KONDO INSULATORS Visualizing the atomic-scale origin of metallic behavior in Kondo insulators

Harris Pirie^{1,2}, Eric Mascot³, Christian E. Matt¹, Yu Liu¹, Pengcheng Chen¹, M. H. Hamidian¹, Shanta Saha⁴, Xiangfeng Wang⁴, Johnpierre Paglione⁴, Graeme Luke⁵, David Goldhaber-Gordon^{6,7}, Cyrus F. Hirjibehedin^{8,9,10}+, J. C. Séamus Davis^{2,11,12,13}, Dirk K. Morr³, Jennifer E. Hoffman¹*

A Kondo lattice is often electrically insulating at low temperatures. However, several recent experiments have detected signatures of bulk metallicity within this Kondo insulating phase. In this study, we visualized the real-space charge landscape within a Kondo lattice with atomic resolution using a scanning tunneling microscope. We discovered nanometer-scale puddles of metallic conduction electrons centered around uranium-site substitutions in the heavy-fermion compound uranium ruthenium silicide (URu₂Si₂) and around samarium-site defects in the topological Kondo insulator samarium hexaboride (SmB₆). These defects disturbed the Kondo screening cloud, leaving behind a fingerprint of the metallic parent state. Our results suggest that the three-dimensional quantum oscillations measured in SmB₆ arise from Kondo-lattice defects, although we cannot exclude other explanations. Our imaging technique could enable the development of atomic-scale charge sensors using heavy-fermion probes.

hen the electrons in a material interact strongly with one another, they often produce unexpected behavior. Above a characteristic temperature $T_{\rm K}$, a lattice of local f moments within a conducting Fermi sea behaves like an ordinary magnetic metal, with a Curie-Weiss susceptibility. But below $T_{\rm K}$, the competition between antiferromagnetic ordering of the local moments and their screening by conduction electrons leads to a rich phase diagram, exhibiting quantum criticality (1), unconventional superconductivity (2), and heavy fermions (3, 4)quasiparticles with *f*-electron character (Fig. 1A). A Kondo insulator forms if the spectral gap opened by hybridization between the conduction band and the renormalized f band spans the Fermi level. Mysteriously, some Kondo insulators seem to "remember" their metallic parent state long after this gap is fully developed. For example, the topological Kondo insulator samarium hexaboride (SmB₆) displays a sizable bulk optical conductivity at terahertz frequencies (5) and a finite electronic specific

 USA. ¹³Max Planck Institute for Chemical Physics of Solids, D-01187 Dresden, Germany.
 *Corresponding author. Email: jhoffman@physics.harvard.edu

Fresent address: Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, MA 02421, USA. heat at low temperatures (6-9). A complete three-dimensional (3D) Fermi surface matching its high-temperature metallic state was reconstructed from quantum oscillation (9, 10)and Compton scattering (11) measurements performed in the insulating regime. Notably, these metallic properties persist even as the bulk resistivity of SmB6 increases by 10 orders of magnitude (12). This discrepancy led to several theoretical proposals: Some argue that the metallic behavior is intrinsic, either a consequence of the small hybridization gap in Kondo insulators (13) or arising from exotic chargeneutral quasiparticles (14, 15). Others suggest an extrinsic origin (16-19), which implies the presence of microscopic metallic pockets.

Charge inhomogeneity is commonplace at nanometer length scales, especially in materials with strong electron interactions that promote competing orders (20). In a Kondo lattice, defects that substitute or remove the f-contributing moment, called Kondo holes, have a widespread impact on the nearby electronic structure (21-23). First, these defects locally untangle the hybridized wave function, leaving puddles of unhybridized conduction electrons behind (Fig. 1B). In theory, these charge puddles should have the same itinerant character as the metallic parent state (22), but they have not been imaged directly. Additionally, the excess conduction electrons released from hybridization adjust the strength of their interactions with the remaining *f* moments (22, 24), leading to enhanced local magnetism (25) (Fig. 1C). For example, $Sm_{1-x}La_xB_6$ samples with nonmagnetic La dopants are known to display increased specific heat and magnetic susceptibility compared with undoped samples (26-28). More recently, the existence of local metallic puddles around Gd dopants in $Sm_{1-x}Gd_xB_6$ was inferred from electron spinresonance measurements (29). Meanwhile, an increased concentration of Sm vacancie Sm_{1-x}B₆ was shown to globally inhibit development of the hybridization gap (*30*),

development of the hybridization gap (30), eventually leading to bulk conduction (12, 31). All of these findings suggest that Sm-site defects manifest as Kondo holes in SmB₆, yet their key signature—the accompanying charge oscillations relating to the parent metallic Fermi surface (22)—remains undetected by any microscopic probe.

