Universal Heat Conduction in the Iron Arsenide Superconductor KFe_2As_2: Evidence of a *d*-Wave State

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(Received 16 January 2012; published 21 August 2012)

The thermal conductivity κ of the iron arsenide superconductor KFe_2As_2 was measured down to 50 mK for a heat current parallel and perpendicular to the tetragonal *c* axis. A residual linear term at $T \to 0$, κ_0/T is observed for both current directions, confirming the presence of nodes in the superconducting gap. Our value of κ_0/T in the plane is equal to that reported by Dong *et al.* [Phys. Rev. Lett. **104**, 087005 (2010)] for a sample whose residual resistivity ρ_0 was 10 times larger. This independence of κ_0/T on impurity scattering is the signature of universal heat transport, a property of superconducting states with symmetry-imposed line nodes. This argues against an *s*-wave state with accidental nodes. It favors instead a *d*-wave state, an assignment consistent with five additional properties: the magnitude of the critical scattering rate Γ_c for suppressing T_c to zero; the magnitude of κ_0/T, and its dependence on current direction and on magnetic field; the temperature dependence of $\kappa(T)$.

DOI: 10.1103/PhysRevLett.109.087001 PACS numbers: 74.25.F−, 74.20.Rp, 74.70.Xa

The pairing mechanism in a superconductor is intimately related to the pairing symmetry, which in turn is related to the gap structure $\Delta(\mathbf{k})$. In a *d*-wave state with $d_{x^2-y^2}$ symmetry, the order parameter changes sign with angle in the *x*-*y* plane, forcing the gap to go to zero along diagonal directions ($k_y = \pm k_x$). Those zeros (or nodes) in the gap are imposed by symmetry. The gap in states with *s*-wave symmetry will in general not have nodes, although accidental nodes can occur, depending on the anisotropy of the pairing interaction. In iron-based superconductors, the gap shows nodes in some materials, as in $BaFe_2(As_{1-x}P_x)_2$ [1] and $Ba(Fe_{1-x}Ru_x)_2As_2$ [2], and not in others, as in $Ba_{1-x}K_xFe_2As_2$ [3,4] and $Ba(Fe_{1-x}Co_x)_2As_2$ [5,6] at optimal doping.

In KFe_2As_2, the end member of the $Ba_{1-x}K_xFe_2As_2$ series (with $x = 1$), the presence of nodes was detected by thermal conductivity [7], penetration depth [8], and NMR [9,10]. The question is whether those nodes are imposed by symmetry or accidental. Calculations differ in their predictions [11–13]. Some favor a *d*-wave state [14], others an *s*-wave state with accidental line nodes that run either parallel to the *c* axis [15] or perpendicular [11]. One can distinguish a *d*-wave state from an extended *s*-wave state with accidental nodes by looking at the effect of impurity scattering [16]. Nodes are robust in the former, but impurity scattering will eventually remove them in the latter, as it makes $\Delta(\mathbf{k})$ less anisotropic.

In this Letter, we investigate the pairing symmetry of KFe_2As_2 using thermal conductivity, a bulk directional probe of the superconducting gap [17]. All aspects of heat transport are found to be in agreement with the theoretical expectation for a *d*-wave gap [18,19], and inconsistent with accidental line nodes, whether vertical or horizontal. Moreover, the critical scattering rate Γ_c for suppressing T_c to zero is of order T_{c0}, as expected for a *d*-wave superconductor, while it is 50 times T_{c0} in optimally doped $BaFe_2As_2$ [20].

Methods.—Single crystals of KFe_2As_2 were grown from self flux [21]. Two samples were measured: one for currents along the *a* axis and one for currents along the *c* axis. Their superconducting temperature, defined by the point of zero resistance, is $T_c = 3.80 \pm 0.05$ K and 3.65 ± 0.05 K, respectively. Since the contacts were soldered with a superconducting alloy, a small magnetic field of 0.05 T was applied to make the contacts normal and thus ensure good thermalization. For more information on sample geometry, contact technique and measurement protocol, see Ref. [6].

