Field-Induced Quantum Critical Point and Nodal Superconductivity in the Heavy-Fermion Superconductor Ce_2PdIn_8

J. K. Dong,¹ H. Zhang,¹ X. Qiu,¹ B. Y. Pan,¹ Y. F. Dai,¹ T. Y. Guan,¹ S. Y. Zhou,¹
D. Gnida,² D. Kaczorowski,² and S. Y. Li^{1,*}

¹*Department of Physics, State Key Laboratory of Surface Physics, and Laboratory of Advanced Materials, Fudan University, Shanghai 200433, China*

²*Institute of Low Temperature and Structure Research, Polish Academy of Sciences, P.O. Box 1410, 50-950 Wrocław, Poland*
(Received 3 August 2010; revised manuscript received 18 July 2011; published 15 September 2011)

The in-plane resistivity ρ and thermal conductivity κ of the heavy-fermion superconductor Ce_2PdIn_8 single crystals were measured down to 50 mK. A field-induced quantum critical point, occurring at the upper critical field H_{c2} , is demonstrated from the $\rho(T) \sim T$ near H_{c2} and $\rho(T) \sim T^2$ when further increasing the field. The large residual linear term κ_0/T at zero field and the rapid increase of $\kappa(H)/T$ at low field give evidence for nodal superconductivity in Ce_2PdIn_8 . The jump of $\kappa(H)/T$ near H_{c2} suggests a first-order-like phase transition at low temperature. These results mimic the features of the famous CeCoIn_5 superconductor, implying that Ce_2PdIn_8 may be another interesting compound to investigate for the interplay between magnetism and superconductivity.

DOI: 10.1103/PhysRevX.1.011010

Subject Areas: Condensed Matter Physics, Magnetism, Superconductivity

The interplay between magnetism and superconductivity has been a central issue for heavy-fermion superconductors [1], high- T_c cuprates [2], and iron pnictides [3]. Among them, one particularly interesting case is the heavy-fermion superconductor CeCoIn_5 , with $T_c = 2.3$ K at ambient pressure [4]. Its superconducting gap has d -wave symmetry [5,6]. While there is no static magnetism in CeCoIn_5 at zero field, a field-induced antiferromagnetic (AF) quantum critical point (QCP) has been clearly demonstrated by resistivity and specific heat measurements [7,8]. Initially, it was very puzzling why the AF QCP is located right at the upper critical field H_{c2} .

Meanwhile, the observations of first-order phase transition at low temperature and H_{c2} and a second magnetization and specific heat anomaly well inside the superconducting state have been interpreted as the signature of a Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) superconducting state [5,9–12]. The novel FFLO state with broken spatial symmetry was predicted in the 1960s [13,14], but it has never been experimentally verified before. The possible FFLO state at the low-temperature–high-field (LTHF) corner of the $H - T$ phase diagram of CeCoIn_5 has stimulated extensive studies [15].

More recently, NMR, neutron scattering, and muon spin rotation (μSR) experiments have provided clear evidence for a field-induced magnetism in this LTHF part of the phase diagram [16–21]. It was identified as a spin-density wave (SDW) order with an incommensurate modulation

$\mathbf{Q} = (0.44, 0.44, 0.5)$. Interestingly, this SDW order disappears in the normal state above H_{c2} , showing that magnetic order and superconductivity in CeCoIn_5 are directly coupled [16,17]. While this has nicely explained the field-induced AF QCP at H_{c2} [7,8], the physical origin of this LTHF superconducting Q phase is still under debate. For example, Yanase and Sigrist have suggested that the incommensurate SDW order is stabilized in the FFLO state by the appearance of the Andreev bound state localized around the zeros of the FFLO order parameter [22]. Aperis, Varelogiannis, and Littlewood have argued that the Q phase is a pattern of coexisting condensates: a d -wave singlet superconducting state, a staggered π -triplet superconducting state, and an SDW [23]. In this latter scenario, the FFLO state is excluded. Therefore, it is still unclear whether the Q phase relates to an FFLO state.

