Universal linear-temperature resistivity: possible quantum diffusion transport in strongly correlated superconductors

Tao Hu1,2, Yinshang Liu1,2, Hong Xiao3, Gang Mu1,2 & Yi-feng Yang4,5,6

The strongly correlated electron fluids in high temperature cuprate superconductors demonstrate an anomalous linear temperature (T) dependent resistivity behavior, which persists to a wide temperature range without exhibiting saturation. As cooling down, those electron fluids lose the resistivity and condense into the superfluid. However, the origin of the linear-T resistivity behavior and its relationship to the strongly correlated superconductivity remain a mystery. Here we report a universal relation $\rho_{\mu} \lambda = \frac{d}{dT}$, which bridges the slope of the linear-T-dependent resistivity ($d\rho/dT$) to the London penetration depth $\lambda$ at zero temperature among cuprate superconductor Bi$_2$Sr$_2$CaCu$_2$O$_8$+$\delta$ and heavy fermion superconductors CeCoIn$_5$, where $\mu_0$ is vacuum permeability, $k_B$ is the Boltzmann constant and $\hbar$ is the reduced Planck constant. We extend this scaling relation to different systems and found that it holds for other cuprate, pnictide and heavy fermion superconductors as well, regardless of the significant differences in the strength of electronic correlations, transport directions, and doping levels. Our analysis suggests that the scaling relation in strongly correlated superconductors could be described as a hydrodynamic diffusive transport, with the diffusion coefficient ($D$) approaching the quantum limit $D \sim \hbar/m^*$, where $m^*$ is the quasi-particle effective mass.

In quantum mechanics, the uncertainty principle gives rise to quantum fluctuations of the system that may impose some universal bound on its physical properties. Calculations based on the AdS/CFT (Anti de-Sitter/Conformal Field Theory) have suggested a lower bound for the liquid viscosity, $\eta/s \geq \hbar/4\pi k_B$, where $\eta$ is the shear viscosity and $s$ the entropy. Recent experiments also revealed a quantum bound $D_s \geq \hbar/m$ for the spin diffusivity $D_s$ in a strongly interacting Fermi gas. Here $\hbar$ is the reduced Planck constant and $m$ is the mass of particles. It is therefore interesting to ask if such a lower bound may be realized in the electron transport of strongly correlated quantum critical systems.

One of the distinguished features of strongly correlated cuprate superconductors is the linear-temperature ($T$) dependent resistivity, which could extend to very high temperature and violate the Mott-Ioffe-Regel (MIR) limit. The linear relationship has also been observed in some heavy fermion superconductors, starting at around the superconducting transition temperature $T_c$, and extending to high temperatures of about 10–20 times $T_c$. Many different mechanisms have been proposed to explain the microscopic origin of the linear-T resistivity behavior including quantum critical theories and the more exotic AdS/CFT calculations. On the other hand, recent experiment suggested that the linear-T resistivity in different materials may share a similar scattering rate.

In the present work, we investigated the linear-T resistivity in a number of strongly correlated superconductors and demonstrate a connection between its coefficient and the superfluid density responsible for the charge carrying in the superconducting state. We show that this can be understood by a diffusion transport of heavy

1State Key Laboratory of Functional Materials for Informatics, Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, 865 Changning Road, Shanghai, 200050, China. 2CAS Center for Excellence in Superconducting Electronics(CENSE), Shanghai, 200050, China. 3Center for High Pressure Science and Technology Advanced Research, Beijing, 100094, China. 4Beijing National Laboratory for Condensed Matter Physics and Institute of Physics, Chinese Academy of Sciences, Beijing, 100190, China. 5Collaborative Innovation Center of Quantum Matter, Beijing, 100190, China. 6School of Physical Sciences, University of Chinese Academy of Sciences, Beijing, 100190, China. Correspondence and requests for materials should be addressed to T.H. (email: thu@mail.sim.ac.cn) or H.X. (email: hong.xiao@hpstar.ac.cn)
quasi-particles whose diffusion coefficient approaches the quantum limit $D = h/m^*,$ where $m^*$ is the effective mass of the quasi-particles.