Resistivity.—To study the effect of impurity scattering in KFe_2As_2, we performed measurements on a single crystal whose residual resistivity ratio (RRR) is 10 times larger than that of the sample studied by Dong *et al.* [7] [Fig. 1(a)]. To remove the uncertainty associated with geometric factors, we normalize the data of Dong *et al.* to our value at $T = 300$ K. A power-law fit below 16 K yields a residual resistivity $\rho_0 = 0.21 \pm 0.02$ $\mu\Omega$ cm (2.24 ± 0.05 $\mu\Omega$ cm) for our (their) sample, so that $\rho(300\text{ K})/\rho_0 = 1180$ (110).

We attribute the lower ρ_0 in our sample to a lower concentration of impurities or defects. Note that except

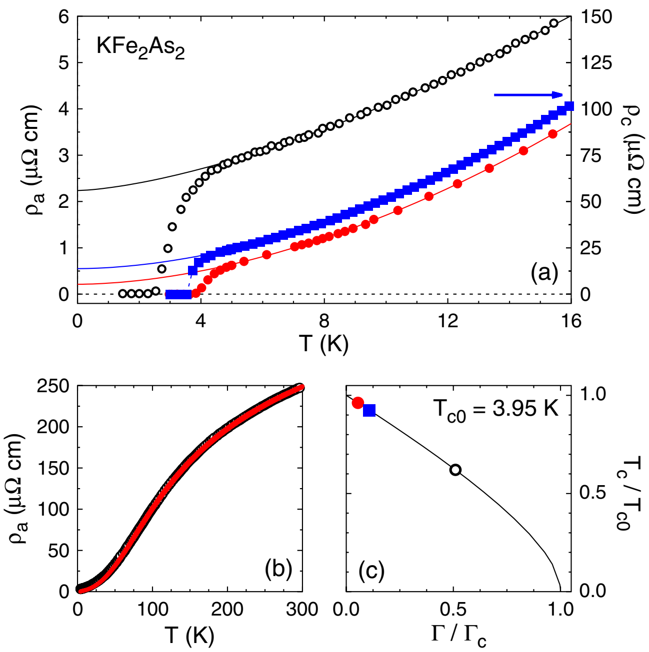

FIG. 1 (color online). (a) Electrical resistivity of the two samples of KFe_2As_2 studied here, with $J \parallel a$ (full red circles, left axis) and $J \parallel c$ (full blue squares, right axis). Our a-axis data are compared to those of Dong *et al.* [7] (open circles, left axis), normalized here to have the same value at $T = 300$ K (see text). The lines are a fit to $\rho = \rho_0 + aT^\alpha$ from which we extrapolate ρ_0 at $T = 0$. (b) Same data for the two a-axis samples, up to 300 K. (c) Abrikosov-Gorkov formula for the decrease of T_c with scattering rate Γ (line), used to obtain a value of Γ/Γ_c for the three samples of KFe_2As_2, given their T_c values and the factor 10 in ρ_0 between the two a-axis samples (circles), assuming a disorder-free value of $T_{c0} = 3.95$ K.

for the different ρ_0, the two resistivity curves $\rho(T)$ are essentially identical [Fig. 1(b)]. Supporting evidence for a difference in impurity or defect concentration is the difference in critical temperature: $T_c = 3.80 \pm 0.05$ K (2.45 ± 0.10 K) for our (their) sample. Assuming that the impurity scattering rate $\Gamma \propto \rho_0$, we can use the Abrikosov-Gorkov formula for the drop in T_c vs Γ to extract a value of Γ/Γ_c for the two samples, where Γ_c is the critical scattering rate needed to suppress T_c to zero [Fig. 1(c)]. We get $\Gamma/\Gamma_c = 0.05$ (0.5) for our (their) sample.

