Lifshitz Transitions in the Ferromagnetic Superconductor UCoGe

Gaël Bastien,[1,2,*] Adrien Gourgout,[1,2] Dai Aoki,[1,2,3] Alexandre Pourret,[1,2] Ilya Sheikin,[4] Gabriel Seyfarth,[4] Jacques Flouquet,[1,2] and Georg Knebel[1,2,†]
[1]University Grenoble Alpes, INAC-PHELIQS, F-38000 Grenoble, France
[2]CEA, INAC-PHELIQS, F-38000 Grenoble, France
[3]IMR, Tohoku University, Oarai, Ibaraki 311-1313, Japan
[4]CNRS, Laboratoire National des Champs Magnétiques Intenses LNCMI (UGA, UPS, INSA), UPR 3228, F-38042 Grenoble Cedex 9, France
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We present high field magnetoresistance, Hall effect and thermopower measurements in the Ising-type ferromagnetic superconductor UCoGe. A magnetic field is applied along the easy magnetization c axis of the orthorhombic crystal. In the different experimental probes, we observed five successive anomalies at $H \approx 4$, 9, 12, 16, and 21 T. Magnetic quantum oscillations were detected both in resistivity and thermoelectric power. At most of the anomalies, significant changes of the oscillation frequencies and the effective masses have been observed, indicating successive Fermi surface instabilities induced by the strong magnetic polarization under a magnetic field.

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Lifshitz transitions (LTs) are continuous quantum phase transitions at zero temperature where the topology of the Fermi surface (FS) changes due to the variation of the Fermi energy and the band structure of a metal [1,2]. They were already studied in the 1960s and can be induced by chemical doping, pressure, or a strong magnetic field (H). However, only recently have LTs been proposed as the driving force to modify the ground-state properties in strongly correlated electron systems. The interplay of a LT with magnetic quantum phase transitions in heavy-fermion systems has been treated in various theoretical models (see, e.g., Refs. [3–8]). The influence of LTs on the appearance of superconductivity is discussed in cuprates [9,10], iron pnictides [11,12], and sulfur hydride [13] as well as for the reentrance of superconductivity in URhGe [14]. Finally, LTs play an important role in topological insulators [15] or in the vortex state of ^{3}He [16].

Usually, the electronic band structure is a rather robust property of the metallic state, especially when applying magnetic fields. Only when the magnetic ground state is modified may changes of the FS be detected. In a normal metal, the Zeeman splitting induced by accessible magnetic fields is weak with respect to the Fermi energy, which is usually of the order of a few eV. Importantly, in heavy-fermion compounds, the Fermi energy scale is significantly reduced due to the hybridization of the conduction and the localized f electrons. Thus, the Zeeman splitting of the flat bands crossing the Fermi level can be so strong that one of the spin-split FS sheets is continuously suppressed and undergoes a LT. In heavy-fermion systems, a LT is often associated with a change in the intersite and/or local magnetic fluctuations; see, e.g., $CeRu_2Si_2$ [17], $CeIn_3$ [18,19], and $YbRh_2Si_2$ [20–22].

In this Letter, we report on the FS properties of UCoGe under a magnetic field, which orders ferromagnetically at $T_C = 2.7$ K. Remarkably, the homogeneous coexistence of ferromagnetism and heavy-fermion superconductivity is observed below $T_{sc} = 0.6$ K [23]. UCoGe crystallizes in an orthorhombic structure (space group $Pnma$). Besides the exceptional superconducting properties [24], some normal state features of UCoGe are unique. The spontaneous magnetization in the ferromagnetic (FM) state is very small $M_0 \approx 0.05\ \mu_B/U$ with Ising moments along the c axis [25], and under a magnetic field, the magnetization is strongly anisotropic with $M_c > M_b > M_a$. For $H \| c$, M_c increases nonlinearly with the field and shows a broad kink at $H \approx 23$ T, but even at $H \sim 50$ T, with $M_c \approx 0.65\ \mu_B/U$ at $T = 1.5$ K, it is far from saturation [26]. Another striking point is the detection of well separated anomalies in the magnetoresistance for $H \| c$ [27–29] far above the collapse of the FM fluctuations ($H > 1$ T) [30] while $M(H)$ rules out thermodynamic phase transitions under a magnetic field at least down to 1.5 K [26].