**Results**

We start with the heavy fermion superconductor CeCoIn$_5$. Among all strongly correlated superconductors, CeCoIn$_5$ is remarkably similar to the high $T_c$ cuprate superconductors in several aspects. For example, it has also a two-dimensional Fermi surface, its superconducting phase is near to an antiferromagnetic phase, and its superconducting gap has $d$-wave symmetry. Besides, CeCoIn$_5$ is one of the purest strongly correlated superconductors, with a tunable linear-$T$ resistivity under modest applied pressure. To examine its transport properties, we have therefore grown high quality CeCoIn$_5$ single crystal samples by an indium self-flux method, and performed detailed transport measurements under pressure to avoid disorder related effects.

Figure 1(a) demonstrates the $T$-dependent resistivity curve of CeCoIn$_5$ under pressure from 0 GPa to 1.0 GPa. All of them exhibit a perfect linear-in-$T$ resistivity from around $T_c$ to about 20 K as indicated by the dashed lines. The inset of Fig. 1(a) shows the $T$-dependent resistivity of CeCoIn$_5$ up to 300 K. For comparison, we also plot in Fig. 1(b) the resistivity of Bi$_2$Sr$_2$CaCu$_2$O$_8$$_{x+y}$ from underdoped to overdoped regime with the oxygen contents from $x = 0.2135$ to 0.2722. Figure 1(c) demonstrates the $d\rho/dT$ versus $1/T$ for both compounds, using the experimental results for the penetration depth measured previously by muon spin spectroscopy and $ac$ susceptibility. We see remarkably that all the investigated samples fall on the same straight line described by $d\rho/dT = (\mu_B k_B/\hbar) \lambda^2$, with a coefficient that is determined entirely by the fundamental constants ($\mu_B$: the vacuum permeability; $k_B$: the Boltzmann constant; $\hbar$: the reduced Planck constant). This indicates a universal origin for the charge transport in both compounds.

The above relation between $d\rho/dT$ and $\lambda^2$ can be extended to various other strongly correlated superconductors with linear-$T$ resistivity. The data are summarized in Fig. 2 on a log-log scale. Most resistivity data were taken from experimental results on high-quality single crystal samples in order to obtain the intrinsic linear-in-$T$ coefficient. The values of the penetration depth were obtained by muon spin spectroscopy, optical conductivity measurement, and some other techniques. Note that for superconducting thin films, the experimental magnetic penetration depth generally deviates from the London penetration depth due to structural disorders in the films. Even in high quality ultrathin films, there is a large difference in superfluid density between the film and the bulk materials with same $T_c$. Consequently all the data of the London penetration depth shown in Fig. 2 were taken only from bulk materials. It is worth noting that Fig. 2 also includes the transport data for cuprate superconductors along different transport directions, e.g., YBa$_2$Cu$_3$O$_{6.93}$ along the $a$, $b$, and $c$-axis. Cuprates generally exhibit a metallic in-plane resistivity but an insulating-like resistivity along the $c$-axis below certain temperature, which reflects the two-dimensional nature of the system. Correspondingly, the penetration depth along the $c$-axis is determined by a Josephson-coupling between superconducting layers, which is different from the in-plane one. Thus it is amazing to observe that the same scaling relation holds true for both directions. Combining the data for all the strongly correlated superconductors summarized here, we see that the scaling $d\rho/dT = (\mu_B k_B/\hbar) \lambda^2$ spans over several orders of magnitude. Note that the in-plane LSCO data in the extremely underdoped regime $0.07 < p < 0.12$ demonstrates a systematic deviation from the scaling relationship as shown in Fig. 2. This deviation could be understood in terms of the complex competing phase, like charge density wave and pseudogap, which become significant in the underdoped regime.
Table 1. Transport parameters and London penetration depth at zero temperature.

| Material label | Temperature range (K) | ρ(T)/μΩ | Refs | Δλ (mm) | Refs |
|----------------|-----------------------|---------|------|---------|------|
| CeCoIn5 (0 Gpa) | 2.63 ± 0.97 | 250–400 | 49 | 92.5 | 26 |
| CeCoIn5 (0.55 Gpa) | 2.58 ± 1.20 | 100–300 | 50, 51 | 24 |
| FeSe | 8 | 5.84 | 22, 58 | 24 |
| La1.84Sr0.16CuO4 | 1.5 | 25 | 0.7 ± 0.1 | 100–300 | 59 | 270 ± 10 | 59 |
| Bi2Sr2CaCu2O8 | 0.95 ± 0.02 | 110–300 | 52 | 160 | 20 |
| UPt3 | 0.5 | 3.3 | 15–10 | 422 | 70 |

