Hall resistivity in the heavy Fermion normal state of UPt_3 up to 26 T

1999 J. Phys.: Condens. Matter 11 221

(http://iopscience.iop.org/0953-8984/11/1/018)

J. Phys.: Condens. Matter **11** (1999) 221–227. Printed in the UK PII: S0953-8984(99)96797-8

Hall resistivity in the heavy Fermion normal state of UPt$_3$ up to 26 T

S Kambe†‡, A Huxley‡, J Flouquet‡, A G M Jansen† and P Wyder†

† Grenoble High Magnetic Field Laboratory, Max-Planck-Institut für Festkörperforschung and Centre National de la Recherche Scientifique, BP 166, 38042 Grenoble Cédex 9, France

‡ CEA/DSM—Département de Recherche Fondamentale sur la Matière Condensée SPSMS, CEA–CENG, 38054 Grenoble Cédex 9, France

Received 17 August 1998, in final form 19 October 1998

Abstract. The Hall resistivity ρ_{xy} has been measured in single crystal UPt$_3$ at low temperatures (0.1–4.2 K) for magnetic field $H \parallel a$-axis up to 26 T. For temperatures $T \to 0$ K, the Hall coefficient goes asymptotically to zero, indicating a compensated-metal ground state. Since the Hall resistivity does not show an anomaly at the metamagnetic crossover of 20 T in the Fermi-liquid state below 0.8 K, a drastic change of the Fermi surface is unlikely at the crossover. A change of the skew scattering contribution to the Hall effect has been observed around 6 and 2 K, i.e. near respectively the magnetic ordering temperature and the temperature below which the Fermi-liquid state appears.

In heavy fermion compounds (Kondo-lattice systems), the electronic and magnetic properties change drastically with decreasing temperatures. At high temperatures the conduction electrons are decoupled from the f electrons which behave as localized moments, below the coherent temperature T^* (roughly Kondo temperature) the conduction electrons scatter coherently with the f electrons and finally below T_I the Fermi-liquid state with heavy quasi-particle masses emerges.

In these compounds, the Hall effect is sensitive to the f-electron magnetism through the skew scattering which comes from an asymmetric probability of electron scattering around a magnetic impurity in metal. In consequence, the Hall effect is a good probe of both electronic and magnetic properties in heavy fermion compounds. The Hall coefficient R_H ($= \rho_{xy}/H$ for $H \to 0$) is considered to be composed of temperature-independent ordinary scattering R_{ord} and skew scattering R_{sk} terms. The skew scattering model for the heavy fermion systems [1] shows that the temperature dependence of the Hall coefficient R_H in the incoherent state ($T > T^*$) roughly follows the static uniform magnetic susceptibility $\chi(T)$.

$$R_H = (\rho_{xy}/H)_{H\to 0} = R_{ord} + R_{sk} \qquad (1)$$

with

$$R_{sk} = c\chi(T)\rho$$

where ρ is the resistivity from quasi-particle scattering, and c is a constant connected with a conducting channel property. Such a T-dependence has been observed in several heavy fermion compounds above T^* [2].

Below T^*, equation (1) is only found to be valid approximately [3]. In the Fermi-liquid state for $T < T_I$, phenomenologically, R_{sk} becomes T independent and small [1]. Thus R_H is constant below T_I in compounds with paramagnetic ground state e.g. below $T_I \sim 0.3$ K in $CeRu_2Si_2$ ($T^* \sim 20$ K) [4], and below $T_I \sim 0.1$ K in $CeAl_3$ ($T^* \sim 5$ K) [2]. Because the fluctuations of the coherent state appear in the T-dependence of the skew scattering Hall constant R_{sk}, R_H is a good probe of the coherent state. In UPt_3, R_H increases with increasing $\chi(T)$ down to $T^* \sim 30$ K and decreases below T^* [5]. However, no measurement has been made on a single crystal below 1.4 K [6], i.e. in the coherent Fermi-liquid state (the T^2 Fermi-liquid resistivity law appears only below $T_I \sim 1.5$ K). Below $T_N \sim 5$ K, antiferromagnetic order has been observed in this compound by neutron scattering but this magnetic order has not been confirmed by NMR measurements [7]. This contradiction indicates that the magnetic order is not static but fluctuates at a frequency faster than the characteristic time scale of the NMR measurements [8].

