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Pressure effects on the high-field magnetoresistance of heavy-fermion $U(Pt_{0.95}Pd_{0.05})_3$

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The effect of hydrostatic pressure ($p \leq 5$ kbar) on the threshold fields for the metamagnetic-like transition (B^*) and the antiferromagnetic phase boundary (B_c) of heavy-fermion $U(Pt_{0.95}Pd_{0.05})_3$ has been investigated by means of high-field magnetoresistance experiments ($B \leq 20$ T) at $T = 2.0$ K. Whereas $B^* \simeq B_c \simeq 12.3$ T at zero pressure, the transitions shift apart under pressure: $B^* = 16.3$ T while $B_c = 11.3$ T at 4.9 kbar. The magnetic phase diagram is discussed.

1. Introduction

The pseudobinary heavy-fermion series $U(Pt_{1-x}Pd_x)_3$ shows an unusually rich phase diagram [1–4]. Pure UPt_3 exhibits unconventional superconductivity and reduced moment antiferromagnetism ($T_N = 5$ K), whereas long-range antiferromagnetism with fairly large ordered moments is observed in the concentration range $0.02 \leq x \leq 0.07$. The maximum Néel temperature amounts to $T_N = 5.8$ K for $x = 0.05$. Neutron diffraction experiments [5] on the 5% Pd compound yield an ordered moment of $0.6\mu_B$/U-atom directed along the b-axis in the hexagonal plane. For higher Pd contents ($x \geq 0.10$) the well-known metamagnetic-like transition observed in pure UPt_3(at $B^* = 21$ T for a field in the hexagonal plane) is no longer observed and instead Kondo-like phenomena appear in the resistivity. This salient change of magnetic behaviour with increasing Pd content can qualitatively be described by a cross-over from a system that is governed by the Ruderman–Kittel–Kasuya–Yosida (RKKY) interaction to a system with dominant Kondo fluctuations. However, the variation of the exchange parameter J and the characteristic temperatures $T_{RKKY}(J)$ and $T_K(J)$ cannot be determined unambiguously in the $U(Pt_{1-x}Pd_x)_3$ series [3] as the electronic parameters are strongly anisotropic which complicates the underlying physics.

In this paper we concentrate on the magnetic phase diagram of the 5% Pd compound (fig. 1). The antiferromagnetic phase boundary for a field directed in the easy plane for magnetization was obtained by specific-heat experiments in applied magnetic fields [6,7]. For $B \parallel a$ and $B \parallel b$ the suppression of the long-range magnetic order occurs at $B_c = 13$ T and $B_c = 12$ T, respectively. Magnetization measurements [8] performed in the temperature range $1.3\text{ K} < T < 20$ K indicate, however, the presence of a weakly temperature-dependent second phase transition at $B^* = 12$–13 T, that is reminiscent of the metamagnetic-like transition for pure UPt_3. B^* is interpreted as the threshold field for the suppression of the pronounced antiferromagnetic spin-fluctuations that were evidence in zero field. Apparently, only a part of the fluctuating moment orders antiferromagnetically below T_N so that the heavy-fermion properties persist at low temperatures (note that the coefficient of the linear electronic specific heat is enhanced considerably (~50%) with respect to pure UPt_3 [1]).

Surprisingly, the extrapolation of both phase lines (fig. 1) suggests that they meet at $T = 0$ K. Apparently, the magnetic energies for suppression of the antiferromagnetic order ($\mu_B B_c$) at 0 K and the antiferromagnetic intersite correlations ($\mu_B B^*$) are approximately equal. On the other hand an intriguing question is whether the metamagnetic-like transition still exists at $T = 0$ K. While the anomaly at B^* becomes more pronounced in pure UPt_3 at decreasing the temperature, the sharp anomaly at B_c thwarts the observation of B^* in the case of the 5% Pd compound. Interestingly, for the heavy-fermion antiferromagnets $Ce_{0.90}La_{0.10}Ru_2Si_2$ ($T_N = 2.7$ K) and $Ce_{0.87}La_{0.13}Ru_2Si_2$ ($T_N = 3.8$ K) a similar magnetic phase diagram has been reported [9], i.e. the boundary for the metamagnetic-like transition (for both compounds at $B^* \simeq 3.5$ T ($T \rightarrow 0$) for B along the tetragonal axis) extrapo-

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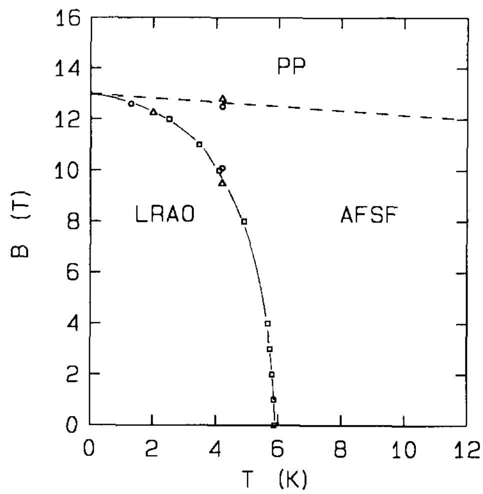

