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Magnetic scaling of non-Fermi-liquid $UCu_{5-x}Pd_x$ (x = 0.8, 0.9, 1, 1.2)

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Abstract. The $UCu_{5-x}Pd_x$ heavy-fermion alloy system is known to exhibit non-Fermi-liquid (NFL) behaviour for compositions with $x \approx 1$. The magnetic properties associated with NFL behaviour of this system are the focus of this study. Results are presented on the temperature ($1.7 \leqslant T \leqslant 300$ K) and magnetic field ($0 \leqslant B \leqslant 5$ T) dependences of the magnetization M and susceptibility χ for polycrystalline $UCu_{5-x}Pd_x$ samples with $x = 0.8$, 0.9, 1.0 and 1.2. We emphasize the observed field dependence of χ at low temperatures and illustrate the instability of NFL properties against magnetic field. Our $\chi(T)$ data present a systematic power-law divergence for NFL $UCu_{5-x}Pd_x$ at low temperatures in the limit of small measuring fields. This is interpreted in terms of Griffiths-phase singularities near a quantum critical point which are treated in a model given by Castro Neto and co-workers that includes the effects of structural disorder and a generic RKKY–Kondo interplay (where RKKY $\equiv$ Ruderman–Kittel–Kasuya–Yosida). For the extended range $1.7 \leqslant T \leqslant 300$ K, we find that $\chi(T)$ scales reasonably well with a theoretical expectation of Souletie and co-workers of NFL behaviour of Kondo systems. Finally, our $M(T, B)$ data for magnetic fields up to 5 T and $1.7 \leqslant T \leqslant 21$ K are shown to conform to a NFL scaling relation that applies to $T = 0$ quantum critical systems. The above analyses support the role that magnetic interactions are thought to play in NFL $UCu_{5-x}Pd_x$.

1. Introduction

A growing number of uranium and cerium compounds have been found to exhibit low-temperature specific heat, magnetic susceptibility and electronic transport properties that are at variance with the predictions of Fermi-liquid theory. Various mechanisms for accounting for such non-Fermi-liquid (NFL) characteristics have been proposed. Firstly, the very comprehensive theoretically studied and exquisite results of the multichannel and in particular the two-channel Kondo model [1, 2] find possible application to several NFL uranium and cerium systems as discussed in reference [2]. Secondly, NFL characteristics are often ascribed to fluctuations of an order parameter near a $T = 0$ quantum critical point [3–6]. This may be attained by application of external pressure or alloying whereby antiferromagnetic order in such materials vanishes ($T_N \rightarrow 0$) at a critical pressure p_c or concentration x_c [7–9]. An exemplary system for which tuning by chemical doping or pressure to its quantum critical point has been studied extensively is $CeCu_{6-x}Au_x$ [7]. Thirdly, the concept of Kondo disorder has been proposed [10, 11] specifically to describe NFL behaviour earlier observed in $UCu_{5-x}Pd_x$ alloys [12].

The $UCu_{5-x}Pd_x$ system ($x = 1, 2$) was studied for the first time by Zołnierek *et al* [13], who found Kondo-like behaviour for these compositions. The system furthermore displays antiferromagnetic order for $0 \leqslant x \leqslant 0.75$ with the Néel temperature rapidly suppressed with Pd substitution from $T_N \approx 16$ K for UCu_5 to vanishing at $x \sim 0.75$ [14]. Spin-glass behaviour is found for alloys with $1.8 \leqslant x \leqslant 2.3$. NFL behaviour was early on observed for alloys with compositions $x = 1.0$ and $x = 1.5$ as evidenced by the low-temperature dependences of the specific heat $C(T)/T \propto -\log T$ [12], magnetic susceptibility $\chi(T) \propto -\log T$ [14] or $\chi(T) \propto T^{-\eta}$ [12] and resistivity $\rho(T) = \rho_0(1 - aT)$ [12, 14].

The initial inelastic neutron scattering experiments by Aronson *et al* [15, 16] on $UCu_{5-x}Pd_x$ ($x = 1, 1.5$) gave a rather similar magnetic response for both compounds which can be described by a universal function of ω/T. This was interpreted as evidence of single-impurity quantum critical fluctuations of the 5f electrons. Subsequent inelastic neutron scattering measurements with full polarization analysis by these authors [17] indicate the development of antiferromagnetic correlations below 10 K in UCu_4Pd but not in $UCu_{3.5}Pd_{1.5}$. This suggests the crossover from a quantum critical regime to a quantum-disordered regime in qualitative agreement with models of quantum critical scattering [18].