One particular phenomenon observed in several heavy fermion systems is the metamagnetic-like crossover between a weakly polarized phase ($H < H_M$) and a strongly polarized phase ($H > H_M$) at a magnetic field H_M. For example in $CeRu_2Si_2$ ($H_M \parallel c$-axis ~ 8 T), the crossover is accompanied by a maximum in the magnetoresistivity ρ_{xx} and a sudden increase of magnetization and volume [9]. Although the measurements of the de Haas–van Alphen effect show a sudden change of quasi-particle bands at the metamagnetic crossover of this compound [10, 11], an anomaly in ρ_{xy} at the crossover disappears in the Fermi-liquid region for $T < T_I$ [4] indicating no discontinuous change of Fermi surface volume nor crossover from itinerant to localized f electrons. In UPt_3, a metamagnetic-like crossover takes place around 20 T ($H \parallel a$-axis) with an anomaly in ρ_{xx} and a substantial jump of magnetization [12]. van Sprang *et al* have measured ρ_{xy} up to 30 T in UPt_3 and found a maximum at the metamagnetic crossover down to 1.4 K [6]. One aim of this study is to confirm whether ρ_{xy} still has an anomaly at the metamagnetic crossover in the coherent Fermi-liquid state of UPt_3 ($T < T_I \sim 1.5$ K).

The experiments have been performed on a high quality single crystal ($2 \times 4 \times 0.2$ mm^3) obtained by the Czochralski method. The residual resistivity ρ_0 is 0.2 $\mu\Omega$ cm ($j \parallel c$), the superconducting critical temperature $T_c = 0.55$ K, the upper critical field $H_{c2}(T = 0\,\mathrm{K}) = 3$ T for $H \parallel a$. Gold wires ($\phi = 40$ μm) were bonded directly to the sample with a small contact diameter (<100 μm) in order to realize good conditions for Hall effect measurements. For the low field measurements (0–8 T), the standard six contacts configuration for Hall effect measurements was employed. For the high field measurements (8–26 T) in the hybrid magnet in Grenoble, the van der Pauw method was used for the same sample [13].

Figures 1(a) and 1(b) show the field-dependence of the Hall resistivity ρ_{xy} at low fields ($H \parallel a$-axis, $j \parallel c$-axis). Since ρ_{xy} is zero in the superconducting state without flux flow, results are presented in the normal state ($H > H_{c2}$). The strong T- and H-dependence of ρ_{xy} is observed down to the lowest temperature (0.1 K). The observed ρ_{xy} for $H = 0$–8 T and $T = 0.1$–4.2 K can be described by the following relation,

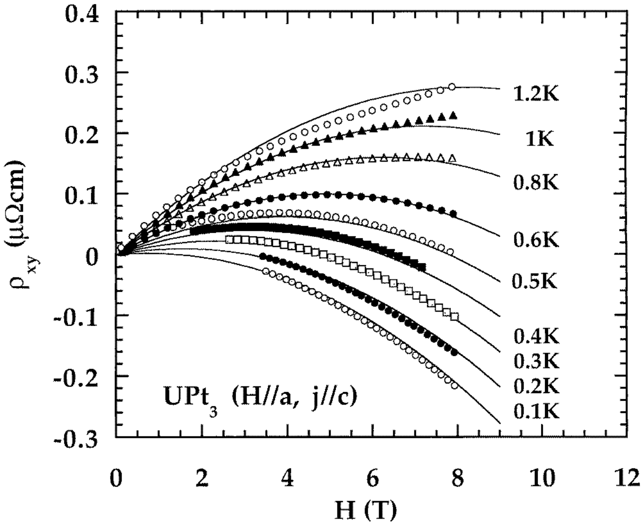
$$\rho_{xy} = R_H(T)H - \beta H^2 \tag{2}$$