Fig. 1. The magnetic phasediagram of $U(Pt_{0.95}Pd_{0.05})_3$ for $B \parallel a$. Data are taken from specific heat (□) [6,7], magnetization (△) [8] and magnetoresistance (○). LRAO denotes long-range antiferromagnetic order, AFSF denotes antiferromagnetic spin fluctuations and PP denotes the polarized paramagnetic phase. The dashed line represents the metamagnetic-like transition [8], i.e. quenching of the antiferromagnetic spin fluctuations. The solid line represent the antiferromagnetic phase boundary.

lates to the antiferromagnetic phase boundary for $T \to 0$.

In order to investigate whether a close connection between B^* and B_c exists or whether the coincidence of B^* and B_c for $T = 0$ K is accidental, we have performed high-field high-pressure experiments. Magnetoresistance was used to probe both B_c and B^*. We expect that the pressure effects on B^* and B_c are rather large as previous experiments on UPt_3 yield an increase of B^* at a rate of 0.60 T/kbar [10], while previous experiments on $U(Pt_{0.95}Pd_{0.05})_3$ yield $dT_N/dp = -0.3$ K/kbar [11] in zero field.

2. Experimental

The high-pressure high-field experiments have been performed in the High Magnetic Field Facility of the University of Amsterdam. The pressure vessel was machined of a copper–beryllium alloy. Helium served as pressure-transmitting medium. Experimental details are given in ref. [10]. Standard DC four-probe magnetoresistance measurements under pressure were performed on a Czochralski-grown single-crystalline $U(Pt_{0.95}Pd_{0.05})_3$ specimen with a cylindrical shape (length 6 mm, diameter 1.3 mm). The current (current density 77 A/cm^2) and magnetic field were both directed along the a-axis. The residual resistance value equals 114 μΩ cm and decrease at a rate of 5.4 μΩ cm/kbar at $T = 4.2$ K, in agreement with previous reports [11].

3. Results

Our zero-pressure results are shown in fig. 2 in a plot of $\Delta\rho = \rho(B) - \rho(0)$ versus B. The anomalous behaviour at low fields ($B < 5$ T) is related to the orientation of magnetic domains [12] and will not be discussed in the present paper. At $T = 2.0$ K we observe a single high-field transition at 12.3 T, while at $T = 4.2$ K clearly two transitions are observed: the suppression of the antiferromagnetic phase at $B_c = 9.5$ T and the metamagnetic-like transition at $B^* = 12.8$ T. Values for B_c and B^* as deduced from fig. 2 are also plotted in fig. 1. The magnetoresistance data under pressure are shown in fig. 3. As the most important result from the present experiments we note that the antiferromagnetic phase boundary and the metamagnetic-like transition that have merged at zero pressure, are separated under pressure. The pressure variation of B_c and B^* is plotted in fig. 4. We observe that B^* increases at a constant rate of 0.81 T/kbar, while the suppression of B_c takes place nonmonotonically so that $B_c = 11.3$ T at 4.9 kbar.

4. Discussion

From the data in fig. 4 we conclude that the coincidence of B_c and B^* for $T \to 0$ at zero pressure is accidental (note that our measurements have been performed at $T = 2.0$ K, but one would have to as-

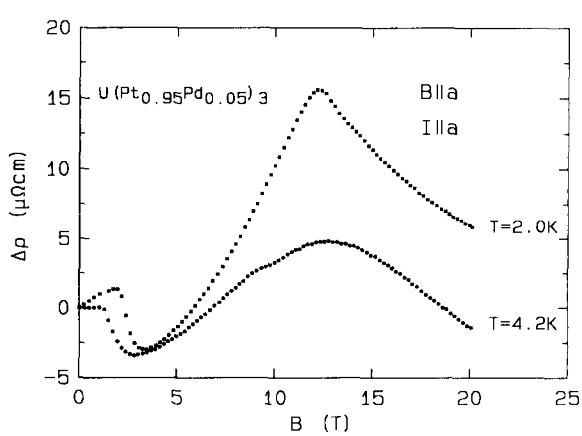

Fig. 2. Magnetoresistance of $U(Pt_{0.95}Pd_{0.05})_3$ for $B \parallel I \parallel a$ at $T = 2.0$ K (■) and $T = 4.2$ K (●).