The Kondo-disorder model is based on the observation of inhomogeneous broadening of the Cu NMR line in UCu_4Pd and $UCu_{3.5}Pd_{1.5}$ samples, thus indicating a broad distribution of local U-spin static susceptibilities [10]. This results in a distribution $P(T_K)$ of local Kondo temperatures T_K. If at a low temperature T a significant number of Kondo impurities have Kondo temperatures $T_K < T$, then these will be unquenched, leading to the formation of a NFL phase. Experimental bulk susceptibility data $\chi(T, B)$ are used to find the parameters that characterize the assumed Gaussian function $P(T_K)$, which in turn is then used to calculate $C(T)/T$ or the NMR linewidths for these alloys in fair agreement with experimental data. $P(T_K)$ given by reference [10] gives a logarithmic divergence in $\chi(T)$ and $C(T)/T$ as the leading low-temperature behaviour [11]. It has also been argued that the uncompensated spins at low temperatures are responsible for the linear-in-temperature resistivity. Results of muon spin-rotation studies [19–21] support the Kondo-disorder model.

Recent experiments identify the origin of the Kondo disorder as structural. For $0 \leqslant x \leqslant 2.3$, $UCu_{5-x}Pd_x$ crystallizes in the fcc $AuBe_5$ structure [12, 13]. In UCu_5 the Cu atoms occupy the two inequivalent 16e and 4c positions in the ratio of 4:1. Neutron diffraction studies [22] on $UCu_{5-x}Pd_x$ alloys indicate that for $x < 1$ the Pd atoms preferentially occupy 4c sites and for $x > 1$ a mixture of Cu and Pd atoms occupy 16e sites. For UCu_4Pd ($x = 1$) the experiment could not distinguish between a full 4c occupancy by Pd or up to 16% occupancy of 4c sites by Cu rather than Pd atoms. Recent x-ray absorption fine-structure measurements of bond lengths in UCu_4Pd are interpreted as indicating that 24 ±3% of Pd atoms reside on the nominally Cu 16e sites [23], thus indicating structural disorder also for the $x = 1$ alloy. In this study a modified Kondo-disorder model has been derived which includes the effects of site interchange as well as bond-length disorder on the f–d hybridization. One of the features of this model is that $\chi(T \to 0)$ is expected to attain a limiting value.

It has recently been argued that instead of considering individually the principal mechanisms for NFL behaviour mentioned earlier, one should rather study the interplay among disorder, Ruderman–Kittel–Kasuya–Yosida (RKKY) interactions and Kondo interactions in f-electron alloys. Thus Castro Neto *et al* [24] propose that NFL behaviour in f-electron systems may be attributed to the existence of Griffiths singularities close to the quantum critical point. Magnetic clusters are formed in the paramagnetic phase due to the competition between the RKKY and Kondo interactions in the presence of disorder. The model *inter alia* predicts a power-law dependence for the specific heat and susceptibility:

$$C(T)/T \propto \chi(T) \propto T^{\lambda-1} \tag{1}$$

with $\lambda < 1$ for the Griffiths phase. Experimental results on a number of NFL uranium systems, including $UCu_{5-x}Pd_x$ ($x = 1.0$ and 1.5) support the validity of (1) with λ-values ranging from 0.6 to 0.85 [25].

Although it is clear that disorder is an important consideration in the description of the NFL behaviour of $UCu_{5-x}Pd_x$, it is less evident which of the various theoretical models apply best for describing the properties of this system. In particular the significance of the disappearance of magnetic order is of interest. To this end we investigated four alloys of the $UCu_{5-x}Pd_x$ system ($x = 0.8$, 0.9, 1.0 and 1.2), thus extending the experimental data for the range of compositions near to where the magnetic order disappears. Magnetization measurements down to 1.7 K are presented and scaling behaviour in the limit of small applied fields, as well as for fields up to 5 T, is discussed.