Directly imaging the metallic puddles around Kondo holes is difficult, because the inherent screening strongly renormalizes the bare charge distribution. However, there are a few promising approaches (32-34). The most common is to decorate the tip of a Kelvin probe force microscope with a single atom or molecule (35, 36). This technique was used to image the charge variations within an adsorbed molecule (37). However, it becomes inaccurate for small tip-sample separations, because of the influence of short-range forces (38, 39), complicating further improvements to its spatial resolution (40). Meanwhile, a scanning tunneling microscope (STM) routinely achieves the subnanometer spatial resolution, cryogenic temperatures, and sub-milli-electron volt (submeV) energy resolution required to access atomic charge distributions, but existing methods to extract the electrostatic potential from the STM vacuum decay length contain substantial artifacts (41). Consequently, simultaneously achieving the high charge precision and high spatial resolution required to measure the charge environment around a Kondo hole is not possible using existing techniques.

We have developed a dedicated STM modality to image the charge environment within a Kondo lattice with sub-angstrom resolution. At temperatures below $T_{\rm K}$, we image charge oscillations matching the parent Fermi surface centered around spinless thorium atoms in the Kondo metal uranium ruthenium silicide (URu₂Si₂) and around three separate Sm-site defects in the Kondo insulator SmB₆. The charge puddles we image in SmB₆ exhibit the same metallic wave vector seen in recent quantum oscillation experiments (9, 10), suggesting that Kondo-lattice defects are the source of those oscillations.

Measuring local charge density in a Kondo lattice

To visualize the conduction-electron density $n_c(\mathbf{r})$ in a Kondo lattice [and hence the local charge $-en_c(\mathbf{r})$, where -e is the electron charge], we first show theoretically that $n_c(\mathbf{r})$ determines the energy position of the Kondo resonance $\tilde{e}_f(\mathbf{r})$, which forms near the Fermi level as the magnetic *f* moments are screened by conduction electrons. Then, we establish an experimental metric capable of detecting the sub-meV variations in $\tilde{e}_f(\mathbf{r})$ around a Kondo hole. Our technique takes advantage of how the manybody Kondo resonance responds to local doping.



¹Department of Physics, Harvard University, Cambridge, MA 02138, USA. ²Clarendon Laboratory, University of Oxford, Oxford OX1 3PU, UK. ³Department of Physics, University of Illinois at Chicago, Chicago, IL 60607, USA. ⁴Maryland Quantum Materials Center, Department of Physics, University of Maryland, College Park, MD 20742, USA. ⁵Department of Physics and Astronomy, McMaster University, Hamilton, ON L8S 4M1, Canada. ⁶Department of Physics, Stanford University, Stanford, CA 94305, USA. ⁷Stanford Institute for Materials and Energy Sciences, SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA. ⁸London Centre for Nanotechnology, University College London (UCL), London WC1H OAH, UK.⁹Department of Physics and Astronomy, UCL, London WC1E 6BT, UK ¹⁰Department of Chemistry, UCL, London WC1H 0AJ, UK. ¹¹Department of Physics, University College Cork, Cork T12 R5C, Ireland. ¹²Laboratory of Atomic and Solid State Physics, Department of Physics, Cornell University, Ithaca, NY 14850,

In the Abrikosov fermion representation for local moments, $\tilde{\varepsilon}_f$ is the Lagrange multiplier that enforces uniform *f*-electron density, typically $n_f = 1$ at each site. As additional charge carriers $\Delta n_{\rm c}$ enter a uniform Kondo lattice, the hybridized Fermi surface reshapes to accommodate them, leading to a corresponding change in $\tilde{\varepsilon}_f$ in order to maintain $n_f = 1$ (Fig. 1D, black triangles, and fig. S2E). The magnitude and direction of the shift in $\tilde{\epsilon}_f$ depend on the details of the band structure. But the relationship between n_c and $\tilde{\epsilon}_f$ is linear over a wide range of band parameters and charge doping (fig. S2), implying that the charge density at position **r** can usually be inferred by measuring $\tilde{\epsilon}_f(\mathbf{r})$. In fact, the linear dependence of $\tilde{\varepsilon}_f(\mathbf{r})$ on $n_c(\mathbf{r})$ was recently verified experimentally by micrometer-scale angle-resolved photoemission spectroscopy (ARPES) measurements in Eu-doped SmB_6 (42).