To clarify this important issue, it will be very helpful to find more compounds with this kind of Q phase. However, none of the related compounds, CeMIn_5 ($M = \text{Rh, Ir}$) and Ce_2MIn_8 ($M = \text{Co, Rh, Ir}$), shows any sign of the Q phase [24–28]. Recently, it was found that Ce_2PdIn_8 is also a heavy-fermion superconductor with $T_c = 0.68$ K at ambient pressure [29]. In this paper, we report the observations of a field-induced QCP, the nodal superconductivity, and a first-order-like phase transition at H_{c2} in Ce_2PdIn_8 by resistivity and thermal conductivity measurements. Our findings suggest that Ce_2PdIn_8 may also have an exotic superconducting state as in CeCoIn_5 .

Single crystals of Ce_2PdIn_8 were grown from indium flux, as described for Ce_2CoIn_8 [26]. It can be viewed as a periodic stacking of two layers of CeIn_3 on a layer of PdIn_2 . To avoid the impurity phase of CeIn_3 [30], very thin crystals were selected for this study, with the typical thickness 40 μm . Contacts were made with soldered indium, which were used for both resistivity and thermal conductivity

*shiyang_li@fudan.edu.cn

Published by the American Physical Society under the terms of the *Creative Commons Attribution 3.0 License*. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI.

FIG. 1. (a) In-plane resistivity of the Ce_2PdIn_8 single crystal in zero field. The curve is very smooth below 20 K, showing no impurity phases in the sample. (b) Low-temperature resistivity of Ce_2PdIn_8 in magnetic fields applied along the c axis. The solid line is a linear fit of the zero-field data between 0.7 and 1.5 K. (c) ρ vs T^2 for $H = 2.4, 3, 4, 5, 6, 8$, and 11 T. (Data sets are offset for clarity.) The solid lines are fits to $\rho = \rho_0 + AT^2$. The arrows indicate the upper limit of the temperature range of T^2 behavior.

measurements. The resulting contact resistance is ~ 5 m Ω at 1.5 K. In-plane thermal conductivity was measured in a dilution refrigerator, using a standard four-wire steady-state method with two RuO_2 chip thermometers, calibrated *in situ* against a reference RuO_2 thermometer. Magnetic fields were applied along the c axis and perpendicular to the heat current. To ensure a homogeneous field distribution in the sample, all fields were applied at temperature above T_c .

Figure 1(a) shows the in-plane resistivity of our Ce_2PdIn_8 single crystal in zero field. A broad peak is found at $T_{\text{coh}} = 25$ K, which is attributed to a crossover between

FIG. 2. The $H - T$ phase diagram of Ce_2PdIn_8 determined from the resistivity measurements. The T_c is defined at 10% of the normal-state resistivity in each field. The T_{FL} is defined as the upper limit of the temperature range of T^2 -dependence Fermi liquid behavior. This phase diagram suggests a field-induced quantum critical point located at $H_{c2} = 2.32$ T. The inset shows the field dependence of the coefficient A of $\rho = \rho_0 + AT^2$, which tends to diverge toward $H_{c2} = 2.32$ T.

incoherent scattering at high temperature and the development of a coherent heavy-fermion state at lower temperatures. The curve is very smooth below 20 K, suggesting that there are no impurity phases, especially for the antiferromagnetic CeIn_3 with $T_N \sim 10$ K [29,30]. In Fig. 1(b), the low-temperature $\rho(T)$ in magnetic fields $H||c$ up to 11 T are plotted. From the zero-field data, $T_c = 0.68$ K is obtained, which is defined at the value of 10% of the normal state. The 10–90% transition width is only 20 mK. It is found that $\rho(T)$ obeys T -linear dependence nicely above $T_c = 0.68$ K, up to about 2 K. A linear fit of the data between 0.7 and 1.5 K gives a residual resistivity $\rho_0 = 2.41 \mu\Omega\text{cm}$.