Note: The slope are directly taken from Hussey et al.67.
The above scaling relation is consistent with several well-known experimental facts. First, considering the special case at $T = T_c$ and neglecting the residual resistivity, the scaling relation $d\rho/dT \propto \lambda^2$ gives the well-known Home's law, $\sigma T_c \propto \lambda^2$, where $\sigma$ is the dc conductivity at $T_c$. Second, the Drude formula is often used to describe the resistivity of conventional metals, $\rho = m^*/ne^2\tau$, where $m^*$ is the effective mass of the quasi-particles, $n_e$ is the carrier density of quasi-particles, $e$ is the charge of electrons, and $\tau$ is the relaxation time. If we naively match the Drude formula with the above scaling relation for a non-quasiparticle system and assume that the normal fluid and the superfluid are composed of the same charge carriers, $\lambda_e = (m^*/\mu_0ne^2)^{1/2}$, we obtain immediately a material-independent scattering rate $\tau^{-1} = k_B T/\hbar$ for all these strongly correlated superconductors. This is consistent with the universal scattering rate recently observed in the linear-in-$T$ resistivity region among good and “bad” metals. However, one can not take it for granted that the normal fluid in Drude model and superfluid in London equation are always the same. Actually, experiments showed that only part of normal carriers condensate into superfluid. In addition, the measurements of the London moment already revealed the mass of Cooper pairs are undressed and have twice of the electron's bare mass, regardless the conventional normal metal superconductors, heavy fermion superconductors or cuprates, which is different from the effective mass in the Drude formula. These results suggest that the mass and carrier density of the superfluid ($n_s$) and the normal fluid ($n_n$) are different in strongly correlated superconductors. So one can not directly obtain the universal scaling relation simply by replacing $\rho$ with Drude model and $\lambda_e$ with London equation. The universal scaling relation $d\rho/dT = (\mu, k_B T/\hbar) \lambda^2$ has much deeper physics, which directly links the superfluid at zero temperature to the normal fluid responsible for the linear-in-$T$ resistivity in strongly correlated superconductors. It reveals an underlying relation between the superfluid and normal carriers: $n_s/\rho_0 = n_s/m^*$. And indeed experimental evidence shows that about one of the fourth normal carriers condensates into superfluid in optimal doped cuprates while the effective mass of optimum cuprates is about 3–4 times of the electron free mass, which validate $n_s/\rho_0 = n_s/m^*$. The above result provides important information on the nature of the electron transport in the quantum critical regime. Recently, several experiments have shown that electrons in solid can exhibit hydrodynamic flows similar to a classical viscous liquid, if the electron fluid equilibrates by the electron-electron collisions. Thus the electron transport in strongly correlated superconductors, where electron-electron interactions play a major role in the scattering processes, might in principle have a hydrodynamic description. Consequently, its linear-in-$T$ resistivity could be described by the well-known Einstein’s relation, an important law for the hydrodynamic transport, which states that the mobility ($\mu$) of a particle in a fluid is related to its diffusion coefficient ($D$), namely, $D = \mu k_B T$. However, we have $\rho = k_B T/\pi e^2 D$ and in the linear-in-$T$ regime, the diffusion coefficient $D$ must be a temperature-independent constant. Combining this and the scaling relation immediately yields $D = h/m^*$, which is the quantum limit of the charge diffusion coefficient for the quasi-particles with an effective mass, $m^*$. This is one of the most important consequence of our observations. Actually, the quantum limit of the diffusion coefficient was recently observed in cold fermionic atomic gases in the unitary limit of scattering. It implies that quantum diffusion transport might be a universal property of strongly correlated fermionic systems where the electron scatterings are so strong that the transport becomes highly incoherent. In fact, it was proposed recently that the transport in an incoherent metal is controlled by the collective diffusion of energy and charge, supporting the proposed scenario of quantum diffusion transport in the present work. Thus, the obtained scaling relation suggests the superfluid could also be governed by the quantum diffusion, since it connects the ground state with the normal state in the strongly correlated superconductors.