The c-axis resistivity $\rho_c(T)$ has the same temperature dependence as $\rho_a(T)$ below $T \simeq 40$ K [Fig. 1(a)], with an intrinsic anisotropy $\Delta\rho_c/\Delta\rho_a = 25 \pm 1$, where $\Delta\rho \equiv \rho(T) - \rho_0$, with $\rho_{c0} = 13 \pm 1$ $\mu\Omega$ cm. We attribute the larger anisotropy at $T \to 0$, $\rho_{c0}/\rho_{a0} = 60 \pm 10$, to a larger Γ in our c-axis sample, consistent with the lower value of T_c, from which we deduce $\Gamma/\Gamma_c = 0.1$ [Fig. 1(c)].

Universal heat transport.—The thermal conductivity is shown in Fig. 2. The residual linear term κ_0/T is obtained from a fit to $\kappa/T = a + bT^\alpha$ below 0.3 K, where $a \equiv \kappa_0/T$. The dependence of κ_0/T on magnetic field H is shown in Fig. 3. Extrapolation to $H = 0$ yields $\kappa_{a0}/T = 3.6 \pm 0.5$ mW/K^2 cm and $\kappa_{c0}/T = 0.18 \pm 0.03$ mW/K^2 cm.

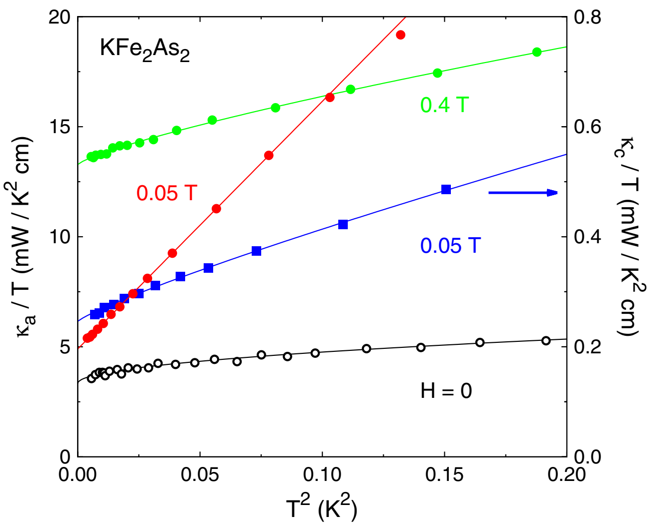

FIG. 2 (color online). Thermal conductivity of KFe_2As_2, plotted as κ/T vs T^2, for $J \parallel a$ (κ_a, circles, left axis) and $J \parallel c$ (κ_c, squares, right axis), for a magnetic field $H \parallel c$ as indicated. Our a-axis data are compared to those of Dong *et al.* [7] (open circles, left axis), normalized by the same factor as in Fig. 1 (see text). Lines are a fit to $\kappa/T = a + bT^\alpha$, used to extrapolate the residual linear term $a \equiv \kappa_0/T$ at $T = 0$. For our a-axis sample (full red circles), $\alpha = 2.0$, while for others $\alpha < 2$.

We compare these to Dong *et al.*'s [7] data, normalized by the same factor as for electrical transport, giving $\kappa_{0a}/T = 3.32 \pm 0.03$ mW/K^2 cm. At $H \to 0$, κ_{a0}/T is the same in the two samples (inset of Fig. 3), within error bars.

This universal heat transport, whereby κ_0/T is independent of the impurity scattering rate, is a classic signature of line nodes imposed by symmetry [18,19]. Calculations show the residual linear term to be independent of scattering rate and phase shift [18], and free of Fermi-liquid and vertex corrections [19]. For a quasi-2D d-wave superconductor [18,19],

$$\frac{\kappa_0}{T} \simeq \frac{\kappa_{00}}{T} \equiv \frac{\hbar}{2\pi}\frac{\gamma_N v_F^2}{\Delta_0}, \qquad (1)$$

where γ_N is the residual linear term in the normal-state electronic specific heat, v_F is the Fermi velocity, and the superconducting gap $\Delta = \Delta_0 \cos(2\phi)$ [22].