In STM measurements, the Kondo resonance normally appears as a peak-dip feature in the tunneling conductance dI/dV (43) (where I is the sample-to-tip tunneling current at applied sample bias V), because of the presence of multiple tunneling channels (44, 45) (see calculation in Fig. 1D). In simple cases, $\tilde{\epsilon}_f$ can be estimated by fitting dI/dV to a Fano-like model (46, 47). However, the exact value of $\tilde{\varepsilon}_f$ depends on the model used, so this approach is not immediately suitable for detecting the small, sub-meV energy shifts in $\tilde{\epsilon}_f(\mathbf{r})$ expected around a Kondo hole. Instead, we track the ratio of forward-to-backward tunneling current, that is, the local rectification $R(\mathbf{r}, V) =$ $|I(\mathbf{r}, +V)/I(\mathbf{r}, -V)|$. This ratio is insensitive to STM setup artifacts, and it was previously used to track charge inhomogeneity from the spectral weight transfer at high biases in holedoped cuprates (48). We focus on low biases, typically $V \leq 10$ mV, where the small shifts in $\tilde{\epsilon}_f(\mathbf{r})$ generate large variations in $R(\mathbf{r}, V)$ owing to the energy asymmetry of dI/dV about the Fermi level at V = 0 (Fig. 1, D and E, and fig. S2). To demonstrate this effect locally, we selfconsistently calculated $dI(\mathbf{r}, V)/dV$, $n_{\rm c}(\mathbf{r})$, and $R(\mathbf{r}, V)$ around a Kondo hole in a metallic Kondo lattice, as shown in Fig. 1, F to H. The calculated $dI(\mathbf{r}, V)/dV$ at V = 0 tracks the local Fermi-level density of states, so it reveals the hybridized Fermi surface of heavy fermions with a wave vector $2k_{\rm F}^{\rm h}$. In contrast, both $n_{\rm c}({\bf r})$ and $R(\mathbf{r}, V)$ are dominated by static oscillations at the unhybridized wave vector $2k_{\rm F}^{\rm c}$, associated with the Friedel-like redistribution of the Kondo screening cloud. The correlation between $n_c(\mathbf{r})$ and $R(\mathbf{r}, V)$ establishes $R(\mathbf{r}, V)$ as a qualitative probe of local charge, except at very short distances from a Kondo hole $(|\mathbf{r}| \sim a)$, likely because $n_f = 1$ is not enforced at that site.

Kondo holes in URu₂Si₂

To test our technique, we first studied the Kondo metal URu_2Si_2 with 1% thorium dop-



Fig. 1. Expected disruption of the screening cloud around Kondo holes. (A) In a uniform Kondo lattice, magnetic moments at each site (gray arrows) are coherently screened by itinerant conduction electrons (blue cloud) to form a spinless ground state of heavy fermions (orange line), characterized by the wave vector $k_{\rm F}^{\rm h}$ (**B**) If one moment is removed to create a Kondo hole, the conduction electrons previously screening it can redistribute themselves. (C) The redistributed screening cloud causes oscillations of the local conduction electron density $n_c(\mathbf{r})$, interaction strength $v(\mathbf{r})$, and magnetic susceptibility $\chi_m(\mathbf{r})$ at the conduction-band wave vector $k_{\rm E}^{\rm c}$, as shown schematically. (**D**) In a uniform Kondo lattice, the Kondo resonance creates a peak-dip feature in the calculated dI/dV, caused by the quantum interference between tunneling into the conduction band and the f-electron states with respective amplitudes t_c and t_f . The energy position of the peak (black triangles) shifts linearly according to the local conduction-electron density n_c , a.u., arbitrary units. (E) The calculated rectification R(V) = |I(+V)/I(-V)| acquires a strong peak because dI/dV is asymmetric around the Fermi level E_F (which occurs at V = 0). The R(V) peak amplitude depends on the dI/dV peak energy. These changes are almost linear over the small range of local doping expected around a Kondo hole (inset). (F) The calculated oscillations in $dl(\mathbf{r},V)/dV$ at the Fermi level around a Kondo hole match the hybridized Fermi surface ($k_{\rm F}^{\rm h}$, orange line in inset). (G) In contrast, the calculated $n_c(\mathbf{r})$ varies according to the circular wave vector of the unhybridized Fermi surface (k_c^c , blue line in inset), as it mainly reflects the disturbance to the screening cloud. (H) Calculated $R(\mathbf{r}, V)$ is dominated by unhybridized electrons for biases within the hybridization gap. The calculations in (D) to (H) are based on a Kondo-Heisenberg model with nearest-neighbor hopping strength t, Kondo coupling J = 2t, antiferromagnetic exchange I = 0.002t, and tunneling amplitudes t_f/t_c = -0.025. In (D) and (E), the hybridization strength is fixed at v = 0.1t, and the antiferromagnetic correlation strength is fixed at χ = 0.0003t. The Fermi wavelength is $\lambda_{\rm F}^{\rm c} = 8a_0$ in (F) to (H), where a_0 is the lattice spacing.