In order to study the field dependence of the FS properties in a highly polarizable heavy-fermion system with small FS pockets, we performed systematic resistivity (ρ), Hall effect (ρ_{xy}), and thermopower (S) experiments in UCoGe. Two different samples (labeled $S1$ and $S2$) with residual resistivity ratios [$RRR = \rho(300\,\mathrm{K})/\rho(1\,\mathrm{K})$] of 105 and 36 have been prepared for experiments with electrical or heat current along the b and a axes, respectively. Details of the experiments are given in the Supplemental Material [31].

Figure 1 shows the field dependence of ρ_{xy} at 40 mK and thermopower at 900 and 450 mK along the c axis for $S1$. At least five successive anomalies can be observed above the superconducting critical field $H_{c2} \approx 0.6$ T in both probes. $S(H)$ exhibits successive marked minima at $H_1 \approx 3.65$ T, $H_2 \approx 9.2$ T, and $H_4 \approx 16$ T. A shoulderlike anomaly appears at $H_3 \approx 12$ T and a small kink at $H_5 \approx 21$ T.

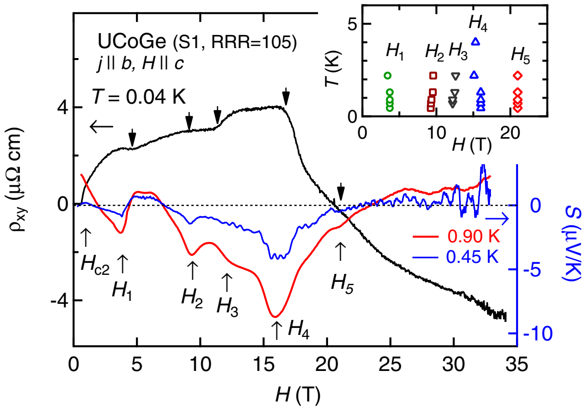

FIG. 1. Hall effect ρ_{xy} at 40 mK (left scale) and thermopower S at 900 and 450 mK (right scale) of UCoGe as a function of magnetic field. A series of transitions can be observed as a function of field. The inset shows the temperature dependence of the anomalies in the thermopower.

At 450 mK, in addition, large quantum oscillations occur in the thermopower (see below). At all these characteristic fields, $\rho_{xy}(H)$ shows rather sharp anomalies with steplike increases or kinks. Up to H_4, $\rho_{xy}(H)$ increases and shows small plateaus, while $S(H)$ exhibits marked minima at $H_1 \approx 3.65$ T and $H_2 \approx 9.5$ T. The anomaly at H_2 is rather broad, and in the following, we will locate H_2 at the minimum of $S(H)$, while the kink in $\rho_{xy}(H)$ coincides with the maximum of $S(H)$ at 11 T. At $H_4 = 16$ T, the most pronounced anomaly is observed and $\rho_{xy}(H)$ decreases abruptly, whereas $S(H)$ has a marked minimum and increases for higher fields. A small kink appears at $H_5 = 21$ T in $S(H)$, but there is no clear anomaly in $\rho_{xy}(H)$. In the whole field range, ρ_{xy} and S have opposite sign, which changes around 22 T, suggesting a change of the dominant carrier type [34]. The temperature dependence of the anomalies observed in $S(H)$ is shown in the inset of Fig. 1. The transitions get less pronounced with increasing temperature and disappear above $T \approx 3$ K, while their field position does not change. The clear signatures of these transitions in transport properties $\rho_{xy}(H)$ and $S(H)$ and the absence of any marked phase transition in thermodynamic properties [26,36] suggest that they are related to topological FS changes.