ARPES measurements on KFe_2As_2 reveal a Fermi surface with three concentric holelike cylinders centered on the Γ point of the Brillouin zone, labeled α, β, and γ, and a 4th cylinder near the X point [23,24]. dHvA measurements detect all of these surfaces except the β, and obtain Fermi velocities in reasonable agreement with ARPES dispersions, with an average value of $v_F \simeq 4 \times 10^6$ cm/s [25]. The measured effective masses account for approximately 80% of the measured $\gamma_N = 85 \pm 10$ mJ/K^2 mol [26,27]. In d-wave symmetry, the gap in KFe_2As_2 will necessarily have nodes on all Γ-centered Fermi surfaces, and possibly on the X-centered surface as well [14]. The total κ_0/T may be estimated from Eq. (1) by using the average v_F

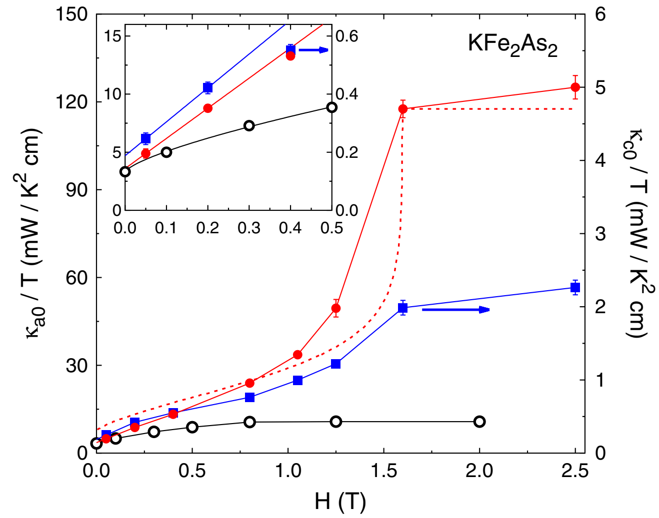

FIG. 3 (color online). Field dependence of κ_0/T obtained as in Fig. 2 (with corresponding symbols). The dashed line is a theoretical calculation for a d-wave superconductor with $\hbar\Gamma/\Delta_0 = 0.1$ [38]. Inset: Zoom at low field. Lines are a power-law fit to extract the value of κ_0/T at $H = 0$.

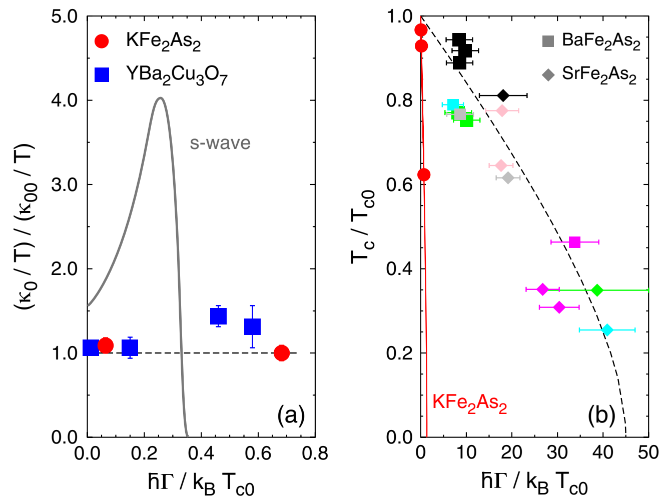

FIG. 4 (color online). Dependence of κ_0/T (a) and T_c (b) on impurity scattering rate Γ, normalized by T_{c0}, the disorder-free superconducting temperature. (a) κ_0/T for KFe_2As_2 (red circles; see text) and the cuprate $YBa_2Cu_3O_7$ (blue squares; from Ref. [30]), normalized by the theoretically expected value for a d-wave superconductor, $\kappa_{00}/T = 3.3$ and $0.16\ \mathrm{mW/K^2\,cm}$, respectively (see text). The typical dependence expected of an s-wave state with accidental nodes is also shown, from a calculation applied to pnictides (black line; from Ref. [31]). (b) T_c for KFe_2As_2 [red circles; from Fig. 1(c)] and for the pnictides $BaFe_2As_2$ and $SrFe_2As_2$ at optimal doping (from Ref. [20]).

and the measured (total) γ_N, which yields $\kappa_{00}/T = 3.3 \pm 0.5\ \mathrm{mW/K^2\,cm}$, assuming $\Delta_0 = 2.14 k_B T_{c0}$, with $T_{c0} = 3.95$ K. This is in excellent agreement with the experimental value of $\kappa_0/T = 3.6 \pm 0.5\ \mathrm{mW/K^2\,cm}$.