2. Experimental details

Polycrystalline samples were prepared using the following elements (with their purities given in weight per cent): U (99.98), Cu (99.99+) and Pd (99.97). Samples in the $UCu_{5-x}Pd_x$ series were prepared by melting the constituent elements on a water-cooled copper plate inside an arc furnace. A titanium getter was used and during melting the samples were kept in a slight underpressure of high-purity argon gas. Each sample was remelted three times with intermittent overturning of the ingot to improve the homogeneity. The observed weight losses due to the melting process were in all cases 0.1 wt.% or less. The phase purities of the samples were checked using x-ray diffraction. The $F\bar{4}3m$ cubic crystal structure was confirmed for all compounds and no traces of unreacted elements could be discerned.

Magnetic susceptibility and magnetization measurements were performed at the W Trzebiatowski Institute of Low Temperature and Structure Research of the Polish Academy of Sciences. The magnetization specimens were in the form of small, solid pieces of polycrystalline specimens. A Quantum Design SQUID magnetometer with a maximum field of 5 T and with the capability of keeping the temperature at fixed values between 1.7 and 400 K, were used for these measurements.

3. Results and discussion

Magnetization (M) measurements for the alloys $UCu_{5-x}Pd_x$ ($x = 0.8$, 0.9, 1.0 and 1.2) were performed either as a function of temperature in various constant magnetic fields or as a function of magnetic field for constant temperatures. The magnetic susceptibility of all the alloys could be fitted to a Curie–Weiss relationship for temperatures $100 \leqslant T \leqslant 400$ K. An effective moment $\mu_{\mathrm{eff}} \sim 3.1\ \mu_{\mathrm{B}}$ (mol f.u.)$^{-1}$ is obtained for the different alloys, whereas the following values of the paramagnetic Curie temperatures $-\theta$ are obtained: 134 ± 1 for $x = 0.8$, 127 ± 1 for $x = 0.9$, 113 ± 2 for $x = 1.0$ and 114 ± 3 for $x = 1.2$. These values are in reasonable agreement with the results obtained by Andraka and Stewart [12] who fitted their data to a Curie–Weiss relationship for $T \geqslant 200$ K. These authors noted a plateau region ($1 \leqslant x \leqslant 1.75$) for their $-\theta$-values.

Magnetization curves for UCu_4Pd are depicted in figure 1. Whereas the higher temperature isotherms display linear behaviour, a clear negative curvature is observed for lower temperatures. This behaviour was observed for all of the alloys investigated. Similar nonlinear magnetization behaviour was also observed for NFL $Y_{1-x}U_xPd_3$ [26], $UCu_{5-x}Pd_x$ [10, 27], $U_{1-x}Th_xPd_2Al_3$ [25, 28], $UCu_{5-x}Al_x$ [29] and $CeCu_{6-x}Au_x$ [30] alloys. One possible interpretation for this is based on the presumed presence of impurities [26, 27, 31].