Figure 2 shows the transverse magnetoresistance $\rho(H)$ of UCoGe up to 34 T (a) in the bc plane with current along the a axis ($S2$) and (b) in the ac plane with a current along b ($S1$). The $\rho(H)$ shows several anomalies in both configurations, and at high field, quantum oscillations can be resolved. For $j \| a$ [see Fig. 2(a)], the resistivity shows a broad maximum around $H_2 \approx 9$ T and a minimum at $H_3 \approx 12$ T. A tiny kink can also be observed at $H_4 \approx 16$ T. The magnetoresistance of $S1$ with current direction $j \| b$ is represented in Fig. 2(b), and $\rho(H)$ increases by more than one order of magnitude between 0 and 34 T. Here, $\rho(H)$ is dominated by the orbital effect in the high quality sample $S1$. Clear anomalies at H_1 and H_4 were detected, while no clear indication of H_2 and

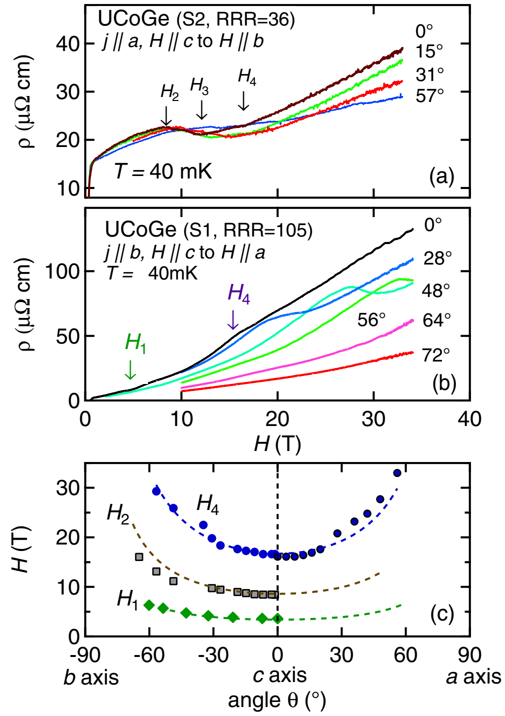

FIG. 2. Transverse magnetoresistance at $T = 40$ mK in UCoGe with (a) current along the a axis on sample $S2$ for different angles in the bc plane and (b) current along b on $S1$ in the ac plane. The arrows indicate the position of the anomalies for 0° along the c axis. (c) Angular dependence of the anomalies at H_1, H_2, and H_4. Dashed lines are fits with $H \propto 1/\cos\theta$.

H_3 is seen. Previously, $\rho(H)$ has been reported in Ref. [29] on a sample with $RRR = 30$ and a current along the b axis. The reported field dependence along the c axis is very different from that found in the very high quality sample $S1$, while it is similar to that found on $S2$ with the current along the a axis and similar RRR suggesting that $\rho(H)$ is strongly sample dependent.

In order to investigate the anisotropy of the detected anomalies, we turned the samples in the bc and in the ac plane, while keeping the transverse configuration in both cases. The rotation of $S2$ in the bc plane shows a shift of the anomalies H_2 and H_4 to higher fields, which can be followed up to a field angle of $\theta \approx 60°$. In the ac plane, $\rho(H)$ is strongly reduced when the field is rotated from the easy c axis to the hard a axis and H_3 increases with angle from the c axis. While the anomaly at H_4 smears out by rotating the field from the c axis toward the b axis, it gets more pronounced by rotating the field toward the a axis, and at 48° a broad maximum in $\rho(H)$ appears at H_4. Figure 2(c) shows the angular dependence of the anomalies in the bc and ac planes. The angular dependence of H_1 in the bc plane was determined by thermopower. The anomalies follow quite well $1/\cos\theta$ dependence for both rotation axes and thus depend mainly on the c axis component of the magnetic field. For H_2, good agreement with previous reports is observed [28,29,37]. For both samples,