To compare with cuprates, the archetypal d-wave superconductors, we use Eq. (1) expressed directly in terms of v_Δ, the slope of the gap at the node, namely, $\kappa_{00}/T \simeq (k_B^2/3\hbar c)(v_F/v_\Delta)$, with c the interlayer separation [18,19]. The ratio v_F/v_Δ was measured by ARPES on $Ba_2Sr_2CaCu_2O_{8+\delta}$ [28], giving $v_F/v_\Delta \simeq 16$ at optimal doping, so that $\kappa_{00}/T \simeq 0.16\ \mathrm{mW/K^2\,cm}$. This is in excellent agreement with the experimental value of $\kappa_0/T = 0.15 \pm 0.01\ \mathrm{mW/K^2\,cm}$ measured in $YBa_2Cu_3O_y$ at optimal doping [29].

In Fig. 4(a), we plot κ_0/T vs Γ for both KFe_2As_2 and $YBa_2Cu_3O_7$, the superconductor in which universal heat transport was first demonstrated [30]. We see that κ_0/T remains approximately constant up to at least $\hbar\Gamma \simeq 0.5 k_B T_{c0}$ in both cases. We conclude that both the magnitude of κ_0/T in KFe_2As_2 and its insensitivity to impurity scattering are precisely those expected of a d-wave superconductor. By contrast, in an extended s-wave superconductor, there is no direct relation between κ_0/T and Δ_0, and a strong nonmonotonic dependence on Γ is expected, since impurity scattering will inevitably make Δ_0 less anisotropic [16]. This is confirmed by calculations applied to pnictides, which typically find that κ_0/T vs Γ first rises and then plummets to zero when nodes are lifted by strong scattering [31] [see Fig. 4(a)].

Critical scattering rate.—In a d-wave superconductor, the critical scattering rate Γ_c is such that $\hbar\Gamma_c \simeq k_B T_{c0}$ [32]. We can estimate Γ_c for KFe_2As_2 from the critical value of ρ_0, evaluated as twice that for which $\Gamma/\Gamma_c = 0.5$ in Fig. 1(c), namely, $\rho_0^{\mathrm{crit}} \simeq 4.5\ \mu\Omega\,\mathrm{cm}$. Using $L_0/\rho_0^{\mathrm{crit}} = \gamma_N v_F^2 \tau_c/3$, where $L_0 \equiv (\pi^2/3)(k_B/e)^2$, we get $\hbar\Gamma_c = \hbar/2\tau_c \simeq 1.3 \pm 0.2 k_B T_{c0}$, in excellent agreement with the expectation for a d-wave state. By contrast, $\hbar\Gamma_c/k_B T_{c0} \simeq 45$ in $BaFe_2As_2$ and $SrFe_2As_2$ at optimal Co, Pt, or Ru doping [20] [see Fig. 4(b)]. This factor 30 difference in the sensitivity of T_c to impurity scattering is proof that the pairing symmetry of KFe_2As_2 is different from the s-wave symmetry of Co-doped $BaFe_2As_2$ [6].