With increasing field, T_c gradually decreases, to 50 mK at $H = 2.32$ T. This field is determined as the bulk H_{c2} for $H||c$. In slightly higher field $H = 2.4$ T, the resistive transition is completely suppressed, and the T -linear behavior of normal-state $\rho(T)$ persists all the way down to 50 mK. In $H > 2.4$ T, the curves show clear deviation from the T -linear dependence. The data of $H = 2.4, 3, 4, 5, 6, 8$, and 11 T are plotted as ρ vs T^2 in Fig. 1(c). It is clearly seen that a Fermi liquid behavior of resistivity, $\rho \sim AT^2$, develops with increasing field. The inset of Fig. 2 plots the field dependence of the coefficient A , which tends to diverge toward $H_{c2} = 2.32$ T. The fitting of $A = A_0(H - 2.32)^\alpha$ gives $\alpha = -0.57 \pm 0.02$. Note that, for CeCoIn_5 (ρ_{ab} in $H||c$) and CeRhIn_5 (ρ_c in $H||ab$ and

FIG. 3. Low-temperature in-plane thermal conductivity of Ce_2PdIn_8 in magnetic fields applied along the c axis. The saturation of κ/T toward 2.32 T confirms it as the bulk H_{c2} . The solid lines are fits to the $H = 0$ and 2.4 T data (see text). The dashed line at the top left of the panel is the normal-state Wiedemann-Franz law expectation $L_0/\rho_0(2.4\text{T})$, with $L_0 = 2.45 \times 10^{-8} \text{ W}\Omega\text{K}^{-2}$ and $\rho_0(2.4\text{T}) = 2.49 \mu\Omega\text{cm}$.

under 2.35 GPa), $\alpha = -1.37$ and -0.5 were obtained, respectively [7,31].

Based on these resistivity results, we have constructed an $H - T$ phase diagram for Ce_2PdIn_8 in the main panel of Fig. 2. Such a phase diagram is very similar to that of CeCoIn_5 [7,8], showing that there is also a field-induced QCP at H_{c2} . To clarify whether it is an AF QCP, more experiments such as NMR, neutron scattering, and μSR are needed to detect the magnetic order below and above H_{c2} , as have been done with CeCoIn_5 [16–21].

Next, we turn to the superconducting gap structure of Ce_2PdIn_8 . Figure 3 shows the temperature dependence of the in-plane thermal conductivity in $H \parallel c$ up to 2.4 T, plotted as κ/T vs T . The Wiedemann-Franz (WF) law is first checked in the normal state. The $H = 2.4$ T curve is fitted to $\kappa/T = 1/(a + bT)$, since $\rho(2.4\text{T})$ is T -linear dependent and electrons dominate the heat transport at low temperature. The extrapolation gives $\kappa_0/T(2.4\text{T}) = 1/a \approx 9.28 \text{ mW K}^{-2} \text{ cm}^{-1}$. This value is about 94% of the WF law expectation, $L_0/\rho_0(2.4\text{T}) = 9.84 \text{ mW K}^{-2} \text{ cm}^{-1}$, with $L_0 = 2.45 \times 10^{-8} \text{ W}\Omega\text{K}^{-2}$ and $\rho_0(2.4\text{T}) = 2.49 \mu\Omega\text{cm}$. The rough satisfaction of the WF law in the normal state shows that our thermal conductivity data are reliable.