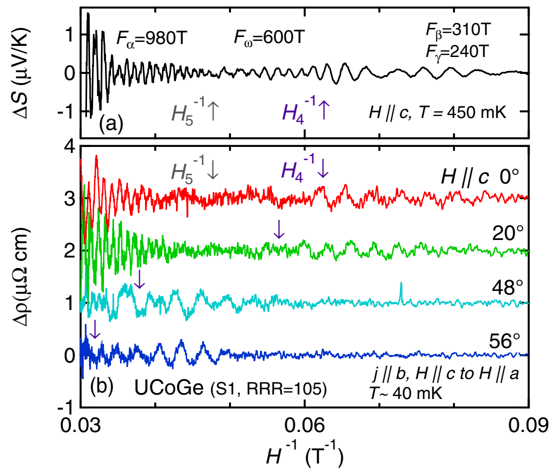

FIG. 3. Quantum oscillations in UCoGe extracted from (a) thermopower and (b) resistivity as a function of inverse magnetic field. The arrows show the positions of H_4 and H_5 anomalies detected in transport measurements. The lower panel (b) also shows quantum oscillations in the *ac* plane measured by resistivity.

Shubnikov–de Haas (SdH) oscillations could be observed in the magnetoresistance.

Figure 3 shows the oscillatory part after subtraction of a nonoscillatory background (see the Supplemental Material) of (a) the thermopower and (b) the magnetoresistance of $S1$ for different angles in the *ac* plane. For $H < 16$ T, slow oscillations were observed for $H \| c$ with two very close frequencies at 240 and 310 T. These low frequencies vanish at H_4, and faster oscillations with a frequency of $F_\omega = 600$ T appear above $H_4 = 16$ T but disappear again at $H_5 = 21$ T in the thermopower. No SdH oscillations were observed between H_4 and H_5. Above H_5, a higher frequency $F_\alpha = 970$ T called the α branch appears in both probes, and it corresponds to that previously reported in Refs. [27,37].

The frequency of the quantum oscillations and the corresponding effective masses in the different field intervals are reported in Table 1 of the Supplemental Material. Figure 3(b) shows SdH oscillations at different angles in the *ac* plane. While H_3 increases to a higher field when approaching the a axis [see Fig. 2(c)], the oscillations at F_γ and F_β are suppressed at H_4 at each angle. At 56°, a continuous increase of F_γ with the field can be observed, when the field gets close to the anomaly $H_4(56°) = 33$ T. This suggests that the FS pocket of the γ branch shrinks continuously, when the field gets close to the FS reconstruction field $H_4(56°) = 33$ T. Such a continuous change of a quantum oscillation frequency could not be observed clearly for the other field directions.

Quantum oscillations below $H_4 = 16$ T are represented in Fig. 4. Above H_2, a modulation of the amplitude of the oscillations in thermopower can be observed due to the beating of two close quantum oscillation frequencies F_β and F_γ. While $S1$ shows large oscillations above H_2, the SdH oscillations below 10 T are more visible on $S2$. The

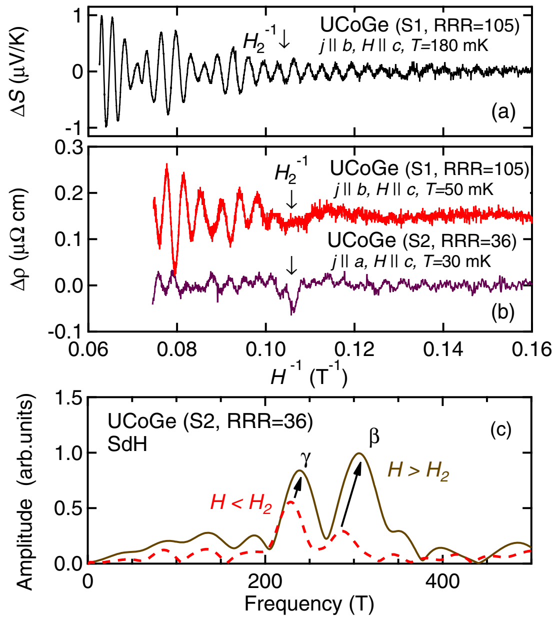

FIG. 4. Quantum oscillations below 16 T as a function of inverse magnetic field for (a) thermopower and (b) resistivity measured more precisely in a superconducting magnet. (c) FFT spectrum of quantum oscillations in the resistivity of sample $S2$ for the field along the c axis below and above $H_2 \approx 9$ T.