Direction dependence.—In the case of a d-wave gap on a single quasi-2D cylindrical Fermi surface (at the zone center), the gap would necessarily have four line nodes that run vertically along the c axis. In such a nodal structure, zero-energy nodal quasiparticles will conduct heat not only in the plane but also along the c axis by an amount proportional to the c-axis dispersion of the Fermi surface. In the simplest case, c-axis conduction will be smaller than a-axis conduction by a factor equal to the mass tensor anisotropy [v_F^2 in Eq. (1)]. In other words, $(\kappa_{a0}/T)/(\kappa_{c0}/T) \simeq (\kappa_{aN}/T)/(\kappa_{cN}/T) = (\sigma_{aN})/(\sigma_{cN})$, the anisotropy in the normal-state thermal and electrical conductivities, respectively. This is confirmed by calculations for a quasi-2D d-wave superconductor [33], whose vertical line nodes yield an anisotropy ratio in the superconducting state very similar to that of the normal state. This is what we see in KFe_2As_2 (inset of Fig. 3): $(\kappa_{a0}/T)/(\kappa_{c0}/T) = 20 \pm 4$, very close to the intrinsic normal-state anisotropy

$(\sigma_{aN})/(\sigma_{cN}) = (\Delta\rho_c)/(\Delta\rho_a) = 25 \pm 1$. This shows that the nodes in KFe_2As_2 are vertical lines running along the c axis, ruling out proposals [11] of horizontal line nodes lying in a plane normal to the c axis.

Moreover, the fact that the Fermi surface of KFe_2As_2 contains several sheets with very different c-axis dispersions [25,34] provides compelling evidence in favor of d-wave symmetry. In an extended s-wave scenario, the gap would typically develop vertical line nodes on some but not all zone-centered sheets of the Fermi surface [15], and so the anisotropy in κ would typically be very different in the superconducting and normal states, unlike what is measured. By contrast, in d-wave symmetry all zone-centered sheets must necessarily have nodes, thereby ensuring automatically that transport anisotropy remains similar in the superconducting and normal states.

Temperature dependence.—So far, we have discussed the limits $T \to 0$ and $H \to 0$, where nodal quasiparticles are excited only by the pair-breaking effect of impurities. Raising the temperature will further excite nodal quasiparticles. Calculations for a d-wave superconductor show that the electronic thermal conductivity grows as T^2 [18,22]:

$$\frac{\kappa}{T} \simeq \frac{\kappa_{00}}{T}\left(1 + a\frac{T^2}{\gamma^2}\right), \tag{2}$$

where a is a dimensionless number and $\hbar\gamma$ is the impurity bandwidth, which grows with the scattering rate Γ [18]. A T^2 slope in κ/T was resolved in $YBa_2Cu_3O_7$ [29].

Our KFe_2As_2 sample shows a clear T^2 dependence below $T \simeq 0.3$ K, with $\kappa_a/T = (\kappa_{a0}/T)(1 + 23T^2)$ (Fig. 2). Comparison with Dong *et al.* 's [7] data reveals that this T^2 term must be due to quasiparticles. Indeed, because phonon conduction at sub-Kelvin temperatures is limited by sample boundaries and not impurities [35], the fact that the slope of κ/T in their sample (of similar dimensions) is at least 10 times smaller (Fig. 2) implies that the larger slope in our data must be electronic.

In the limit of unitary scattering, $\gamma^2 \propto \Gamma$, so that a 10 times larger Γ would yield a 10 times smaller T^2 slope [18], consistent with the observation. The temperature below which the T^2 dependence of κ_e/T sets in, $T \simeq 0.1T_c$, is a measure of γ. It is in excellent agreement with the temperature below which the penetration depth $\lambda_a(T)$ of KFe_2As_2 (in a sample with similar RRR) deviates from its linear T dependence [8], as expected of a d-wave superconductor [36]. Note that the T dependence of κ/T for an extended s-wave gap is not T^2 [31].

Magnetic field dependence.—Increasing the magnetic field is another way to excite quasiparticles. If the gap has nodes, the field will cause an immediate rise in κ_0/T [17,37,38], as observed in all three samples of KFe_2As_2 (inset of Fig. 3). Calculations for a d-wave superconductor in the clean limit ($\hbar\Gamma \ll k_B T_c$) yield a nonmonotonic increase of κ_0/T vs H [38] in remarkable agreement with data on the clean sample (Fig. 3).