In zero field, κ/T of Ce_2PdIn_8 behaves in a way similar to that of CeCoIn_5 [32,33], increasing below T_c , showing a broad peak at ~ 0.45 K, and then decreasing toward $T = 0$. Below 250 mK, $\kappa/T \propto T$ and extrapolates to $\kappa_0/T = 2.09 \pm 0.02 \text{ mW K}^{-2} \text{ cm}^{-1}$, more than 20% of

FIG. 4. Normalized κ/T to the normal-state value for Ce_2PdIn_8 at 60 mK, and for CeCoIn_5 at 50 mK [33], as a function of H/H_{c2} . For both compounds, the sharp jump of κ/T near H_{c2} indicates a first-order phase transition. Similar data of the clean s -wave superconductor Nb [37] and an overdoped d -wave superconductor Tl-2201 [38] at $T \rightarrow 0$ are also shown for comparison.

the normal-state value. For the d -wave superconductor CeCoIn_5 , one measurement down to 50 mK obtained $\kappa_0/T = 17 \text{ mW K}^{-2} \text{ cm}^{-1}$ [32], while another measurement down to 10 mK got $\kappa_0/T \approx 3 \text{ mW K}^{-2} \text{ cm}^{-1}$ [33]. The significant κ_0/T of Ce_2PdIn_8 in zero field is strong evidence for nodes in the superconducting gap [34]. Further angle-dependent experiments will be able to show whether this nodal superconductivity is also d -wave, as in CeCoIn_5 [5,6], CeRhIn_5 under pressure [35], and CeIrIn_5 [36].

The field dependence of κ_0/T may provide further support for the nodes [34]. In Fig. 3, however, the temperature dependence of κ/T changes dramatically in fields, and it is hard to extrapolate κ_0/T reliably for all the curves. Therefore, we plot κ/T at 60 mK, normalized to its normal-state value (in bulk $H_{c2} = 2.32$ T), vs H/H_{c2} in Fig. 4. For comparison, similar data of the clean s -wave superconductor Nb [37] and an overdoped d -wave superconductor Tl-2201 [38] at $T \rightarrow 0$ are also shown. At low field ($H/H_{c2} < 0.5$), $\kappa(H)/T$ of Ce_2PdIn_8 shows downward curvature as in Tl-2201, providing further support for the nodes. In contrast to the s -wave superconductor Nb, the rapid increase of $\kappa(H)/T$ at low field in nodal superconductors results from the Volovik effect of the nodal quasiparticles [39].

It is worth pointing out that the $\kappa(H)/T$ of Ce_2PdIn_8 at 60 mK is quite different from the abnormal one of CeCoIn_5 at 50 mK [33], which is also plotted in Fig. 4. For CeCoIn_5 , the decrease of $\kappa(H)/T$ above 20 mT was attributed to the

vortex scattering, since the quasiparticle mean free path l in zero field is very large (≈ 4000 Å) due to the high purity of the sample [33]. However, for Ce_2PdIn_8 , $l \approx 420$ Å has been estimated [29], roughly one order smaller than CeCoIn_5 . In this case, vortex scattering does not show a significant effect, and $\kappa(H)/T$ of Ce_2PdIn_8 behaves more like the typical d -wave superconductor Tl-2201 at low field [38].

From Fig. 4, $\kappa(H)/T$ of CeCoIn_5 shows an abrupt jump near H_{c2} . This is evidence for the first-order transition [5,9–12], which apparently corresponds to the disappearance of the Q phase at H_{c2} [17,18]. For Ce_2PdIn_8 , a less sharp jump of $\kappa(H)/T$ is also found near H_{c2} , which hints that the superconducting-to-normal-state transition at very low temperature is first-order-like. This result, together with the field-induced QCP at H_{c2} and the nodal superconductivity, all mimic those features of CeCoIn_5 . Therefore, it is possible that there may exist an exotic superconducting state at the LTHF corner of the phase diagram of Ce_2PdIn_8 . It will be very interesting to search for the Q phase and FFLO state in this second compound after CeCoIn_5 .