ants, which are known to induce Kondo-hole behavior (24, 49). Previous STM measurements mapped a metal-like Fermi surface in URu₂Si₂ for temperatures above $T_o = 17.5$ K, consisting of a single conduction band with wave vector $k_{\rm F}^c \approx 0.3 \pi/a$, where *a* is the lattice constant (Fig. 2A) (46). The onset of coherent heavy fermion bands below T_o (50) is accompanied by the appearance of a peak-dip feature in dI/dV, that is, the Kondo-Fano resonance (Fig. 2B). Close to a thorium dopant, this feature shifts upward in energy, toward the Fermi level. This energy shift—and even the barely perceptible shifts 2 nm away from the dopant—are easily detected in the amplitude of $R(\mathbf{r}, V)$

(Fig. 2C). For biases within the hybridization gap $|V| < \Delta/e \approx 5$ mV (where Δ is the gap magnitude), $R(\mathbf{r}, V)$ displays widespread spatial oscillations emanating from thorium dopants, as shown in Fig. 2, D to F. Their wave vector of 0.29 \pm 0.01 ($2\pi/a$) agrees with the hybridization oscillations previously measured around Kondo holes in this compound (24). It matches the URu₂Si₂ parent metallic Fermi surface detected above $T_{\rm o}$ from our measured quasiparticle interference patterns in $dI(\mathbf{r}, V)/dV$ at V = 0, but it is distinct from the heavy bands that we measured below $T_{\rm o}$ (Fig. 2G). As a final check, we independently extracted $\tilde{e}_f(\mathbf{r})$ by fitting $dI(\mathbf{r}, V)/dV$ curves to a Fano model (fig. S3).

The excellent agreement between $\tilde{\varepsilon}_f(\mathbf{r})$ and $R(\mathbf{r}, V)$ corroborates the existence of charge oscillations at $2k_{\mathrm{F}}^{\mathrm{c}}$ in URu₂Si₂, indicating that some electrons retain their itinerant character around Kondo holes, even below T_{o} .

Metallic puddles in SmB₆

In our Kondo insulating SmB_6 samples, any atomic defect that replaces a Sm atom to alter the 4f moment could generate metallic puddles like those seen in URu₂Si₂. We searched

Fig. 2. Thorium dopants induce Kondo-hole

behavior in URu₂Si₂. (A) Schematic band structure of URu₂Si₂ showing the onset of heavy fermion bands (gray solid lines) at temperatures below T_0 = 17.5 K, as itinerant conduction electrons (blue dashed line) hybridize with a renormalized 5f level (gray dashed line), reducing the Fermi wave vector from $k_{\rm F}^{\rm c}$ to $k_{\rm F}^{\rm h}$. (B) Experimental measurement of an asymmetric Fano line shape in the tunneling conductance at temperatures below T_0 on the U termination (gray curve). This feature shifts toward the Fermi level near a thorium dopant (black triangles), consistent with an expected change in local charge density. (C) For a fixed bias, the R(V) peak amplitude (black triangle) is highly sensitive to the dI/dV peak position. The spectra in (B) and (C) are averaged over the 18 well-isolated thorium dopants marked in (D). (D) The measured $R(\mathbf{r}, V)$ exhibits clear oscillations that manifest as a

for these puddles in flux-grown samples lightly doped with Fe, which contain two clear Smsite defects: Sm vacancies and Fe substitutions (Fig. 3B). We focused on the (2×1) Sm termination, as its charge environment most closely represents that of the bulk (*51*). As in URu₂Si₂, we noticed that the dI/dV peak attributed to the Kondo resonance changes its energy position near candidate Kondo holes (Fig. 3C), strongly affecting the $R(\mathbf{r},V)$ peak amplitude (Fig. 3D). Similar shifts in dI/dV peak position were previously linked to the buildup of charge around boron clusters on the Sm (1×1) termination (52). For biases within the hybridization gap $|V| < \Delta/e \approx 10$ mV, $R(\mathbf{r}, V)$ reveals prominent oscillations around Sm-site defects (Fig. 3, E and F). These oscillations create a sharp ellipse in the Fourier transform of $R(\mathbf{r}, V)$, as shown in Fig. 3G. The wave vectors of the $R(\mathbf{q}, V)$ ellipse are larger than those of the surface state detected by quasiparticle interference imaging (53), and they do not disperse