A rapid initial rise in κ_0/T vs H has been observed in the cuprate superconductors $YBa_2Cu_3O_7$ [39] and $Tl_2Ba_2CuO_{6+\delta}$ [40]. In the dirty limit, KFe_2As_2 [7] and $Tl_2Ba_2CuO_{6+\delta}$ [40] show nearly identical curves of κ_0/T vs H/H_{c2} (see Ref. [7]). Measurements on cuprates in the clean limit, such as optimally doped $YBa_2Cu_3O_y$, have so far been limited to $H \ll H_{c2}$.

In summary, all aspects of the thermal conductivity of KFe_2As_2, including its dependence on impurity scattering, current direction, temperature, and magnetic field, are in detailed and quantitative agreement with theoretical calculations for a d-wave superconductor. The scattering rate needed to suppress T_c to zero is exactly as expected of d-wave symmetry, and vastly smaller than that found in other pnictide superconductors where the gap is believed to have an s-wave symmetry. This is compelling evidence that, for this iron arsenide superconductor, the gap has a d-wave symmetry, in agreement with renormalization-group calculations [14]. Replacing K in KFe_2As_2 by Ba leads to a superconducting state with a 10 times higher T_c, but with a full gap without nodes [4], necessarily of a different symmetry. Understanding the relation between this factor 10 and the pairing symmetry is expected to provide insight into what boosts T_c in these systems.

We thank A. Carrington, J. Chang, A. Chubukov, R. Fernandes, R. W. Hill, P. J. Hirschfeld, J. Paglione, S. Y. Li, M. Sutherland, R. Thomale, and I. Vekhter for fruitful discussions and J. Corbin for his assistance with the experiments. Work at Sherbrooke was supported by a Canada Research Chair, CIFAR, NSERC, CFI, and FQRNT. Work at the Ames Laboratory was supported by the DOE-Basic Energy Sciences under Contract No. DE-AC02-07CH11358. Work in Japan was supported by Grants-in-Aid for Scientific Research (No. 21540351 and No. 22684016) from MEXT and JSPS and Innovative Areas "Heavy Electrons" (No. 20102005 and No. 21102505) from MEXT, Global COE and AGGST financial support program from Chiba University.

Note added in proof.—By adding Co impurities in KFe_2As_2, a recent study [41] has confirmed that T_c falls rapidly to zero with impurity scattering, roughly at $\rho_{crit} = 4.5\ \mu\Omega$ cm, and the residual linear term in the thermal conductivity is indeed universal, remaining approximately constant even when the normal-state conductivity is decreased by a factor of 30.

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[1] K. Hashimoto *et al.*, Phys. Rev. B **81**, 220501 (2010).
[2] X. Qui *et al.*, Phys. Rev. X **2**, 011010 (2012).
[3] X. G. Luo *et al.*, Phys. Rev. B **80**, 140503 (2009).
[4] J.-Ph. Reid *et al.*, arXiv:1105.2232.