Finally, we check the conditions for Ce_2PdIn_8 to form an FFLO state. There are two requirements for the formation of an FFLO state: a very large Maki parameter ($\alpha > 1.8$) and a very clean compound ($\xi \ll l$) [15]. The Maki parameter $\alpha = \sqrt{2}H_{\text{orb}}/H_P$, where H_{orb} and H_P are the orbital and Pauli limiting H_{c2} , reflects the relative strength of the Pauli paramagnetic effect and the orbital effect when a magnetic field is suppressing the superconductivity [40]. For CeCoIn_5 , $\alpha = 4.6$ and 5.0 were obtained in $H||ab$ and $H||c$, respectively [41]. For our Ce_2PdIn_8 in $H||c$, $H_{\text{orb}} = -0.7T_c dH_{c2}/dT|_{T=T_c} \approx 6.8$ T is obtained from the initial slope $dH_{c2}/dT|_{T=T_c} = -14.3$ T/K in Fig. 2. By assuming $H_P \approx H_{c2}(0) = 2.32$ T, we get $\alpha \approx 2.9$. Therefore, both CeCoIn_5 and Ce_2PdIn_8 meet the required minimum value of α . The in-plane superconducting coherence length $\xi = 47\text{--}50$ Å was estimated for CeCoIn_5 [42]. This value is about 100 times smaller than the mean free path $l \approx 4000$ Å [33], showing that CeCoIn_5 is in the clean limit $\xi \ll l$. For Ce_2PdIn_8 , $\xi \approx 82$ Å and $l \approx 420$ Å were estimated [29]. This shows that Ce_2PdIn_8 is a clean compound ($\xi < l$) too, although not as clean as CeCoIn_5 . Therefore, Ce_2PdIn_8 may also fulfill the requirements for the formation of an FFLO state.

In summary, we have measured the resistivity and thermal conductivity of the heavy-fermion superconductor Ce_2PdIn_8 single crystal down to 50 mK. A field-induced QCP at H_{c2} is demonstrated by the observation of $\rho \sim T$ near H_{c2} and the development of $\rho \sim T^2$ Fermi liquid behavior at higher fields. The large κ_0/T at zero field and the rapid increase of $\kappa(H)/T$ at low field give strong evidence for nodal superconductivity. Moreover, the jump of κ/T near H_{c2} indicates a first-order-like phase transition from the superconducting to the normal state at low

temperature. These features are similar to those of CeCoIn_5 , which implies that Ce_2PdIn_8 may be another interesting compound to investigate for the interplay between magnetism and superconductivity. The comparison between CeCoIn_5 and Ce_2PdIn_8 could be valuable for understanding the physical origin of the Q phase and possible FFLO state.

We thank W. Bao, Y. Chen, and Y. Y. Wang for discussions. This work is supported by the National Natural Science Foundation of China, the Ministry of Science and Technology of China (National Basic Research Program No. 2009CB929203), the Program for New Century Excellent Talents in University, Program for Professor of Special Appointment (Eastern Scholar) at Shanghai Institutions of Higher Learning, and the Science and Technology Commission of Shanghai Municipality (STCSM) of China Contract Nos. 08dj1400200 and 08PJ1402100.

