cuprates is insensitive to magnetic field, at least up to 85 T. This con-"
12. Doiron-Leyraud, N. et al. Correlation between linear resistivity and $T_c$ in the Bechgaard salts and the pnictide superconductor Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$. Phys. Rev. B 80, 214531 (2009).
13. Kasahara, S. et al. Evolution from non-Fermi- to Fermi-liquid transport via isovalent doping in BaFe$_2$(As$_{1-x}$P$_x$)$_2$ superconductors. Phys. Rev. B 81, 184519 (2010).
14. Analytis, J. G. et al. Transport near a quantum critical point in BaFe$_2$(As$_{1-x}$P$_x$)$_2$. Nat. Phys. 10, 194–197 (2014).
15. Taillefer, L. Scattering and pairing in cuprate superconductors. Annu. Rev. Condens. Matter Phys. 1, 51–70 (2010).
16. Collignon, C. et al. Fermi-surface transformation across the pseudogap critical point of the cuprate superconductor La$_{1.62}$Nd$_{0.4}$Sr$_{0.6}$CuO$_4$. Phys. Rev. B 95, 224517 (2017).
17. Matt, C. E. et al. Electron scattering, charge order and pseudogap physics in La$_{1.62}$Nd$_{0.4}$Sr$_{0.6}$CuO$_4$: an angle-resolved photoemission spectroscopy study. Phys. Rev. B 92, 134524 (2015).
18. Cyr-Choinière, O. et al. Pseudogap temperature $T^*$ of cuprate superconductors from the Nernst effect. Phys. Rev. B 97, 064502 (2018).
19. Collignon, C. et al. Thermopower across the phase diagram of the cuprate La$_{1.62}$Nd$_{0.4}$Sr$_{0.6}$CuO$_4$: signatures of the pseudogap and charge density wave phases. Phys. Rev. B 103, 155102 (2021).
20. Gupta, N. K. et al. Vanishing nematic order beyond the pseudogap phase in overdoped cuprate superconductors. Proc. Natl Acad. Sci. USA 118, e2106881118 (2021).
21. Nachumi, B. et al. Muon spin relaxation study of the stripe phase order in La$_{1.62}$Nd$_{0.4}$Sr$_{0.6}$CuO$_4$ and related 214 cuprates. Phys. Rev. B 58, 8760–8772 (1998).
22. Michon, B. et al. Wiedemann-Franz law and abrupt change in conductivity across the pseudogap critical point of a cuprate superconductor. Phys. Rev. X 8, 041010 (2018).
23. Horio, M. et al. Three-dimensional Fermi surface of overdoped La-based cuprates. Phys. Rev. Lett. 121, 077004 (2018).
24. Abrahams, E. & Varma, C. M. What angle-resolved photoemission experiments tell about the microscopic theory for high-temperature superconductors. Proc. Natl Acad. Sci. USA 97, 5714–5716 (2000).
25. Maksimovic, N. et al. Magnetoresistance scaling and the origin of $H$-linear resistivity in BaFe$_2$(As$_{1-x}$P$_x$)$_2$. Phys. Rev. X 10, 041062 (2020).
26. Helm, T. et al. Magnetic breakdown in the electron-doped cuprate superconductor Nd$_{1.875}$Ce$_{0.125}$CuO$_4$: the reconstructed Fermi surface survives in the strongly overdoped regime. Phys. Rev. Lett. 105, 247002 (2010).
27. Michon, B. et al. Thermodynamic signatures of quantum criticality in cuprate superconductors. Nature 567, 218–222 (2019).
28. Bianchi, A. Possible Fulde-Ferrell-Larkin-Ovchinnikov superconducting state in CeCoIn$_5$. Phys. Rev. Lett. 91, 187004 (2003).

Publisher’s note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit http://creativecommons.org/licenses/by/4.0/.

© The Author(s) 2022
Methods

Samples

Nd-LSCO. Single crystals of Nd-LSCO with a Sr content such that \( p = 0.24 \) were prepared with the floating zone technique at the University of Texas (by J.-S.Z.). A platelet sample was cut with dimensions \( 2 \times 0.5 \times 0.05 \text{ mm}^3 \) with the \( c \) axis along the shortest dimension. Longitudinal contacts were made with silver epoxy annealed in oxygen for 1 h at 300 °C. The high-symmetry crystallographic directions were determined with a precision better than 5° and they were normal to the faces of the sample. The superconducting critical temperature of this sample obtained from resistivity measurements in zero field, where \( \rho = 0 \), is \( T_c = 10 \pm 1 \text{ K} \).

LSCO. Single crystals of LSCO were grown with the floating zone technique, with a Sr content such that \( p = 0.24 \). Two samples were prepared, with similar dimensions and contacts to that of our Nd-LSCO sample. LSCO sample S1 was prepared by S.O. and sample S2 by H.T. Sample S1 was annealed for several weeks in oxygen flow to reduce the oxygen deficiency, yielding a lower \( \rho_c \) compared to S2. The superconducting transition temperatures of samples S1 and S2 are \( T_c = 17 \pm 1 \text{ K} \) and \( 16 \pm 1 \text{ K} \), respectively.

Transport measurements

Electrical d.c. resistance was measured at Sherbrooke on all samples with an in-plane excitation current in the range of 0.5–2 mA and with a steady field of 16 T applied normal to the \( \text{CuO}_2 \) planes.