[5] M. A. Tanatar, J.-Ph. Reid, H. Shakeripour, X. G. Luo, N. Doiron-Leyraud, N. Ni, S. L. Bud'ko, P. C. Canfield, R. Prozorov, and L. Taillefer, Phys. Rev. Lett. **104**, 067002 (2010).
[6] J.-Ph. Reid, M. A. Tanatar, X. G. Luo, H. Shakeripour, N. Doiron-Leyraud, N. Ni, S. L. Bud'ko, P. C. Canfield, R. Prozorov, and L. Taillefer, Phys. Rev. B **82**, 064501 (2010).
[7] J. K. Dong, S. Y. Zhou, T. Y. Guan, H. Zhang, Y. F. Dai, X. Qiu, X. F. Wang, Y. He, X. H. Chen, and S. Y. Li, Phys. Rev. Lett. **104**, 087005 (2010).
[8] K. Hashimoto *et al.*, Phys. Rev. B **82**, 014526 (2010).
[9] H. Fukazawa *et al.*, J. Phys. Soc. Jpn. **78**, 083712 (2009).
[10] S. W. Zhang, L. Ma, Y. D. Hou, J. Zhang, T.-L. Xia, G. F. Chen, J. P. Hu, G. M. Luke, and W. Yu, Phys. Rev. B **81**, 012503 (2010).
[11] K. Suzuki, H. Usui, and K. Kuroki, Phys. Rev. B **84**, 144514 (2011).
[12] S. Graser, T. A. Maier, P. J. Hirschfeld, and D. J. Scalapino, New J. Phys. **11**, 025016 (2009).
[13] S. Maiti, M. M. Korshunov, T. A. Maier, P. J. Hirschfeld, and A. V. Chubukov, Phys. Rev. Lett. **107**, 147002 (2011).
[14] R. Thomale, C. Platt, W. Hanke, J. Hu, and B. A. Bernevig, Phys. Rev. Lett. **107**, 117001 (2011).
[15] S. Maiti, M. M. Korshunov, and A. V. Chubukov, Phys. Rev. B **85**, 014511 (2012).
[16] L. S. Borkowski and P. J. Hirschfeld, Phys. Rev. B **49**, 15 404 (1994).
[17] H. Shakeripour, C. Petrovic, and L. Taillefer, New J. Phys. **11**, 055065 (2009).
[18] M. J. Graf, S. K. Yip, J. A. Sauls, and D. Rainer, Phys. Rev. B **53**, 15 147 (1996).
[19] A. C. Durst and P. A. Lee, Phys. Rev. B **62**, 1270 (2000).
[20] K. Kirshenbaum *et al.*, arXiv:1203.5114.
[21] K. Kihou *et al.*, J. Phys. Soc. Jpn. **79**, 124713 (2010).
[22] M. J. Graf, S. -K. Yip, and J. A. Sauls, J. Low Temp. Phys. **102**, 367 (1996).
[23] T. Sato *et al.*, Phys. Rev. Lett. **103**, 047002 (2009).
[24] T. Yoshida *et al.*, J. Phys. Chem. Solids **72**, 465 (2011).
[25] T. Terashima *et al.*, J. Phys. Soc. Jpn. **79**, 053702 (2010).
[26] M. Abdel-Hafiez *et al.*, Phys. Rev. B **85**, 134533 (2012).
[27] H. Fukazawa *et al.*, J. Phys. Soc. Jpn. **80**, SA118 (2011).
[28] I. M. Vishik *et al.*, Phys. Rev. Lett. **104**, 207002 (2010).
[29] R. W. Hill *et al.*, Phys. Rev. Lett. **92**, 027001 (2004).
[30] L. Taillefer, B. Lussier, R. Gagnon, K. Behnia, and H. Aubin, Phys. Rev. Lett. **79**, 483 (1997).
[31] V. Mishra, A. Vorontsov, P. J. Hirschfeld, and I. Vekhter, Phys. Rev. B **80**, 224525 (2009).
[32] H. Alloul, J. Bobroff, M. Gabay, and P. J. Hirschfeld, Rev. Mod. Phys. **81**, 45 (2009).
[33] I. Vekhter and A. Vorontsov, Phys. Rev. B **75**, 094512 (2007).
[34] T. Yoshida *et al.*, arXiv:1205.6911.
[35] S. Y. Li, J.-B. Bonnemaison, A. Payeur, P. Fournier, C. H. Wang, X. H. Chen, and L. Taillefer, Phys. Rev. B **77**, 134501 (2008).
[36] P. J. Hirschfeld and N. Goldenfeld, Phys. Rev. B **48**, 4219 (1993).
[37] C. Kübert and P. J. Hirschfeld, Phys. Rev. Lett. **80**, 4963 (1998).
[38] I. Vekhter and A. Houghton, Phys. Rev. Lett. **83**, 4626 (1999).
[39] M. Chiao, R. W. Hill, C. Lupien, B. Popić, R. Gagnon, and L. Taillefer, Phys. Rev. Lett. **82**, 2943 (1999).
[40] C. Proust, E. Boaknin, R. W. Hill, L. Taillefer, and A. P. Mackenzie, Phys. Rev. Lett. **89**, 147003 (2002).
[41] A. F. Wang *et al.*, arXiv:1206.2030.