with

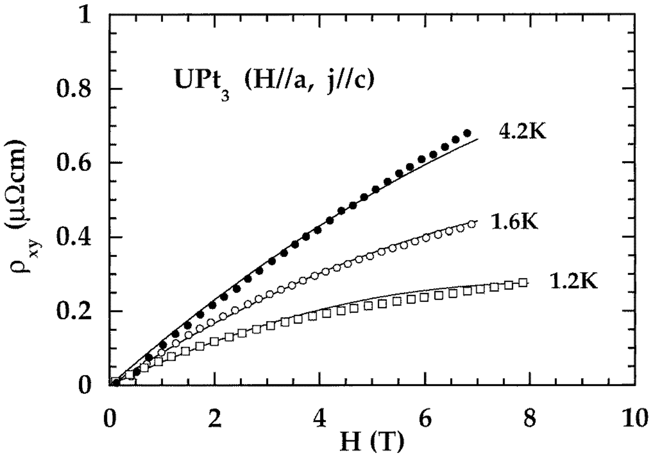
$$\beta = 0.0041\ \mu\Omega\ \mathrm{cm}\ \mathrm{T}^{-2}$$

as shown by the full lines in figures 1(a), 1(b) and 3. β is constant below 4.2 K, decreases with T above 5 K and finally reaches 0 above $T^* \sim 30$ K. The deduced T-dependence of $R_H(T)$ is shown in figure 2.

The Hall coefficient $R_H(T) = R_{ord} + R_{sk}$ is asymptotic to 0 as $T \to 0$ K, implying $R_{ord} \sim 0$ because $R_{sk} \sim 0$ as $T \to 0$ K. This means that UPt_3 would have a compensated-metal ground state if no superconducting transition occurred as has already been suggested from band structure calculations [14].



(a)



(b)

Figure 1. Field-dependence of Hall resistivity ρ_{xy} ($H \parallel a$-axis, $j \parallel c$-axis) in single crystal UPt$_3$ in low magnetic field (0–8 T); (a) 0.1–1.2 K, (b) 1.2–4.2 K. Data for $H > H_{c2}$ are presented. Full lines are calculated from equation (2).

The remarkable point is that $R_H(T)$ shows no tendency towards saturation down to 0.1 K. In a compensated metal, R_{ord} can be T-dependent due to a different T-dependence of the electron and hole mobilities (the multi-band model). Nevertheless, R_{ord} becomes constant in a compensated metal such as Cd when the ordinary scattering is dominated by T-independent elastic scattering at low temperatures [15]. From ρ_{xx} and thermal conductivity κ measurements in a single crystal UPt$_3$ of the same quality, ρ_{xx} and κ/T are observed to approach and constant values around 0.1 K at 3 T (just above H_{c2}) and the Wiedemann–Franz relation is obeyed [16]. Therefore the elastic scattering is predominant and R_{ord} can be considered to be T independent up to 0.1 K as observed for the ρ_{xx} and κ. At high temperatures, it is possible that R_{ord} depends on temperature.

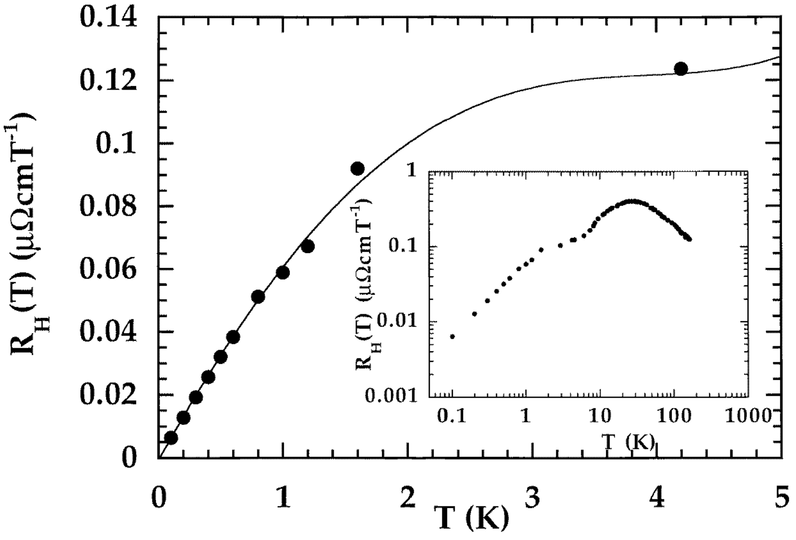


Figure 2. Temperature-dependence of the Hall coefficient $R_H(T)$. The full line is a guide to the eye. Inset: T-dependence of $R_H(T)$ including high temperatures.