fast Fourier transformation (FFT) spectra of the oscillations for $S2$ are represented in Fig. 4(c), both for fields below and above H_2. Two frequencies can be observed below H_2 at 230 and 280 T. For $H > H_2$, these two frequencies are shifted to 240 and 310 T. A previous dHvA study suggested a splitting of one frequency from below to above H_2 [38]. On the contrary, our measurements show that both quantum oscillation frequencies exist below H_2 within the resolution of the FFT. Thus, a small abrupt change in the size of the FS is directly observed by quantum oscillations at the anomaly $H_2 = 9$ T.

The angular dependences of the oscillation frequencies for the different field intervals are represented in Fig. 5. Data in the vicinity of the b axis are taken from Ref. [38] and connect perfectly to those presented here. At low field $H < H_2$, two small FS pockets elongated along the c axis (ellipsoidal or cylindrical) exist. These pockets change in size at H_2 but disappear abruptly above H_4. The angular dependence of the frequency at $F_\omega = 600$ T has not been measured. The pocket α with the heavy effective mass ranging from $17m_0$ to $23m_0$ seems to be nearly spherical with a frequency around $F_\alpha \approx 1000$ T [Fig. 5(c)] and is experimentally observed above 22 T, independent of the field angle.

The main observation is that most anomalies observed in the field dependence of the transport properties (see Figs. 1 and 2) coincide with abrupt changes in the quantum oscillation frequencies and effective masses (see Table 1 in the Supplemental Material). They are related to modifications of the FS topology, with the most drastic change occurring at H_4 where the Hall effect collapses and $S(H)$ has a pronounced minimum. The FS can be easily modified by applying a

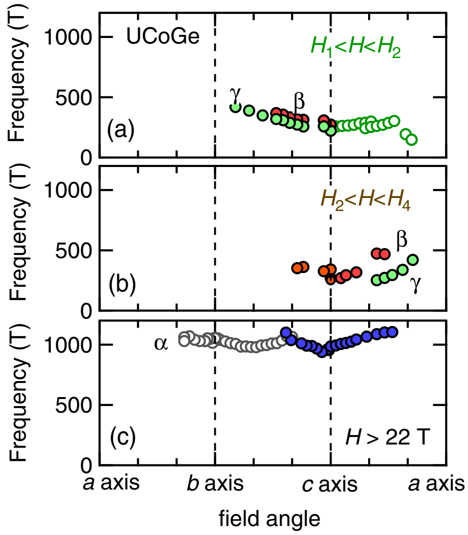

FIG. 5. Angular dependence of quantum oscillation frequencies in UCoGe for the different field intervals delimited by the anomalies observed in transport measurements. Open circles in (a) and (c) have been taken from Refs. [37,38].

magnetic field, and the small FS pockets disappear through a LT. We can estimate the characteristic energy of each detected pocket with $\epsilon_i = \hbar^2 k_{F,i}^2/2m_i^\star \approx \hbar e F_i/m_i^\star c$, and we find $\epsilon_\gamma \approx 2.5$ meV, $\epsilon_\omega \approx 5$ meV, and $\epsilon_\alpha \approx 6.6$ meV. These energies can be compared to the Zeeman energy scale of a free electron divided by field $\epsilon_Z/\mu_0 H = g\mu_B \approx 0.12$ meV/T for $g = 2$. As UCoGe is a weak ferromagnet, this effect will even be strengthened by the internal field. Hence, an important polarization of the bands can be achieved by easily accessible magnetic fields, and thus a series of magnetic field-induced LTs appears.