-
- [1] Christian Pfleiderer, *Superconducting Phases of f -Electron Compounds*, *Rev. Mod. Phys.* **81**, 1551 (2009).
 - [2] P. A. Lee, N. Nagaosa, and X. G. Wen, *Doping a Mott Insulator: Physics of High-Temperature Superconductivity*, *Rev. Mod. Phys.* **78**, 17 (2006).
 - [3] D. C. Johnston, *The Puzzle of High Temperature Superconductivity in Layered Iron Pnictides and Chalcogenides*, *Adv. Phys.* **59**, 803 (2010).
 - [4] C. Petrovic, P. G. Pagliuso, M. F. Hundley, R. Movshovich, J. L. Sarrao, J. D. Thompson, Z. Fisk, and P. Monthoux, *Heavy-Fermion Superconductivity in CeCoIn_5 at 2.3 K*, *J. Phys. Condens. Matter* **13**, L337 (2001).
 - [5] K. Izawa, H. Yamaguchi, Yuji Matsuda, H. Shishido, R. Settai, and Y. Onuki, *Angular Position of Nodes in the Superconducting Gap of Quasi-2D Heavy-Fermion Superconductor CeCoIn_5* , *Phys. Rev. Lett.* **87**, 057002 (2001).
 - [6] K. An, T. Sakakibara, R. Settai, Y. Onuki, M. Hiragi, M. Ichioka, and K. Machida, *Sign Reversal of Field-Angle Resolved Heat Capacity Oscillations in a Heavy Fermion Superconductor CeCoIn_5 and $d_{x^2-y^2}$ Pairing Symmetry*, *Phys. Rev. Lett.* **104**, 037002 (2010).
 - [7] J. Paglione, M. A. Tanatar, D. G. Hawthorn, Etienne Boaknin, R. W. Hill, F. Ronning, M. Sutherland, Louis Taillefer, C. Petrovic, and P. C. Canfield, *Field-Induced Quantum Critical Point in CeCoIn_5* , *Phys. Rev. Lett.* **91**, 246405 (2003).
 - [8] A. Bianchi, R. Movshovich, I. Vekhter, P. G. Pagliuso, and J. L. Sarrao, *Avoided Antiferromagnetic Order and Quantum Critical Point in CeCoIn_5* , *Phys. Rev. Lett.* **91**, 257001 (2003).
 - [9] T. P. Murphy, Donavan Hall, E. C. Palm, S. W. Tozer, C. Petrovic, Z. Fisk, R. G. Goodrich, P. G. Pagliuso, J. L. Sarrao, and J. D. Thompson, *Anomalous Superconductivity and Field-Induced Magnetism in CeCoIn_5* , *Phys. Rev. B* **65**, 100514(R) (2002).