The skew scattering can induce a large contribution to ρ_{xy} with a T-dependence different from the ordinary scattering. The observed strong T-dependence of $R_H(T)$ below T_I is probably due to the skew scattering by the ordered moment. Since $R_{ord} \sim 0$ in UPt$_3$, the T-dependence of R_{sk} can be studied down to very low temperatures. In the magnetic ordered state below $T_N \sim 5$ K, equation (1) is no longer valid. Here the skew scattering due to the antiferromagnetic sublattice magnetization m_Q should be considered. A model of the skew scattering in the antiferromagnetic ordered state far below the Neél temperature is not well developed [17]. On the other hand, for a ferromagnetic ordered state, magnon excitations lead to $R_{sk} \propto (m_0^2(0\text{ K}) - m_0^2(T))$ [18, 19] ($m_0(T)$ being the sublattice magnetization at $q = 0$). In case of an antiferromagnet, a similar relation $R_{sk} \propto (m_Q^2(0\text{ K}) - m_Q^2(T))$ might be expected. Actually, neutron scattering measurements of m_Q in UPt$_3$ show that $(m_Q^2(0\text{ K}) - m_Q^2(T))$ increases linearly from T_c to T_N [20], in magnetic field up to 10 T, a similar linear T-dependence of m_Q^2 has been observed [21]. This linear T-dependence of m_Q^2 agrees with the T-dependence of $R_H(T)$ below 1 K. The non-linear T-dependence of $R_H(T)$ above 1 K may due to the T-dependence of R_{ord}. In contrast, the uniform sublattice magnetization m_0 of the normal state ($H = 3$ T) is almost independent of T between 0.1 K and 4.2 K [22]. Therefore the strong T-dependent skew scattering term is considered to be related with the evolution of the sublattice magnetization at $q = Q$ but not with that at $q = 0$.

The inset of figure 2 shows at least three different regimes in the temperature dependence of $R_H(T)$: a maximum around 30 K $\sim T^*$ well correlated with a corresponding maximum in the uniform magnetic susceptibility, a kink near $T_N \sim 5$ K and another change near $T_I = 1.5$ K. The low temperature behaviour which may be connected with the skew scattering mechanism in the presence of an antiferromagnetic order appears only below T_I i.e. when the coherence is well established among the heavy quasi-particles. The origin of T_I (low energy scale compared with T^*) is an open question. One possible explanation is that T_I is connected with a new screening effect of the Nozières exhaustion principle [23].

The second term of equation (2) which dominates ρ_{xy} in high field may be a contribution of the ordinary Hall effect. In compensated metals, the ρ_{xx} and ρ_{xy} components of the resistivity tensor show a H^2 law in the high field limit ($\omega_c\tau > 1$; ω_c is the cyclotron frequency). The high field condition is considered to be almost satisfied in the present measurement since $\omega_c\tau \sim 1$ for $H \sim 3$ T at 0.1 K in the present sample. At high temperatures, this term disappears because the high field picture is no longer valid. The field-dependence of ρ_{xx} is different from the H^2-law, particularly below 0.05 K, which might be due to an impurity or a quantum effect for $\omega_c\tau \gg 1$ [24].

Figure 3 shows ρ_{xy} at high fields for several temperatures. The anomaly of ρ_{xy} at the metamagnetic crossover around $H_M \sim 20$ T becomes weaker for decreasing temperatures and vanishes below 0.8 K, indicating that the Fermi surface is not modified discontinuously at the metamagnetic crossover if the coherence is well developed. The f electrons still participate in the Fermi surface and a localization of f electrons is unlikely at the crossover. In contrast, ρ_{xx} shows an anomaly at the transition even at 0.1 K (figure 4) as reported previously [25, 26]. The present result suggests that ρ_{xy} is quasi-insensitive to the metamagnetic crossover in the coherent state of the heavy fermion system. The full lines in figure 3 reveal that equation (2) reproduces the experiment at high field and low temperatures ($T < 0.8$ K), supporting the strong field limit picture obtained previously. Above $T_I \sim 1.5$ K, the anomaly of ρ_{xy} appears at the metamagnetic crossover and equation (2) is no longer valid. From the Shubnikov–de Haas measurements in UPt$_3$ in fields up to 30 T below 0.1 K, it is found that the effective mass above the metamagnetic crossover is still very large ($\sim$110 m_e) [26], in agreement with the present result. The Shubnikov–de Haas measurements have also suggested a magnetic splitting of the quasi-particle band with magnetization.