The magnetization up to 50 T [26] has a strongly nonlinear field dependence, suggesting that the electronic magnetic response must vary strongly with the magnetic field while the FM fluctuations are already fully suppressed for $H > 1$ T along the c axis [24,30]. Thus, the electronic instabilities seem to occur in the paramagnetic regime without any additional phase transitions and far above the field where the FM intersite magnetic correlations collapse. The key phenomenon is that FS changes are induced by crossing some critical values of magnetic polarization. In some systems, such FS changes are accompanied by a metamagneticlike transition, depending on the nature of the electronic instability. Very recent magnetization measurements [39] point to a tiny metamagneticlike transition at H_2 but do not detect any anomaly at H_1, and the high field measurements [26] exclude it for H_4 and H_5. The case of UCoGe can be compared to the series of FS reconstructions observed inside the hidden order phase of URu_2Si_2. In this compound, no detectable effects on the bulk magnetization have been observed [40], but the LTs are related to the polarization of the small FS pockets [22,41–43]. In $CeRu_2Si_2$, the LT is linked to the pseudometamagnetic transition where one spin-split FS vanishes continuously at the transition [17,44], while in $YbRh_2Si_2$, the LT [20,45] goes along with a suppression of the local Kondo effect, as has been demonstrated by renormalized band structure calculations under a magnetic field [21]. Recently, a LT occurring at 28 T has been reported in paramagnetic $CeIrIn_5$ [46].

Different LDA band structure calculations have been performed on UCoGe [47,48], showing strong differences in the FS topology. In the paramagnetic state, three bands are contributing to FS sheets with rather small volume, characteristic for a low carrier or semimetallic system. Two cigarlike [47] or pillarlike [48] electron FSs centered around the S point have been predicted, which may correspond to the small FSs observed below H_2. In Ref. [47], the FM state with a magnetic polarization along the c axis has also been calculated. The FSs (with a moment of $-0.47\mu_B/U$ much larger than in experiment) differ significantly from the paramagnetic ones and do not at all agree with our experiment. In ARPES experiments at zero field, details of the FS could not be resolved up to now [48], and it will be of great interest to see the differences of the FS above and below T_C.

In conclusion, we give clear evidence by quantum oscillation experiments for FS instabilities under a magnetic field in UCoGe for a field along the easy magnetization axis. The occurrence of several LTs under a field in the polarized phase of UCoGe shows that FS properties of heavy-fermion systems can be easily tuned by magnetic field. The LTs are decoupled from intersite correlations and seem to be driven only by changes in the local fluctuations induced by reaching a critical magnetic polarization. It unveils a strong interplay between magnetic polarization and FS topology, which is directly linked with the dual localized and itinerant nature of the $5f$ electrons. A key challenge in theory is now to take into account the feedback between polarization and FS to model the influence of the magnetic field on the electronic structure.

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*gael.bastien@cea.fr
†georg.knebel@cea.fr

[1] I. M. Lifshitz, Zh. Eksp. Teor. Fiz. **38**, 1569 (1960) [Sov. Phys. JETP **11**, 1130 (1960)].
[2] Y. M. Blanter, M. I. Kaganov, A. V. Pantsulaya, and A. A. Varlamov, Phys. Rep. **245**, 159 (1994).
[3] Y. Yamaji, T. Misawa, and M. Imada, J. Phys. Soc. Jpn. **75**, 094719 (2006).
[4] P. Schlottmann, Phys. Rev. B **83**, 115133 (2011).