- [10] T. Tayama, A. Harita, T. Sakakibara, Y. Haga, H. Shishido, R. Settai, and Y. Onuki, *Unconventional Heavy-Fermion Superconductor CeCoIn₅: dc Magnetization Study at Temperatures Down to 50 mK*, *Phys. Rev. B* **65**, 180504 (R) (2002).
- [11] A. Bianchi, R. Movshovich, N. Oeschler, P. Gegenwart, F. Steglich, J. D. Thompson, P. G. Pagliuso, and J. L. Sarrao, *First-Order Superconducting Phase Transition in CeCoIn₅*, *Phys. Rev. Lett.* **89**, 137002 (2002).
- [12] A. Bianchi, R. Movshovich, C. Capan, P. G. Pagliuso, and J. L. Sarrao, *Possible Fulde-Ferrell-Larkin-Ovchinnikov Superconducting State in CeCoIn₅*, *Phys. Rev. Lett.* **91**, 187004 (2003).
- [13] P. Fulde and R. A. Ferrell, *Superconductivity in a Strong Spin-Exchange Field*, *Phys. Rev.* **135**, A550 (1964).
- [14] A. I. Larkin and Y. N. Ovchinnikov, *Inhomogeneous State of Superconductors*, *Zh. Eksp. Teor. Fiz.* **47**, 1136 (1964) [*Inhomogeneous State of Superconductors*, *Sov. Phys. JETP* **20**, 762 (1965)].
- [15] Y. Matsuda and H. Shimahara, *Fulde-Ferrell-Larkin-Ovchinnikov State in Heavy Fermion Superconductors*, *J. Phys. Soc. Jpn.* **76**, 051005 (2007), and references therein.
- [16] B. L. Young, R. R. Urbano, N. J. Curro, J. D. Thompson, J. L. Sarrao, A. B. Vorontsov, and M. J. Graf, *Microscopic Evidence for Field-Induced Magnetism in CeCoIn₅*, *Phys. Rev. Lett.* **98**, 036402 (2007).
- [17] M. Kenzelmann, Th. Strässle, C. Niedermayer, M. Sigrist, B. Padmanabhan, M. Zolliker, A. D. Bianchi, R. Movshovich, E. D. Bauer, J. L. Sarrao, and J. D. Thompson, *Coupled Superconducting and Magnetic Order in CeCoIn₅*, *Science* **321**, 1652 (2008).
- [18] J. Spehling, R. H. Heffner, J. E. Sonier, N. Curro, C. H. Wang, B. Hitti, G. Morris, E. D. Bauer, J. L. Sarrao, F. J. Litterst, and H.-H. Klauss, *Field-Induced Coupled Superconductivity and Spin Density Wave Order in the Heavy Fermion Compound CeCoIn₅*, *Phys. Rev. Lett.* **103**, 237003 (2009).
- [19] G. Koutroulakis, M. D. Stewart, Jr., V. F. Mitrović, M. Horvatić, C. Berthier, G. Lapertot, and J. Flouquet, *Field Evolution of Coexisting Superconducting and Magnetic Orders in CeCoIn₅*, *Phys. Rev. Lett.* **104**, 087001 (2010).
- [20] M. Kenzelmann, S. Gerber, N. Egetenmeyer, J. L. Gavilano, Th. Strässle, A. D. Bianchi, E. Ressouche, R. Movshovich, E. D. Bauer, J. L. Sarrao, and J. D. Thompson, *Evidence for a Magnetically Driven Superconducting Q Phase of CeCoIn₅*, *Phys. Rev. Lett.* **104**, 127001 (2010).
- [21] K. Kumagai, H. Shishido, T. Shibauchi, and Y. Matsuda, *Evolution of Paramagnetic Quasiparticle Excitations Emerged in the High-Field Superconducting Phase of CeCoIn₅*, *Phys. Rev. Lett.* **106**, 137004 (2011).
- [22] Y. Yanase and M. Sigrist, *Antiferromagnetic Order and π -Triplet Pairing in the Fulde-Ferrell-Larkin-Ovchinnikov State*, *J. Phys. Soc. Jpn.* **78**, 114715 (2009).
- [23] A. Aperis, G. Varelogiannis, and P. B. Littlewood, *Magnetic-Field-Induced Pattern of Coexisting Condensates in the Superconducting State of CeCoIn₅*, *Phys. Rev. Lett.* **104**, 216403 (2010).
- [24] T. Park, F. Ronning, H. Q. Yuan, M. B. Salamon, R. Movshovich, J. L. Sarrao, and J. D. Thompson, *Hidden Magnetism and Quantum Criticality in the Heavy Fermion Superconductor CeRhIn₅*, *Nature (London)* **440**, 65 (2006).
- [25] C. Capan, L. Balicas, T. P. Murphy, E. C. Palm, R. Movshovich, D. Hall, S. W. Tozer, M. F. Hundley, E. D. Bauer, J. D. Thompson, J. L. Sarrao *et al.*, *Unusual Metamagnetism in CeIrIn₅*, *Phys. Rev. B* **80**, 094518 (2009).