ring in (**E**) the fourfold-symmetrized Fourier transform. H, high; L, low. (**F**) These oscillations match the high-temperature Fermi wave vector of $2k_F^c \approx 0.3 (2\pi/a)$, both above and below T_0 . (**G**) In contrast, a conventional dI/dV measurement couples to the temperature-dependent Fermi surface, which changes drastically from 18.6 K to 5.9 K. For clarity, the 18.6 K data have been scaled in (F) and offset in (G).

Fig. 3. Kondo holes nucleate metallic puddles in SmB₆. (A) Schematic band structure of SmB₆

showing the hybridization between conduction electrons (blue dashed line) and localized 4f moments (gray dashed line), which leads to an inverted band structure (gray solid line) hosting emergent heavy Dirac surface states with a reduced Fermi wave vector (orange). (B) STM topography of the (2×1)-reconstructed Sm surface of lightly Fe-doped SmB₆. Both the Fe dopant and Sm vacancy in this image are expected to act as Kondo holes because they each displace a 4f moment. (C and D) Near the Fe dopant, the measured dI/dV peak changes energy position (black triangles), leading to large variations in the $R(\mathbf{r}, V)$ peak amplitude. The spectra in (C) and (D) have been offset for clarity. (E) $R(\mathbf{r}, V)$ in the same area as shown in (B) contains clear oscillations around the two impurities. (**F**) Linecut of $R(\mathbf{r}, V)$ along the white dashed line in (B). (G) $R(\mathbf{r}, V)$ oscillations appear as a sharp ring in the twofold-symmetrized Fourier transform (taken from a larger 65 nm by 80 nm area for enhanced **q** resolution), which matches the unhybridized 5d Fermi surface inferred



from ARPES experiments (dashed line) (54). The surface reconstruction creates a sharp peak in $R(\mathbf{r}, V)$ at $\mathbf{Q}_{\text{Bragg}} = (0, \pi/a)$.

, 2023

for biases within the hybridization gap, indicating a different origin (fig. S4). On the other hand, the size and shape of the ellipse matches the unhybridized 5d band found by extrapolating ARPES data (54) to the Fermi level (i.e., it matches the SmB_6 metallic parent state), after accounting for band folding on the (2×1) surface (Fig. 2G and fig. S5). Our observation of this 5d wave vector within the Kondo insulating gap is direct evidence of atomic-scale metallicity around Kondo holes. This metallicity is supported by the large residual dI/dV at V = 0 mV that we measured around Kondo holes (Fig. 3C, green curve), indicating a sizable Fermilevel density of states even when the metallic surface states are suppressed (55). We confirmed this discovery by checking for $R(\mathbf{r}, V)$ oscillations around a third type of Kondo hole, Gd dopants, as detailed in fig. S6.

Magnetic fluctuations at Kondo holes in SmB₆

Our *R*(**r**,*V*) maps show the real-space structure of the metallic puddles around Kondo holes in SmB₆. For these puddles to contribute to the measured de Haas-van Alphen oscillations in magnetization, they must have a finite magnetic susceptibility. Several Sm-site defects are already suspected to be locally magnetic from their impact on bulk susceptibility (7, 26, 27, 56) and their influence on the topologically emergent surface states (53, 55). In general, topological surface states can provide a test of local magnetism because they are protected against backscattering from nonmagnetic defects but not from magnetic defects that locally break time-reversal symmetry (57). This additional magnetic backscattering was previously imaged around Fe dopants in two Bi-based topological insulators (58, 59). We visualized the intensity of magnetic fluctuations at Sm-site defects in SmB₆ by identifying spatial regions where its surface states backscatter. For biases within the hybridization gap, we measured large-area $dI(\mathbf{r}, V)/dV$ maps that contain clear quasiparticle interference patterns at the backscattering wave vector $\mathbf{q} \equiv \mathbf{k}_{f} - \mathbf{k}_{i} = 2\mathbf{k}^{ss}$ (Fig. 4B), consistent with our previous report (53). We determined the spatial origin of this signal by Fourierfiltering $dI(\mathbf{r}, V)/dV$ at the wave vector $2\mathbf{k}^{ss}$ to create an image of the local backscattering strength (Fig. 4C). Most of the peaks in this image align with the positions of Sm vacancies or Fe dopants, indicating that these Kondo holes harbor the necessary magnetic fluctuations to backscatter topological states.