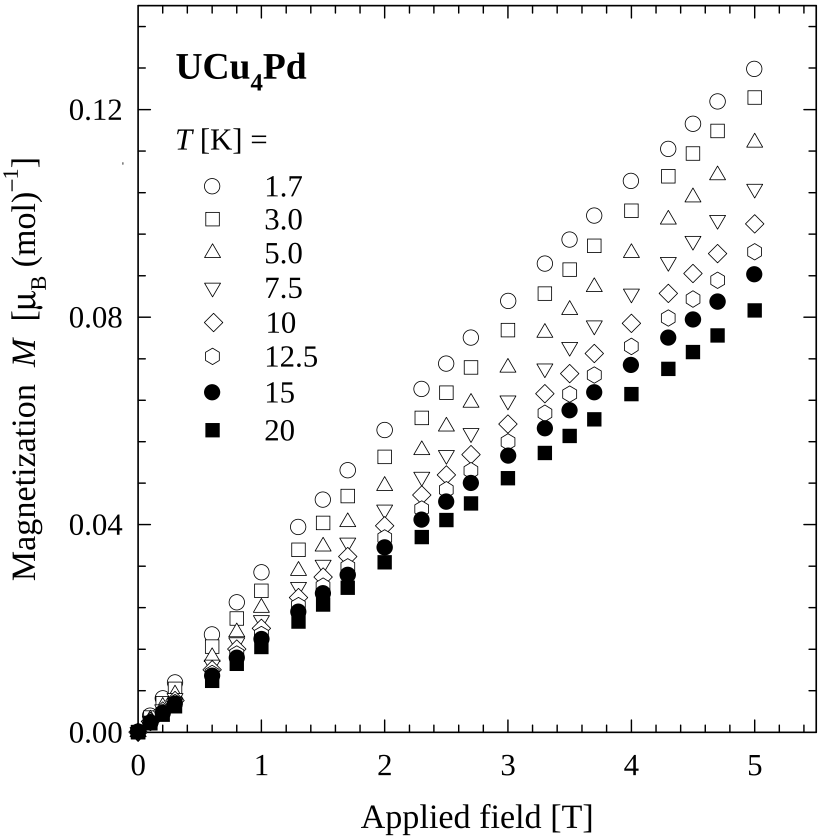

Figure 1. Magnetization isotherms for UCu_4Pd at low temperatures. Data are shown for both increasing and decreasing magnetic fields.

A so-called intrinsic susceptibility has thus been obtained for alloys of $Y_{1-x}U_xPd_3$ and $UCu_{5-x}Pd_x$ [26, 27, 31] by assuming that the intrinsic magnetization is linear in B while the assumed impurity contribution is given by a Brillouin function. We note that our magnetization curves show excellent reproducibility through the origin as measured in increasing and decreasing fields, thus negating the possible existence of ferromagnetic or ferrimagnetic impurity contributions to the magnetization. Considering the high purity of the metals used in our sample preparation, it seems unlikely that impurities could lead to the observed non-linear magnetization curves. We rather consider the measured curves as intrinsic properties of our alloys. In the Kondo-disorder model a non-linear magnetization behaviour (or field-dependent susceptibility) is expected at low temperature because of the presence of low-T_K free spins, the magnetization of which approximately follows a Brillouin function and saturates in sufficiently strong magnetic field [20]. It is also noted that non-linear magnetization curves are predicted in the $T \to 0$ limit of the multichannel Kondo model [1, 2].

Low-temperature susceptibility $\chi(T)$ data measured for UCu_4Pd in several constant fields are depicted in figure 2 on double-logarithmic axes. A significant field dependence of $\chi(T)$ is observed. In the limiting case of small fields, $\chi(T)$ follows a power-law dependence over one decade of temperature:

$$\chi(T) \propto T^{-\eta} \propto T^{\lambda-1} \tag{2}$$

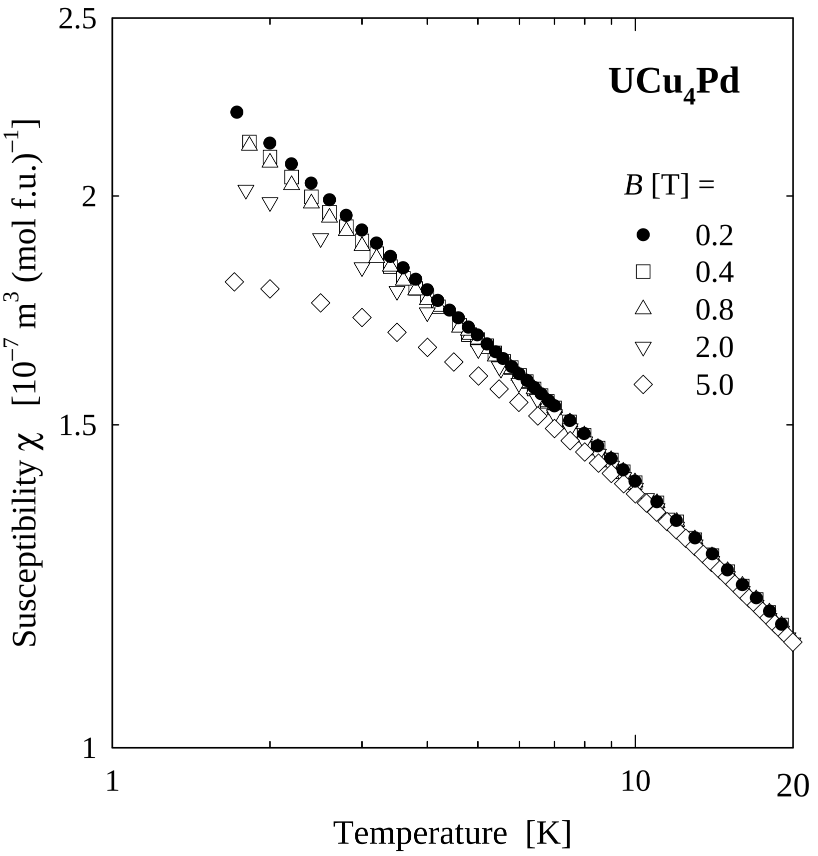

Figure 2. A double-logarithmic plot of UCu_4Pd susceptibility data below 20 K for various values of the measuring field. Towards the low-field measurements the data are seen to acquire power-law behaviour, in contrast to the considerably weaker temperature dependence of χ at low temperatures when measured in 5 T.

with $\lambda = 1 - \eta = 0.73 \pm 0.01$.