Our results also provide some insights on the nature of strongly correlated superconductivity, which is often born out of strongly correlated normal fluid in the quantum critical regime. Since the latter already approaches...
the quantum diffusion limit before it transits into the superfluid state, it implies a zero-point motion of the superfluid. Some people considered the quantum diffusion as a necessary condition for the presence of superfluid\(^\text{36, 47}\). In fact, the quantum diffusion might explain the Uemura results for superconducting transition temperatures. Y. Uemura et al. observed that the underdoped cuprate superconductors exhibit a Bose-Einstein-condensation (BEC)-like superconducting transition but with a reduced transition temperature\(^\text{25, 48}\). Actually, the BEC generally occurs when the thermal de Broglie wavelength \(\lambda_{\text{dB}}\) is comparable to the distance between bosons, where \(\lambda_{\text{dB}}\) characterizes a length scale within which the bosons can be regarded as quantum mechanical wave-packets. However, the quantum diffusion gives a new length scale \(\xi_{\text{BEC}} = \sqrt{D\tau}\) with \(\tau = h/k_B T\), which characterizes the length scale that carriers can travel before losing their quantum coherence. Since the diffusion length \(\xi_{\text{BEC}} = \sqrt{Dh^2/m^*k_B T}\) is less than \(\lambda_{\text{dB}} = \sqrt{2\pi\hbar^2/2m^*k_B T}\) of electron pairs under certain temperature, it makes \(\xi_{\text{BEC}}\) a new dephasing length to determine the BEC temperature. Thus the BEC temperature \(T_{\text{BEC}}\) is reduced to \(T_{\text{BEC}} = (\xi_{\text{BEC}}/\lambda_{\text{dB}})^2 = 1/\pi\) as observed in the Uemura plot\(^\text{25, 48}\).

**Conclusion**

In summary, we observed a universal scaling relation \(d\rho/dT = (\mu/e^2h)\lambda_{\text{dB}}^2\), which connects linear-\(T\)-dependent resistivity to superconducting superfluid density at zero temperature in strongly correlated superconductors. Our analysis suggests that the quantum diffusion might be the origin of this scaling relation. In this case, the charge transport is viewed as a diffusion process of quasi-particles with a diffusion coefficient that approaches the quantum limit, \(D = h/m^*\).

**Method**

The high quality CeCoIn\(_5\), single crystal samples are grown by an inductum self-flux method\(^\text{4}\). High quality crystals were chosen to perform the transport measurements. Four leads were attached to the single crystal, with the current applied parallel to the crystallographic \(a\) axis. The resistivity was measured both in ambient pressure as well as under hydrostatic pressure \(P\).