Discussion and outlook

The charge puddles around Kondo holes present an alternative yet compelling origin for many of the strange observations of metallic behavior in SmB₆. First, the detection of de Haas-van Alphen (magnetic) oscillations without accompanying Shubnikov-de Haas (resistiv-



Fig. 4. Kondo holes backscatter heavy Dirac fermions. (A) Topography of an SmB₆ region that contains 15 well-isolated Kondo holes (position indicated by red and green triangles) on several (2×1)- or (1×2)-reconstructed domains (dotted lines). (B) For energies within the Kondo insulating gap, the Fourier-transformed dI/dV along q_v (perpendicular to Sm rows) contains a linearly dispersing signal (black dashed line) corresponding to quasiparticle interference from backscattered heavy Dirac fermions. The Fourier transform from the (1×2) domains was rotated by 90° before being averaged with that from the (2×1) domains. (C) The intensity of backscattering from topological states, calculated from Fourier-filtering dl/dV at the y component of the backscattering wave vector $q_y = 2k_y^{ss}$, is strongly peaked around each Kondo hole. This map is computed only for ordered patches of the sample, as marked in (A), and excludes step edges. H, high; L, low.

ity) oscillations (8-10) is expected for electrically isolated metallic puddles, provided that they do not meet the percolation threshold [which could be unreachable (17)]. Second, the large Fermi surface size and light effective mass extracted by bulk probes (9-11) is in excellent agreement with our observation of itinerant 5d electrons. Third, the magnetic length of the high-frequency (large- $k_{\rm F}$) quantum oscillations that onset above 35 T (9, 10) is comparable to the $R(\mathbf{r})$ decay length of $\gamma = 2.6$ nm, such that a Landau orbit could fit inside a metallic puddle. Additionally, many of the metallic properties were detected in floating zone-grown samples (5, 6, 9-11), which are known to have higher concentrations of Sm vacancies than samples grown with an aluminum flux (60). Floating-zone samples also contain a higher concentration of dislocations (31), which may similarly disrupt the Kondo screening cloud and thus further enhance the quantum oscillation amplitude beyond that expected from Sm vacancies alone. In contrast, the quantum oscillations completely disappear in flux-grown samples once embedded aluminum is removed (8).

Atomic-scale charge inhomogeneity has a profound impact on many interacting quantum materials, but it has typically not been possible to measure. In Kondo-lattice systems, $R(\mathbf{r}, V)$ provides a peek at the ground-state charge landscape, which is strongly perturbed by Kondo holes. These Kondo holes nucleate nanometer-scale metallic puddles that could explain many of the strange phenomena detected by bulk probes. More broadly, the sensitivity to local charge within a Kondo lattice may enable atomic-scale charge imaging using STM tips decorated with a Kondo impurity (61) or fabricated from heavy-fermion materials (62).

REFERENCES AND NOTES

- S. Doniach, Physica B+C 91, 231-234 (1977). 1.
- 2 F. Steglich et al., Phys. Rev. Lett. 43, 1892-1896 (1979).
- 3. K. Andres, J. E. Graebner, H. R. Ott, Phys. Rev. Lett. 35,
- 1779-1782 (1975). 4 Z. Fisk, H. R. Ott, T. M. Rice, J. L. Smith, Nature 320, 124-129 (1986)
- 5 N. J. Laurita et al., Phys. Rev. B 94, 165154 (2016). K. Flachbart et al., Physica B 378-380, 610-611 (2006). 6.
- 7 W. T. Fuhrman et al., Nat. Commun. 9, 1539 (2018).
- S. M. Thomas et al., Phys. Rev. Lett. 122, 166401 (2019).
- M. Hartstein et al., Nat. Phys. 14, 166-172 (2018).
- 10. B. S. Tan et al., Science 349, 287-290 (2015).
- 11. T. E. Millichamp et al., arXiv:2111.07727 [cond-mat.str-el] (2021)
- 12. Y. S. Eo et al., Proc. Natl. Acad. Sci. U.S.A. 116, 12638-12641 (2019).
- 13. J. Knolle, N. R. Cooper, Phys. Rev. Lett. 115, 146401 (2015)
- 14. G. Baskaran, arXiv:1507.03477 [cond-mat.str-el] (2015).
- 15. O. Erten, P.-Y. Chang, P. Coleman, A. M. Tsvelik, Phys. Rev. Lett. 119. 057603 (2017).
- 16. H. Shen, L. Fu, Phys. Rev. Lett. 121, 026403 (2018).
- 17. B. Skinner, Phys. Rev. Mater. 3, 104601 (2019).
- 18. W. T. Fuhrman, P. Nikolić, Phys. Rev. B 101, 245118 (2020).
- 19. M. Abele, X. Yuan, P. S. Riseborough, Phys. Rev. B 101, 094101 (2020)
- 20. E. Dagotto, Science 309, 257-262 (2005)
- 21. R. Sollie, P. Schlottmann, J. Appl. Phys. 70, 5803-5805 (1991).
- 22. J. Figgins, D. K. Morr, Phys. Rev. Lett. 107, 066401 (2011).
- 23. J. Figgins et al., Nat. Commun. 10, 5588 (2019).
- 24. M. H. Hamidian et al., Proc. Natl. Acad. Sci. U.S.A. 108. 18233-18237 (2011).
- 25. R. R. Urbano et al., Phys. Rev. Lett. 99, 146402 (2007).
- 26. E. V. Nefedova et al., J. Exp. Theor. Phys. 88, 565-573
- 27. S. Gabáni et al., Czech. J. Phys. 52 (suppl. 1), A225-A228 (2002).
- 28. M. Orendáč et al., Phys. Rev. B 96, 115101 (2017).
- 29. J. C. Souza et al., Phys. Rev. Res. 2, 043181 (2020).
- 30. M. E. Valentine et al., Phys. Rev. B 94, 075102 (2016).