In figure 3 the possible validity of a logarithmic temperature dependence is probed by plotting $\chi(T)$ measured in different fields. It is clear that $\chi(T)$ measured in $B = 0.2$ T cannot be fitted to a logarithmic temperature dependence over any significant temperature interval. It is further noted that $\chi(T) \sim -\log T$ over one decade of temperature for data measured in 2 T. This presents an intermediate case at low temperatures between the upward curvature of the 0.2 T data and downward curvature exhibited by the 5 T data when $\log T$ is decreased. Earlier $\chi(T)$ studies by Andraka and Stewart [12] indicate a power-law relationship for $UCu_{3.5}Pd_{1.5}$ between 1.6 K and 12 K for measurements in 10^{-2} T, while results obtained in a higher field of 1 T by Chau and Maple [14] on UCu_4Pd and $UCu_{3.5}Pd_{1.5}$ were fitted to a $-\log T$ dependence ($2 \leqslant T \leqslant 10$ K). The behaviour of $\chi(T, B)$ shown in figure 2 is observed for all of the alloys investigated. It is our contention that the power-law behaviour of $\chi(T, B \rightarrow 0)$ at low temperature presents a useful and probably a fundamentally significant way of presenting the NFL behaviour of this system. A $-\log T$ low-temperature behaviour of $\chi(T)$ is observed for this system only by using an appropriate intermediate value of the applied field, thus leading to a fortuitous compliance with such a dependence.

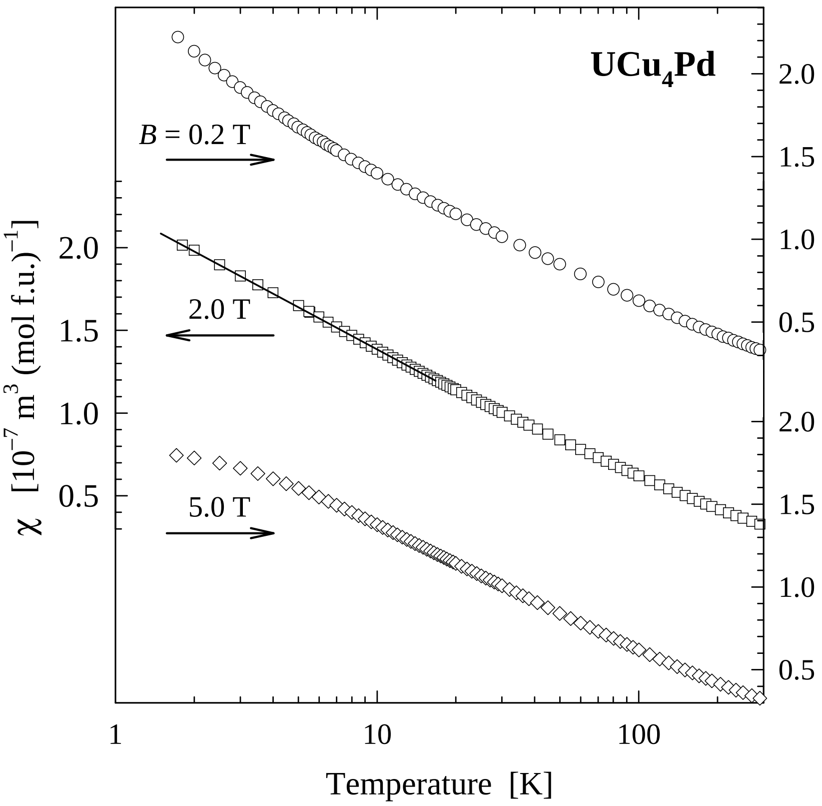

Figure 3. A semi-logarithmic plot of UCu_4Pd susceptibility data below 300 K for three values of the measuring field. For a field value of $B = 2$ T, the $T \leqslant 20$ K data follow a logarithmic temperature dependence as indicated by the solid line. However, for both $B = 0.2$ T and 5 T the observed low-temperature $\chi(T)$ behaviours do not conform to a logarithmic dependence.