[5] M. Bercx and F. F. Assaad, Phys. Rev. B **86**, 075108 (2012).
[6] S. Hoshino and Y. Kuramoto, Phys. Rev. Lett. **111**, 026401 (2013).
[7] A. Benlagra and M. Vojta, Phys. Rev. B **87**, 165143 (2013).
[8] K. Kubo, J. Phys. Soc. Jpn. **84**, 094702 (2015).
[9] M. R. Norman, J. Lin, and A. J. Millis, Phys. Rev. B **81**, 180513 (2010).
[10] D. LeBoeuf, N. Doiron-Leyraud, B. Vignolle, M. Sutherland, B. J. Ramshaw, J. Levallois, R. Daou, F. Laliberté, O. Cyr-Choinière, J. Chang, Y. J. Jo, L. Balicas, R. Liang, D. A. Bonn, W. N. Hardy, C. Proust, and L. Taillefer, Phys. Rev. B **83**, 054506 (2011).
[11] C. Liu, T. Kondo, R. M. Fernandes, A. D. Palczewski, E. D. Mun, N. Ni, A. N. Thaler, A. Bostwick, E. Rotenberg, J. Schmalian, S. L. Bud'ko, P. C. Canfield, and A. Kaminski, Nat. Phys. **6**, 419 (2010).
[12] Y. Wang, M. N. Gastiasoro, B. M. Andersen, M. Tomić, H. O. Jeschke, R. Valentí, I. Paul, and P. J. Hirschfeld, Phys. Rev. Lett. **114**, 097003 (2015).
[13] T. Jarlborg and A. Bianconi, Sci. Rep. **6**, 24816 (2016).
[14] E. A. Yelland, J. M. Barraclough, W. Wang, K. V. Kamenev, and A. D. Huxley, Nat. Phys. **7**, 890 (2011).
[15] C.-C. Liu, J.-J. Zhou, Y. Yao, and F. Zhang, Phys. Rev. Lett. **116**, 066801 (2016).
[16] M. A. Silaev, E. V. Thuneberg, and M. Fogelström, Phys. Rev. Lett. **115**, 235301 (2015).
[17] R. Daou, C. Bergemann, and S. R. Julian, Phys. Rev. Lett. **96**, 026401 (2006).
[18] N. Harrison, S. E. Sebastian, C. H. Mielke, A. Paris, M. J. Gordon, C. A. Swenson, D. G. Rickel, M. D. Pacheco, P. F. Ruminer, J. B. Schillig, J. R. Sims, A. H. Lacerda, M.-T. Suzuki, H. Harima, and T. Ebihara, Phys. Rev. Lett. **99**, 056401 (2007).
[19] S. E. Sebastian, N. Harrison, C. D. Batista, S. A. Trugman, V. Fanelli, M. Jaime, T. P. Murphy, E. C. Palm, H. Harima, and T. Ebihara, Proc. Natl. Acad. Sci. U.S.A. **106**, 7741 (2009).
[20] P. M. C. Rourke, A. McCollam, G. Lapertot, G. Knebel, J. Flouquet, and S. R. Julian, Phys. Rev. Lett. **101**, 237205 (2008).
[21] H. Pfau, R. Daou, S. Lausberg, H. R. Naren, M. Brando, S. Friedemann, S. Wirth, T. Westerkamp, U. Stockert, P. Gegenwart, C. Krellner, C. Geibel, G. Zwicknagl, and F. Steglich, Phys. Rev. Lett. **110**, 256403 (2013).
[22] A. Pourret, A. P. Morales, S. Krämer, L. Malone, M. Nardone, D. Aoki, G. Knebel, and J. Flouquet, J. Phys. Soc. Jpn. **82**, 034706 (2013).
[23] N. T. Huy, A. Gasparini, D. E. de Nijs, Y. Huang, J. C. P. Klaasse, T. Gortenmulder, A. de Visser, A. Hamann, T. Görlach, and H. v. Löhneysen, Phys. Rev. Lett. **99**, 067006 (2007).
[24] D. Aoki, T. D. Matsuda, F. Hardy, C. Meingast, V. Taufour, E. Hassinger, I. Sheikin, C. Paulsen, G. Knebel, H. Kotegawa, and J. Flouquet, J. Phys. Soc. Jpn. **80**, SA008 (2011).
[25] N. T. Huy, D. E. de Nijs, Y. K. Huang, and A. de Visser, Phys. Rev. Lett. **100**, 077002 (2008).
[26] W. Knafo, T. D. Matsuda, D. Aoki, F. Hardy, G. W. Scheerer, G. Ballon, M. Nardone, A. Zitouni, C. Meingast, and J. Flouquet, Phys. Rev. B **86**, 184416 (2012).
[27] D. Aoki, I. Sheikin, T. D. Matsuda, V. Taufour, G. Knebel, and J. Flouquet, J. Phys. Soc. Jpn. **80**, 013705 (2011).