- 31. Y. S. Eo et al., Phys. Rev. Mater. 5, 055001 (2021).
- 32. B. Koslowski, C. Baur, J. Appl. Phys. 77, 28-33 (1995).
- 33. C. Wagner et al., Phys. Rev. Lett. 115, 026101 (2015).
- 34. P. Hapala et al., Nat. Commun. 7, 11560 (2016).
- M. Nonnenmacher, M. P. O'Boyle, H. K. Wickramasinghe, Appl. Phys. Lett. 58, 2921–2923 (1991).
- L. Gross, F. Mohn, N. Moll, P. Liljeroth, G. Meyer, *Science* 325, 1110–1114 (2009).
- F. Mohn, L. Gross, N. Moll, G. Meyer, *Nat. Nanotechnol.* 7, 227–231 (2012).
- U. Zerweck, C. Loppacher, T. Otto, S. Grafström, L. M. Eng, Phys. Rev. B 71, 125424 (2005).
- S. Sadewasser et al., Phys. Rev. Lett. 103, 266103 (2009).
- 40. F. Albrecht et al., Phys. Rev. Lett. 115, 076101 (2015).
- F. Albrecht, M. Fleischmann, M. Scheer, L. Gross, J. Repp, Phys. Rev. B 92, 235443 (2015).
- Kotta et al., Research Square [Preprint] (2022). https://www.researchsquare.com/article/rs-1239795/v1.
- V. Madhavan, W. Chen, T. Jamneala, M. F. Crommie, N. S. Wingreen, *Science* 280, 567–569 (1998).
- 44. M. Maltseva, M. Dzero, P. Coleman, *Phys. Rev. Lett.* **103**, 206402 (2009).
- 45. J. Figgins, D. K. Morr, Phys. Rev. Lett. 104, 187202 (2010).
- 46. A. R. Schmidt et al., Nature 465, 570-576 (2010).
- 47. I. Giannakis et al., Sci. Adv. 5, eaaw9061 (2019).
- 48. Y. Kohsaka *et al.*, *Science* **315**, 1380–1385 (2007). 49. A. de la Torre, P. Visani, Y. Dalichaouch, B. Lee, M. Maple,
- Physica B 179, 208–214 (1992).
 50. A. F. Santander-Syro et al., Nat. Phys. 5, 637–641 (2009).
- 51. C. E. Matt et al., Phys. Rev. B 101, 085142 (2020).

- 52. Z. Sun et al., Phys. Rev. B 97, 235107 (2018).
- 53. H. Pirie et al., Nat. Phys. 16, 52–56 (2020).
- 54. J. Jiang et al., Nat. Commun. 4, 3010 (2013).
- 55. L. Jiao et al., Sci. Adv. 4, eaau4886 (2018).
- 56. K. Akintola et al., Phys. Rev. B 95, 245107 (2017).
- Q. Liu, C.-X. Liu, C. Xu, X.-L. Qi, S.-C. Zhang, *Phys. Rev. Lett.* 102, 156603 (2009).
- 58. Y. Okada et al., Phys. Rev. Lett. **106**, 206805 (2011).
- B. Jäck, Y. Xie, B. Andrei Bernevig, A. Yazdani, Proc. Natl. Acad. Sci. U.S.A. 117, 16214–16218 (2020).
- 60. W. A. Phelan et al., Sci. Rep. 6, 20860 (2016).
- 61. J. Bork et al., Nat. Phys. 7, 901–906 (2011).
- 62. A. Aishwarya et al., Science 377, 1218–1222 (2022).
- H. Pirie et al., Dataset for visualizing the atomic-scale origin of metallic behavior in Kondo insulators, Zenodo (2023); https://doi.org/10.5281/zenodo.7510910.