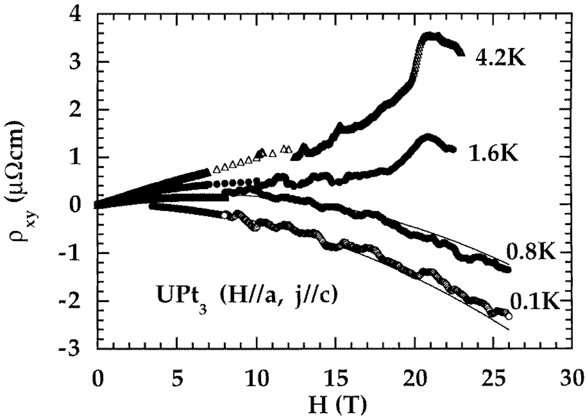


Figure 3. Field dependence of ρ_{xy} ($H \parallel a$-axis, $j \parallel c$-axis) at high field. Full lines are calculated from equation (2).

A similar behaviour of ρ_{xy} and ρ_{xx} at the metamagnetic crossover has been observed in CeRu$_2$Si$_2$ [4]. Since CeRu$_2$Si$_2$ is not a compensated metal, the usual low field relation $\rho_{xy} \propto \tau\rho_{xx}H$ and the absence of an anomaly in ρ_{xy} lead that $\tau\rho_{xx}$ should be monotonic over the metamagnetic crossover. Therefore the observed maximum of ρ_{xx} at the metamagnetic crossover indicates that τ has a minimum [4]. The minimum of τ is simply explained by the relation $1/\tau \propto m^{*2}$ for the heavy fermion state [27] where m^* is the quasi-particle's effective mass which has a maximum at the crossover in CeRu$_2$Si$_2$ [9].

In contrast, the relation $\rho_{xy} \propto \tau\rho_{xx}H$ at high field is not valid for a compensated metal as found in the case of UPt$_3$ because the H-linear term of ρ_{xy} in the resistivity tensor is cancelled out. Unfortunately the H^2-term of ρ_{xy} is a quantity which has no simple physical meaning.

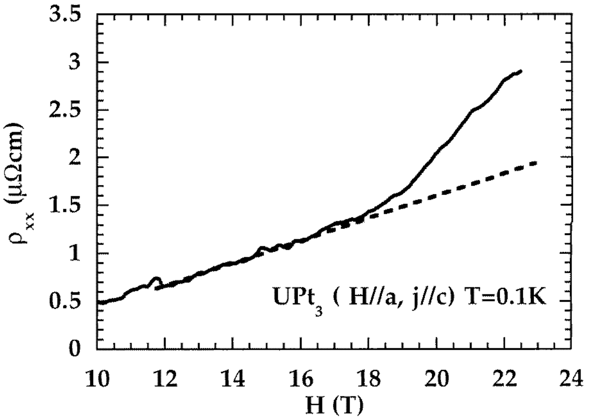


Figure 4. Field dependence of magnetoresistance ρ_{xx} ($H \parallel a$-axis, $j \parallel c$-axis) at 0.1 K in single crystal UPt$_3$. Dashed line is the guide to the eye.

The absence of an anomaly in ρ_{xy} is a general property of the heavy Fermi liquid since similar behaviour is observed in both UPt$_3$ and CeRu$_2$Si$_2$. One puzzle is that ρ_{xy} is quasi-insensitive to the jump of magnetic polarization at the crossover whereas ρ_{xx} shows an anomaly. Theoretical advances for these problems have still to be made.