**References**

1. Kovtun, P. K., Son, D. T. & Starinets, A. O. Viscosity in Strongly Interacting Quantum Field Theories from Black Hole Physics. *Phys. Rev. Lett.* **94**, 111601 (2005).
2. Sommer, A., Ku, M., Roati, G. & Zwierlein, M. W. Universal spin transport in a strongly interacting Fermi gas. *Nature* **472**, 201–204 (2011).
3. Bardon, A. et al. Transverse demagnetization dynamics of a unitary Fermi gas. *Science* **344**, 722–724 (2014).
4. Gurvitch, M. & Fiory, A. T. Resistivity of La\(_{1.825}\)Sr\(_{0.175}\)CuO\(_4\) and YBa\(_2\)Cu\(_3\)O\(_7\) to 1100 K: absence of saturation and its implications. *Phys. Rev. Lett.* **59**, 1337 (1987).
5. Ioffe, A. & Regel, A. Non-crystalline, amorphous and liquid electronic semiconductors. *Prog. Semicond.* **4**, 237–291 (1960).
6. Petrovic, C. Fermi liquid theory and non-Fermi liquid metals. *J. Phys.: Condens. Matter* **16**, L253 (2004).
7. Paglione, J. et al. Nonvanishing energy scales at the quantum critical point of CeCoIn\(_5\). *Phys. Rev. Lett.* **97**, 106606 (2006).
8. Young, P. G. & Tinkham, M. The Role of Quantum Interference and Interactions in the Quantum Critical Point. *Phys. Rev. B* **79**, 134510 (2008).
9. Howald, L. & Tinkham, M. Superfluidity in a Dilute Fermi Gas. *Phys. Rev. B* **79**, 134511 (2008).
10. Hall, D. et al. Fermi liquid surface of the heavy-fermion superconductor CeCoIn\(_5\). The de Haas–van Alphen effect in the normal state. *Phys. Rev. B* **64**, 113208 (2001).
11. Settai, R. et al. Quasi-two-dimensional fermi surfaces and the de Haas-van Alphen oscillation in both the normal and superconducting mixed states of CeCoIn\(_5\). *J. Phys.: Condens. Matter* **13**, L627 (2001).
12. Noh, S. et al. Quantum Critical Behavior in the Heavy-Fermion Superconductor CeCoIn\(_5\). *Phys. Rev. Lett.* **102**, 087001 (2009).
13. Zaanen, S. et al. Towards the Identification of a Quantum Critical Line in the \((p, B)\) Phase Diagram of CeCoIn\(_5\) with Thermal-Expansion Measurements. *Phys. Rev. Lett.* **109**, 077003 (2013).
14. Hu, T. et al. Strong Magnetic Fluctuations in a Superconducting State of CeCoIn\(_5\). *Phys. Rev. Lett.* **108**, 056401 (2012).
15. Stock, C., Broholm, C., Hufnagel, S., Kang, H. J. & Petrovic, C. Spin Resonance in the \(d\)-Wave Superconductor CeCoIn\(_5\). *Science* **339**, 804–807 (2012).
16. Xiao, H., Hu, T., Almasan, C., Sayles, T. & Maple, M. Pairing symmetry of CeCoIn\(_5\), detected by in-plane torque measurements. *Phys. Rev. B* **78**, 014510 (2008).
17. Zhou, B. B. et al. Visualizing nodal heavy fermion superconductivity in CeCoIn\(_5\). *Nat. Phys.* **9**, 474–479 (2013).
18. Sidorov, V. A. et al. Superconductivity and quantum criticality in CeCoIn\(_5\). *Phys. Rev. Lett.* **89**, 157004 (2002).
19. Bianchi, A., Movshovich, R., Vekhter, I., Laglouso, P. & Sarrao, J. Avoided Antiferromagnetic Order and Quantum Critical Point in CeCoIn\(_5\). *Phys. Rev. Lett.* **91**, 237001 (2003).
20. Sato, S. et al. Disorder in quantum critical superconductors. *Nat. Phys.* **10**, 120–125 (2014).
21. Park, T. et al. Hidden magnetism and quantum criticality in the heavy fermion superconductor CeRhIn\(_5\). *Nature* **440**, 65–68 (2006).
22. Watanabe, T., Fujiwara, T. & Matsuda, A. Anisotropic Resistivities of Precisely Oxygen Controlled Single-Crystal Bi\(_2\)Sr\(_2\)CaCu\(_2\)O\(_6+x\))\(_2\). *J. Phys. Soc. Jpn.* **68**, 474–479 (2003).
23. Howald, L. et al. Strong Temperature Dependence of the Magnetic Penetration Depth in Single Crystals of the Heavy-Fermion Superconductor CeCoIn\(_5\). *Phys. Rev. B* **70**, 014505 (2003).
24. Anukool, W., Barakat, S., Togano, S., Cooper, C. & Cooper, J. Effect of hole doping on the magnetic penetration depth in Bi\(_2\)Sr\(_2\)CaCu\(_2\)O\(_8\))\(_2\). *Phys. Rev. B* **80**, 042516 (2009).