ACKNOWLEDGMENTS

We thank A.-P. Li, B. Skinner, C. Wagner, F. Lüpke, S. Ulrich, Y. S. Eo, and Z. Fisk for helpful conversations. We thank A. Soumyanarayanan, M. Yee, and Y. He for their help measuring Gd-doped SmB₆- **Funding**: This project was supported by the Gordon and Betty Moore Foundation's EPIQS Initiative through grants GBMF4536, GBMF9071, and GBMF9457. The experiments at Harvard were supported by US National Science Foundation grant DMR-1410480. The data interpretation received support from AFOSR grant FA9550-21:1-0429. The work of E.M. and D.K.M. was supported by the US Department of Energy, Office of Science, Basic Energy Sciences, under award DE-FG02-05ER46225. C.E.M. is supported by the Swiss National Science Foundation under fellowship P400P2_183890. Work at the University of Maryland was supported by AFOSR FA9550-22-1-0023. Research at McMaster University was supported by the Natural Sciences and Engineering Research Council. J.C.S.D. acknowledges support from the Science Foundation of Ireland under award SEI 17/RP/ 5445, from the Royal Society under award R64897, and from the European Research Council under award DLV-788932. This project received funding from the European Union's Horizon 2020 research and innovation program under the Marie Skłodowska-Curie grant agreement 893097. Author contributions: H.P., C.E.M., Y.L., P.C., and M.H.H. carried out the STM experiments. S.S., X.W., J.P., and G.L. synthesized the samples. E.M. and D.K.M. developed the theoretical model. D.G.-G., C.F.H., and J.C.S.D. contributed to the understanding of the results. H.P. and J.E.H. analyzed the data and wrote the manuscript with contributions from E.M., C.F.H., J.C.S.D., and D.K.M. Competing interests: The authors have no competing interests. Data and materials availability: All data and analysis presented in this paper are deposited in Zenodo (63). License information: Copyright © 2023 the authors, some rights reserved; exclusive licensee American Association for the Advancement of Science. No claim to original US government works. https://www. science.org/about/science-licenses-iournal-article-reuse

SUPPLEMENTARY MATERIALS

science.org/doi/10.1126/science.abq5375 Materials and Methods Supplementary Text Figs. S1 to S7 Table S1 References (64–69)

Submitted 18 April 2022; accepted 28 February 2023 10.1126/science.abq5375



Visualizing the atomic-scale origin of metallic behavior in Kondo insulators

Harris Pirie, Eric Mascot, Christian E. Matt, Yu Liu, Pengcheng Chen, M. H. Hamidian, Shanta Saha, Xiangfeng Wang, Johnpierre Paglione, Graeme Luke, David Goldhaber-Gordon, Cyrus F. Hirjibehedin, J. C. Samus Davis, Dirk K. Morr, and Jennifer E. Hoffman

Science, **379** (6638), . DOI: 10.1126/science.abq5375

Metallic puddles in an insulator

Certain properties of metals can oscillate as a function of applied magnetic fields, a phenomenon known as quantum oscillations. This process should not happen in insulators, which is what made the observation of quantum oscillations in the Kondo insulator samarium hexaboride so surprising. Multiple mechanisms, both intrinsic and extrinsic, have been proposed to explain these findings. Pirie *et al.* used scanning tunneling microscopy to study the vicinity of defects, including substitutions and vacancies. They found that the defects caused the formation of localized metallic puddles, which could explain the previously observed metal-like properties of this insulator. —JS

View the article online

https://www.science.org/doi/10.1126/science.abq5375 Permissions https://www.science.org/help/reprints-and-permissions

Use of this article is subject to the Terms of service

Science (ISSN) is published by the American Association for the Advancement of Science. 1200 New York Avenue NW, Washington, DC 20005. The title Science is a registered trademark of AAAS.

Copyright © 2023 The Authors, some rights reserved; exclusive licensee American Association for the Advancement of Science. No claim to original U.S. Government Works