The longitudinal resistance was measured with a conventional four-point configuration in pulsed fields up to 85 T in Toulouse. The in-plane excitation current was 5 mA or lower, with a frequency range between 10 and ~60 kHz that was applied along the \( \text{ax} \) axis in all samples.

A high-speed acquisition system was used to digitize the reference signal (current) and the voltage drop across the sample at a frequency of 500 kHz. The data were post-analysed with software to perform the phase comparison.

MR calculations based on the Boltzmann model

All the simulations were obtained by solving the Boltzmann equation below (all further details are discussed in refs. 28–30):

\[
\frac{1}{\rho_{xx}} = \frac{e^2}{4\pi^2} \int d^2k \, D(k) \nu_x |k(t = 0)| \int_0^\infty \nu_x \left| k(t) \right| e^{-\tau t} dt,
\]

where the contour integral is over the Fermi surface, \( D(k) \) is the density of states at point \( k \), \( \nu_x \) is the component of the Fermi velocity in the \( x \) direction, and the second integral is an integral of the Fermi velocity in the \( x \) direction that calculates the probability that a quasiparticle with lifetime \( \tau \) scatters after time \( t \). The magnetic field enters through the Lorentz force and modifies the velocity by introducing a cyclotron motion to the quasiparticles.

Data availability

Data that support the plots within this paper are available from the corresponding authors upon reasonable request. Source data are provided with this paper.

Code availability

The code used to compute the resistivity is available from the corresponding authors upon reasonable request.

References

29. Fang, Y. et al. Fermi surface transformation at the pseudogap critical point of a cuprate superconductor. Nat. Phys. 18, 558–564 (2022).

Acknowledgements

We thank J. G. Analytis, R. L. Greene, N. E. Hussey, S. A. Kivelson, D. Sénéchal and B. J. Ramshaw for fruitful discussions. A portion of this work was performed at the LNCMI, a member of the European Magnetic Field Laboratory (EMFL). D.V. and C.P. acknowledge support from the EUR grant NanoX no ANR-17-EURE-0009 and from the ANR grant NEPTUN no ANR-19-CE30-0019-01. L.T. acknowledges support from the Canadian Institute for Advanced Research (CIFAR) as a Fellow and funding from the Natural Sciences and Engineering Research Council of Canada (NSERC; PIN:123817), the Fonds de recherche du Québec - Nature et Technologies (FRQNT), the Canada Foundation for Innovation (CFI) and a Canada Research Chair. This research was undertaken thanks, in part, to funding from the Canada First Research Excellence Fund. J.-S.Z. was supported by an NSF grant (MRSEC DMR-1720595). S.O. was supported by a JSPS KAKENHI grant (20H0304).

Author contributions

A.A., A.G., S.B., J.B., L.C., M.-E.B., V.O., S.B., D.V. and C.P. performed the transport and characterization measurements at Sherbrooke. J.-S.Z. prepared the Nd-LSCO sample, S.O. prepared the LSCO S1 sample, and H.T. prepared the LSCO S2 sample. A.A. analysed the data and made the simulation figures in consultation with G.G. and L.T. A.A. and L.T. wrote the manuscript, in consultation with all the authors. L.T. supervised the project.

Competing interests

The authors declare no competing interests.

Additional information

Extended data is available for this paper at https://doi.org/10.1038/s41567-022-01763-0.

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41567-022-01763-0.

Correspondence and requests for materials should be addressed to Amirreza Ataei or Louis Taillefer.

Peer review information Nature Physics thanks Subir Sachdev and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

Reprints and permissions information is available at www.nature.com/reprints.
| $t$ (meV) | $t'$ | $t''$ | $\mu$ | $p$ | $1/\tau_0$ (ps$^{-1}$) | $1/\tau_{\text{aniso}}$ (ps$^{-1}$) | $v$ | $\alpha$ |
|-----------|------|-------|-------|-----|-------------------|------------------|-----|--------|
| 160       | -0.1364$t$ | 0.0682$t$ | -0.8243$t$ | 0.248 | 8.65              | 63.5             | 12  | 1.2    |

Tight-binding values that were taken from refs. 3,20 to perform the calculations in this work: $t$, $t'$ and $t''$ are the first-, second- and third-nearest-neighbour hoping parameters, $\mu$ is the chemical potential and $p$ is the doping. The remaining four parameters are from equation (1): $1/\tau_0$ is the amplitude of the isotropic scattering rate at $T=0$, $1/\tau_{\text{aniso}}$ is the amplitude of the anisotropic scattering rate (which is $T$-independent), $v$ is the power of the cosine function and $\alpha$ is a constant. The value of $1/\tau_0$ at $T > 0$ is: 9.45, 13.52, 15.10, 16.66 and 24.35 ps$^{-1}$ at $T=4$, 30, 40, 50 and 100K, respectively.
Extended Data Fig. 1 | Field dependence of resistivity. In-plane resistivity as a function of magnetic field ($B \parallel a$) in a) Nd-LSCO, b) LSCO sample S1 and c) LSCO sample S2, at the indicated temperatures.
Extended Data Fig. 2 | Magnetoresistance in different LSCO samples. Magnetic field dependence of the in-plane resistivity ($J_a$) in LSCO at $p = 0.19$ (a), compared with b) LSCO sample S1 and c) LSCO sample S2 at $p = 0.24$, at temperatures as indicated. In all cases, $B \parallel c$. 

![Image showing magnetoresistance in different LSCO samples](https://doi.org/10.1038/s41567-022-01763-0)