25. Uemura, Y. et al. Universal Correlations between \(T_c\) and \(n/m^*\) (Carrier Density over Effective Mass) in High-\(T_c\) Cuprate Superconductors. *Phys. Rev. Lett.* **62**, 2317 (1989).
26. Homes, C. et al. Coherence, incoherence, and scaling along the \(c\) axis of YBa\(_2\)Cu\(_3\)O\(_7\)). *Phys. Rev. B* **71**, 184515 (2005).
27. Homes, C. et al. Universal scaling relation in high-temperature superconductors. *Nature* **430**, 539–541 (2004).
28. Tinkham, M. *Introduction to Superconductivity: Second Edition* (Dover Publications, 2004).
29. Lemberger, T. R., Hetel, I., Tsukada, A., Naito, M. & Randeria, M. Superconductor-to-metal quantum phase transition in overdoped La\(_{2.8}\)Sr\(_{0.2}\)CuO\(_4\). *Phys. Rev. B* **83**, 140507 (2011).
31. Hetel, I., Lemberger, T. R. & Randiera, M. Quantum critical behaviour in the superfluid density of strongly underdoped ultrathin copper oxide films. Nat. Phys. 3, 700–702 (2007).
32. Basov, D. N., Timusk, T., Dabrowski, B. & Jorgensen, J. D. c-axis response of YBa2Cu3O6+δ: A pseudogap and possibility of Josephson coupling of CuO2 planes. Phys. Rev. B 50, 3511–3514 (1994).
33. Dordiev, S. V. et al. Global trends in the interplane penetration depth of layered superconductors. Phys. Rev. B 65, 134511 (2002).
34. Shibasahi, T. et al. Anisotropic penetration depth in La2−xSrxCuO4. Phys. Rev. Lett. 72, 2263–2266 (1994).
35. Drude, P. Über elektrometrie der metalle. Annalen der Physik 206, 566–613 (1906).
36. Tanne, D. et al. Superfluid and normal fluid density in high-tc superconductors. Physica B: Condensed Matter 244, 1–8 (1998).
37. Hildebrandt, A. F. Magnetic field of a rotating superconductor. Physical Review Letters 12, 190 (1964).
38. Sanzari, M. A., Cui, H. & Karwacki, F. London moment for heavy-fermion superconductors. Applied physics letters 68, 3802–3804 (1996).
39. Verheijen, A., Van Ruitenbeeck, J., de Bruyn Ouboter, R. & de Jongh, L. Measurement of the London moment in two high-temperature superconductors. Nature 345, 418–419 (1990).
40. Padilla, W. I. et al. Constant effective mass across the phase diagram of high-Tc cuprates. Phys. Rev. B 72, 060511 (2005).
41. Bandurin, D. et al. Negative local resistance caused by viscous electron backflow in graphene. Science 351, 1055–1058 (2016).
42. Cossano, J. et al. Observation of the Dirac fluid and the breakdown of the Wiedemann-Franz law in graphene. Science 351, 1058–1061 (2016).
43. Moll, P. J. W., Kushwaha, P., Nandi, N., Schmidt, B. & Mackenzie, A. P. Evidence for hydrodynamic electron flow in PdCoO2. 54. Puchkov, A., Timusk, T., Doyle, S. & Hermann, A. (1998).
45. Hartnoll, S. A. Theory of universal incoherent metallic transport. Nat. Phys. 11, 54–61 (2015).
46. Mandelsohn, K. The frictionless state of aggregation. Proc. Phys. Soc. 57, 371 (1945).
47. Hirsch, J. E. Kinetic energy driven superconductivity and superfluidity. Mod. Phys. Lett. 25, 2219–2237 (2011).
48. Uemura, Y. et al. Basic similarities among cuprate, bismuthate, organic, chevrel-phase, and heavy-fermion superconductors shown by penetration-depth measurements. Phys. Rev. Lett. 66, 2665 (1991).
49. Takezaki, K., Mizahashi, K., Takagi, H. & Uchida, S. Interplane charge transport in YBa2Cu3Oy: Spin-gap effect on in-plane and out-of-plane resistivity. Phys. Rev. B 50, 6534 (1994).
50. Tallon, J. et al. In-plane Anisotropy of the Penetration Depth Due to Superconductivity on the Cu-O Chains in YBa2Cu3Oy. Phys. Rev. Lett. 74, 1008 (1995).
51. Basov, D. et al. In-Plane Anisotropy of the Penetration Depth in YBa2Cu3Oy and YBa2Cu4Oy Superconductors. Phys. Rev. Lett. 74, 598 (1995).