- [26] G. Chen, S. Ohara, M. Hedo, Y. Uwatoko, K. Saito, M. Sorai, and I. Sakamoto, *Observation of Superconductivity in Heavy-Fermion Compounds of Ce₂CoIn₈*, *J. Phys. Soc. Jpn.* **71**, 2836 (2002).
- [27] M. Nicklas, V. A. Sidorov, H. A. Borges, P. G. Pagliuso, C. Petrovic, Z. Fisk, J. L. Sarrao, and J. D. Thompson, *Magnetism and Superconductivity in Ce₂RhIn₈*, *Phys. Rev. B* **67**, 020506 (2003).
- [28] J. D. Thompson, R. Movshovich, Z. Fisk, F. Bouquet, N. J. Curro, R. A. Fisher, P. C. Hammel, H. Hegger, M. F. Hundley, M. Jaime *et al.*, *Superconductivity and Magnetism in a New Class of Heavy-Fermion Materials*, *J. Magn. Magn. Mater.* **226–230**, 5 (2001).
- [29] D. Kaczorowski, A. P. Pikul, D. Gnida, and V. H. Tran, *Emergence of a Superconducting State from an Antiferromagnetic Phase in Single Crystals of the Heavy Fermion Compound Ce₂PdIn₈*, *Phys. Rev. Lett.* **103**, 027003 (2009).
- [30] D. Kaczorowski, A. P. Pikul, D. Gnida, and V. H. Tran, *Reply*, *Phys. Rev. Lett.* **104**, 059702 (2010).
- [31] T. Park, Y. Tokiwa, F. Ronning, H. Lee, E. D. Bauer, R. Movshovich, and J. D. Thompson, *Field-Induced Quantum Critical Point in the Pressure-Induced Superconductor CeRhIn₅*, *Phys. Status Solidi B* **247**, 553 (2010).
- [32] M. A. Tanatar, Johnpierre Paglione, S. Nakatsuji, D. G. Hawthorn, E. Boaknin, R. W. Hill, F. Ronning, M. Sutherland, Louis Taillefer, C. Petrovic, P. C. Canfield, and Z. Fisk, *Unpaired Electrons in the Heavy-Fermion Superconductor CeCoIn₅*, *Phys. Rev. Lett.* **95**, 067002 (2005).
- [33] G. Seyfarth, J. P. Brison, G. Knebel, D. Aoki, G. Lapertot, and J. Flouquet, *Multigap Superconductivity in the Heavy-Fermion System CeCoIn₅*, *Phys. Rev. Lett.* **101**, 046401 (2008).
- [34] H. Shakeripour, C. Petrovic, L. Taillefer, *Heat Transport as a Probe of Superconducting Gap Structure*, *New J. Phys.* **11**, 055065 (2009).
- [35] T. Park, E. D. Bauer, and J. D. Thompson, *Probing the Nodal Gap in the Pressure-Induced Heavy Fermion Superconductor CeRhIn₅*, *Phys. Rev. Lett.* **101**, 177002 (2008).
- [36] Y. Kasahara, T. Iwasawa, Y. Shimizu, H. Shishido, T. Shibauchi, I. Vekhter, and Y. Matsuda, *Thermal Conductivity Evidence for a $d_{x^2-y^2}$ Pairing Symmetry in the Heavy-Fermion CeIrIn₅ Superconductor*, *Phys. Rev. Lett.* **100**, 207003 (2008).
- [37] J. Lowell and J. Sousa, *Mixed-State Thermal Conductivity of Type II Superconductors*, *J. Low Temp. Phys.* **3**, 65 (1970).
- [38] C. Proust, E. Boaknin, R. W. Hill, Louis Taillefer, and A. P. Mackenzie, *Heat Transport in a Strongly Overdoped Cuprate: Fermi Liquid and a Pure*

- d*-Wave BCS Superconductor, *Phys. Rev. Lett.* **89**, 147003 (2002).
- [39] G. E. Volovik, *Superconductivity with Lines of Gap Nodes: Density of States in the Vortex*, JETP Lett. **58**, 469 (1993) [http://www.jetpletters.ac.ru/ps/1189/article_17954.shtml].
- [40] K. Maki, *Effect of Pauli Paramagnetism on Magnetic Properties of High-Field Superconductors*, *Phys. Rev.* **148**, 362 (1966).
- [41] K. Kumagai, M. Saitoh, T. Oyaizu, Y. Furukawa, S. Takashima, M. Nohara, H. Takagi, and Y. Matsuda, *Fulde-Ferrell-Larkin-Ovchinnikov State in a Perpendicular Field of Quasi-Two-Dimensional CeCoIn₅*, *Phys. Rev. Lett.* **97**, 227002 (2006).
- [42] L. DeBeer-Schmitt, C. D. Dewhurst, B. W. Hoogenboom, C. Petrovic, and M. R. Eskildsen, *Field Dependent Coherence Length in the Superclean, High- κ Superconductor CeCoIn₅*, *Phys. Rev. Lett.* **97**, 127001 (2006).