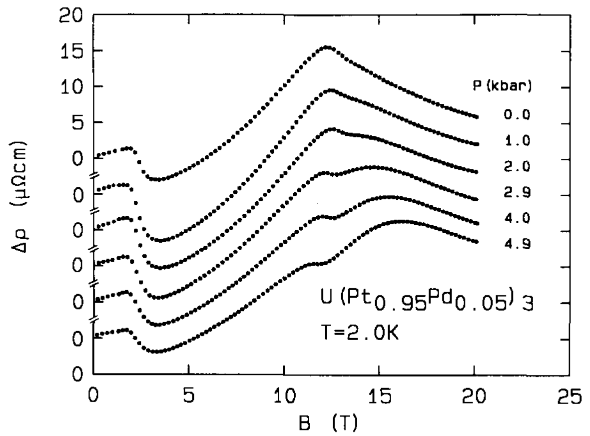

Fig. 3. Magnetoresistance of $U(Pt_{0.95}Pd_{0.05})_3$ for $B \| I \| a$ at $T = 2.0$ K under hydrostatic pressures up to 4.9 kbar as indicated.

sume an exceptionally strong temperature variation of B^* and B_c under pressure in order to arrive at $B_c = B^*$ for $T \to 0$). Under pressure $\Delta\rho$ at B^* is nearly constant (as was also observed for pure UPt_3 [10] and $CeRu_2Si_2$ [13]), suggesting that the metamagnetic-like transition also takes place at zero pressure. Concurrently, the decrease of the total $\Delta\rho$ at B_c with pressure might be explained by the shift of the contribution from the metamagnetic-like transition B^* towards higher fields with pressure. At present a method for the separation of the contributions from the long-range antiferromagnetic order and the metamagnetic-like transition to $\Delta\rho$ is not at hand. Therefore, other types of experiments are necessary to elucidate the magnetoresistance data. In particular magnetization measurements under pressure might enable us to follow the pressure variation of the 'steps' in the magnetization associated with B_c and B^*.

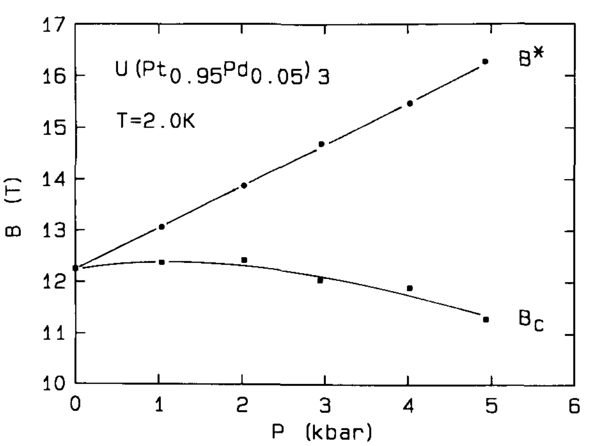

Fig. 4. Pressure variation of B^* (●) and B_c (■) for $U(Pt_{0.95}Pd_{0.05})_3$ at $T = 2.0$ K.

In the case of UPt_3 [10] and $CeRu_2Si_2$ [13] it was found that the thermal and magnetic energy scales for the heavy-fermion contribution are closely related, i.e. $k_B T^* \approx \mu_B B^*$ (where T^* is given by the maximum in the magnetic susceptibility). In particular it was demonstrated that the free energy could be scaled by one single volume-dependent energy parameter $F = F(T/T^*(V), B/B^*(V))$, as the magnetic and thermal Grüneisen parameters are almost equal: $\Gamma_B (= -\mathrm{d}\ln B^*/\mathrm{d}\ln V) \approx \Gamma_T (= -\mathrm{d}\ln T^*/\mathrm{d}\ln V)$. For $U(Pt_{0.95}Pd_{0.05})_3$ we derive, from the data in fig. 4, a magnetic Grüneisen parameter $\Gamma_B = 136$ (the compressibility of UPt_3 amounts to $0.48\,\mathrm{Mbar}^{-1}$ [2]), while for pure UPt_3 and $CeRu_2Si_2$ values for Γ_B of 59 [10] and 180 [13] have been reported, respectively. The strong variation of Γ_B (and Γ_T [14]) in the $U(Pt,Pd)_3$ series underlines that the effects of substituting Pd for Pt cannot simply be accounted for by chemical pressure (or even shape effects). So far, the thermal Grüneisen parameter of $U(Pt_{0.95}Pd_{0.05})_3$ has not been probed directly in a pressure experiment. An indirect deduction from a combination of thermal-expansion and specific-heat data results in a value for Γ_T of approximately 60 at $T = 1$ K, which indicates that the single energy parameter scaling does no longer hold. The failure of the simple scaling law might have been conjectured from the rich and complex (magnetic) phase diagrams that are observed for the $U(Pt,Pd)_3$ series.

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