[28] E. Steven, A. Kiswandhi, D. Krstovska, J. S. Brooks, M. Almeida, A. P. Gonalves, M. S. Henriques, G. M. Luke, and T. J. Williams, Appl. Phys. Lett. **98**, 132507 (2011).
[29] T. V. Bay, A. M. Nikitin, T. Naka, A. McCollam, Y. K. Huang, and A. de Visser, Phys. Rev. B **89**, 214512 (2014).
[30] T. Hattori, Y. Ihara, Y. Nakai, K. Ishida, Y. Tada, S. Fujimoto, N. Kawakami, E. Osaki, K. Deguchi, N. K. Sato, and I. Satoh, Phys. Rev. Lett. **108**, 066403 (2012).
[31] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.117.206401, which includes Refs. [32,33], for a description of the experimental details, analysis of the quantum oscillations, and summary of the quantum oscillation frequencies and effective masses.
[32] A. Pantsulaya and A. Varlamov, Phys. Lett. A **136**, 317 (1989).
[33] A. Palacio Morales, A. Pourret, G. Knebel, G. Bastien, V. Taufour, D. Aoki, H. Yamagami, and J. Flouquet, Phys. Rev. B **93**, 155120 (2016).
[34] From the opposite sign of ρ_{xy} and S, it seems that both quantities are sensitive to different charge carriers. However, UCoGe is a compensated metal with equal carrier numbers of holes and electrons. As it is a multiband system, it is difficult to conclude on dominant charge carriers. Furthermore, as shown for URhGe in Ref. [35], the sign of S may also depend on the current direction.
[35] A. Gourgout, A. Pourret, G. Knebel, D. Aoki, G. Seyfarth, and J. Flouquet, Phys. Rev. Lett. **117**, 046401 (2016).
[36] B. Wu *et al.* (private communication).
[37] D. Aoki and J. Flouquet, J. Phys. Soc. Jpn. **83**, 061011 (2014).
[38] D. Aoki, A. Gourgout, A. Pourret, G. Bastien, G. Knebel, and J. Flouquet, C.R. Phys. **15**, 630 (2014).
[39] S. Nakamura (private communication).
[40] G. W. Scheerer, W. Knafo, D. Aoki, G. Ballon, A. Mari, D. Vignolles, and J. Flouquet, Phys. Rev. B **85**, 094402 (2012).
[41] M. M. Altarawneh, N. Harrison, S. E. Sebastian, L. Balicas, P. H. Tobash, J. D. Thompson, F. Ronning, and E. D. Bauer, Phys. Rev. Lett. **106**, 146403 (2011).
[42] L. Malone, T. D. Matsuda, A. Antunes, G. Knebel, V. Taufour, D. Aoki, K. Behnia, C. Proust, and J. Flouquet, Phys. Rev. B **85**, 245117 (2011).
[43] A. Pourret, A. Palacio-Morales, S. Krämer, L. Malone, M. Nardonne, D. Aoki, G. Knebel, and J. Flouquet, J. Phys. Soc. Jpn. **82**, 034706 (2013).
[44] M. Boukahil, A. Pourret, G. Knebel, D. Aoki, Y. Ōnuki, and J. Flouquet, Phys. Rev. B **90**, 075127 (2014).
[45] A. Pourret, G. Knebel, T. D. Matsuda, G. Lapertot, and J. Flouquet, J. Phys. Soc. Jpn. **82**, 053704 (2013).
[46] D. Aoki, G. Seyfarth, A. Pourret, A. Gourgout, A. McCollam, J. A. N. Bruin, Y. Krupko, and I. Sheikin, Phys. Rev. Lett. **116**, 037202 (2016).
[47] M. Samsel-Czekała, S. Elgazzar, P. M. Oppeneer, E. Talik, W. Walerczyk, and R. Troć, J. Phys. Condens. Matter **22**, 015503 (2010).
[48] S. I. Fujimori, T. Ohkochi, I. Kawasaki, A. Yasui, Y. Takeda, T. Okane, Y. Saitoh, A. Fujimori, H. Yamagami, Y. Haga, E. Yamamoto, and Y. Ōnuki, Phys. Rev. B **91**, 174503 (2015).