Finally, the effect of disorder should be addressed. The skew scattering is probably sensitive to the magnetic disorder in the Kondo lattice. Thus a magnetic disorder contribution to the T-dependence of $R_H(T)$ can not be excluded. In fact the T-dependence of the resistivity near the magnetic instability of heavy fermion systems can be explained as the sum of contributions from spin fluctuations and magnetic disorder [28].

In conclusion, the Hall resistivity in UPt$_3$ shows a strong T-dependent skew scattering at temperatures below T_I and a crossover to the classical strong field region at high field. The absence of an anomaly of ρ_{xy} at the metamagnetic crossover around 20 T implies that the modification of the Fermi surface is continuous in the heavy Fermi-liquid state at $T < T_I$.

Acknowledgments

The authors would like to acknowledge P van der Linden for his valuable technical supports. We are grateful to H Suderow, J-P Brison and N H van Dijk for many stimulating discussions.

References

[1] Fert A and Levy P M 1987 *Phys. Rev.* B **36** 1907
[2] Lapierre F, Haen P, Briggs R, Hamzic A, Fert A and Kappler J P 1987 *J. Magn. Magn. Mater.* **63/64** 338
[3] Kohno H and Yamada K 1990 *J. Magn. Magn. Mater.* **90/91** 431
[4] Kambe S, Flouquet J, Lejay P and Haen P 1996 *J. Low Temp. Phys.* **102** 477
[5] Schoenes J and Franse J J M 1986 *Phys. Rev.* B **33** 5138
[6] van Sprang M, Boer R A, Riemersma A J, Roeland L W, Menovsky A and Franse J J M 1988 *J. Magn. Magn. Mater.* **76/77** 229
[7] Tou H, Kitaoka Y, Asayama K, Kimura N, Onuki Y, Yamamoto E and Maezawa K 1996 *Phys. Rev. Lett.* **77** 1374
[8] Okuno Y and Miyaka K 1998 *J. Phys. Soc. Japan* **10** 3342
[9] Flouquet J, Kambe S, Regnault L P, Haen P, Brison J P, Lapierre F and Lejay P 1995 *Physica* B **215** 77
[10] Takashita M, Aoki H, Terashima T, Uji S, Maezawa K, Settai R and Onuki Y 1996 *J. Phys. Soc. Japan* **65** 515
[11] Tautz F S, Julian S R, McMullan G J and Lonzarich G G 1995 *Physica* B **206/207** 29

[12] Frings P H, Franse J J M, de Boer F R and Menovsky A 1983 *J. Magn. Magn. Mater.* **31/34** 240
[13] van der Pauw L J 1958 *Philips Res. Rep.* **13** 1
[14] Oguchi T and Freeman A J 1986 *J. Magn. Magn. Mater.* **61** 233
[15] Katyal O P and Gerritsen A N 1969 *Phys. Rev.* **178** 1073
[16] Suderow H, Brison J P, Huxley A and Flouquet J 1997 *J. Low Temp. Phys.* **108** 11
[17] Maranzana F E 1967 *Phys. Rev.* **160** 421
[18] Irkin Yu P and Abel'skii Sh Sh 1964 *Sov. Phys.–Solid State* **6** 1283
[19] Kagan Yu and Makisimov L A 1965 *Sov. Phys.–Solid State* **7** 422
[20] Aeppli G, Bucher E, Broholm C, Kjems J K, Baumann J and Hufnagl J 1988 *Phys. Rev. Lett.* **60** 615
[21] van Dijk N H, Fak B, Regnault L P, Huxley A and Fernandez-Diaz M T 1998 *Phys. Rev.* B **58** 3186
[22] Paulsen C, private communications
[23] Nozières P 1997 *Lecture Notes at Institute Laue–Langevin*
[24] Taillefer L, Flouquet J and Joss W 1988 *J. Magn. Magn. Mater.* **76/77** 218
[25] Franse J J M, de Visser A, Menovsky A and Frings P H 1985 *J. Magn. Magn. Mater.* **52** 61
[26] Julian S R, Teunissen P A A and Wiegers S A J 1992 *Phys. Rev.* B **46** 9821
[27] Yamada K, Okada K, Yoshida K and Hanzawa K 1987 *Prog. Theor. Phys.* **77** 1097
[28] Kambe S and Flouquet J 1997 *Solid State Commun.* **103** 551