52. Ando, Y., Segawa, K., Komiyama, S. & Lavrov, A. Electrical resistivity anisotropy from self-organized one dimensionality in high-temperature superconductors. Phys. Rev. Lett. 88, 137005 (2002).
53. Tyler, A. et al. High-field study of normal-state magnetotransport in Tl2Ba2CaCu2O8+δ. Phys. Rev. B 57, R728 (1998).
54. Puchkov, A., Timusk, T., Doyle, S. & Hermann, A. Ab-plane optical properties of Tl2Ba2CaCu2O8+δ. Phys. Rev. B 51, 3312 (1995).
55. Schilling, J. et al. Experimental test of the interlayer pairing models for high-Tc superconductivity using grazing-incidence infrared reflectometry. Phys. Rev. B 55, 11118 (1997).
56. Tsvelkov, A. et al. Global and local measures of the intrinsic josephson coupling in YBa2Cu3Oy, as a test of the interlayer tunnelling model. Nature 395, 360–362 (1998).
57. Moler, K. A., Kirtley, J. R., Hinko, D., Li, T. & Xu, M. Images of interlayer Josephson vortices in Tl2Ba2CaCu2O8+δ. Science 279, 1193–1196 (1998).
58. Matsuda, A., Sugita, S. & Watanabe, T. Temperature and doping dependence of the Bi1−xSrxCa2Cu3Oy pseudogap and superconducting gap. Phys. Rev. B 60, 1377 (1999).
59. Takahashi, H. et al. Investigation of the superconducting gap structure in SrFe1−xPtxAs1−y, by magnetic penetration depth and flux flow resistivity analysis. Phys. Rev. B 86, 144525 (2012).
60. Kasahara, S. et al. Evolution from non-Fermi-to fermi-liquid transport via isovalent doping in BaFe2(As1−yPty)2 superconductors. Phys. Rev. B 81, 184519 (2010).
61. Hashimoto, K. et al. A sharp peak of the zero-temperature penetration depth at optimal composition in BaFe2(As1−yPty)2 superconductors. Science 336, 1554–1557 (2012).
62. Okada, T. et al. Magnetic penetration depth and flux-flow resistivity measurements on NaFe1−xCoxAs single crystals. Physica C: Superconductivity 494, 109–112 (2013).
63. Abdel-Hafiez, M. et al. Temperature dependence of lower critical field Hc2(T) shows nodeless superconductivity in FeSe. Phys. Rev. B 88, 174512 (2013).
64. Hsu, F.-C. et al. Superconductivity in the PBO-type structure α-FeSe. Proc. Natl. Acad. Sci. 105, 14262–14264 (2008).
65. Nakamura, Y. & Uchida, S. Anisotropic transport properties of single-crystal La2−xSrxCuO4: Evidence for the dimensional crossover. Phys. Rev. B 47, 8369 (1993).
66. Panagopoulos, C. et al. Superfluid response in monolayer high-Tc cuprates. Phys. Rev. B 67, 220502 (2003).
67. Hussey, N. et al. Dichotomy in the t-linear resistivity in hole-doped cuprates. Philos. Trans. R. Soc. London A Math. Phys. Eng. Sci. 369, 1626–1639 (2011).
68. Ando, Y., Komiyama, S., Segawa, K., Ono, S. & Kurita, Y. Electronic phase diagram of high-Tc cuprate superconductors from a mapping of the in-plane resistivity curvature. Phys. Rev. Lett. 93, 267001 (2004).
69. Russo, P. et al. Muon spin relaxation study of superconducting Ba1−xSrxLa2−yCa2+yO8. Phys. Rev. B 75, 054511 (2007).
70. Joynt, R. & Taillefer, L. The superconducting phases of UPt3. Rev. Mod. Phys. 74, 235 (2002).

Acknowledgements
We sincerely thank Prof. Mianheng Jiang, Prof. Xiaoming Xie, Dr. Wei Li, Prof. Haicang Ren, Prof. Ting-Kuo Lee, Prof. Yan Chen and Prof. Ang Li for discussions. This study was supported by the National Natural Science Foundation of China (Grant Nos 11574338, U1530402, 11522435), the Strategic Priority Research Program (B) of the Chinese Academy of Sciences (Grant Nos XDB04040300, XDB07020200) and the Youth Innovation Promotion Association of the Chinese Academy of Sciences.

Author Contributions
T.H. Planned the research. Y.L. carried out the experiment. T.H. and H.X. wrote the manuscript. G.M. and Y.Y. gave fruitful discussions. All authors were intensively involved in the research.

Additional Information
Competing Interests: The authors declare that they have no competing interests.
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) 2017