In figure 4 it is indicated that a power-law behaviour of $\chi(T, B = 0.2\ \mathrm{T})$ is observed over approximately one decade in temperature for alloys with $x = 1$, 0.9 and 0.8 and over a smaller temperature region for $x = 1.2$. In table 1 we compare our values of λ obtained from the power-law fits according to (2) as shown by solid lines in figure 4 with values of λ derived from recent measurements of both $\chi(T)$ and $C(T)$ [25, 32]. We also include in table 1 values of λ which we obtain from earlier studies [12, 33] by writing their observed power laws in terms of λ as given in (1) and (2). An indication is also given in table 1 of the temperature intervals in which the power-law behaviour has been observed. Values of λ from different groups are in reasonable agreement for those alloys where multiple entries to table 1 exist. Our study suggests a minimum in the value of λ near $x = 0.9$.

The behaviour of selected $UCu_{5-x}Pd_x$ samples at very low temperatures has recently been investigated. Vollmer *et al* [33] found $C/T \sim -\log T$ between 0.2 K and 2 K and $C/T \sim T^{-0.35}$ between 1 K and 3.5 K for UCu_4Pd. At still lower temperature, C/T deviates from the $-\log T$ dependence and exhibits a maximum at $T \approx 0.12$ K. The DC zero-field-cooled magnetic susceptibility and AC susceptibility likewise show a maximum at these low temperatures, whereas a field-cooled sample does not exhibit this maximum. These results were interpreted as evidence of spin-glass freezing in UCu_4Pd [33]. Scheidt *et al* [32] measured $C(T)$ for $UCu_{5-x}Pd_x$ alloys with $x = 0.8$, 1 and 1.5 down to 0.075 K. For samples with $x = 0.8$

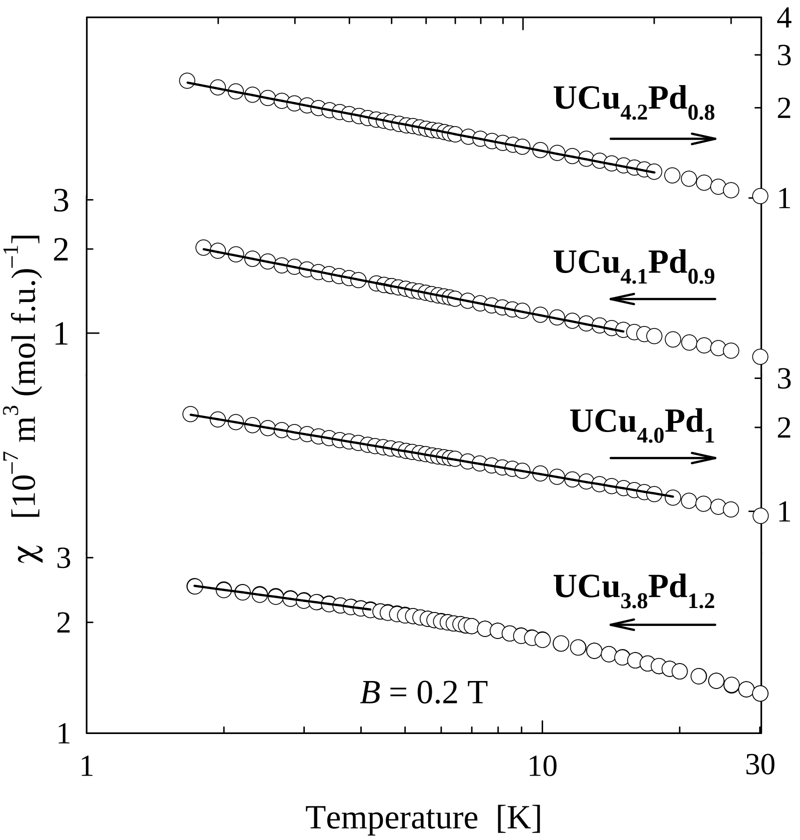

Figure 4. A comparison of the $\chi(T \leqslant 30$ K, $B = 0.2$ T) susceptibility data for $UCu_{5-x}Pd_x$ compositions near the non-Fermi-liquid region. The solid lines are obtained through least-squares power-law fits to the respective data sets with parameters given in table 1.

and 1 the C/T values levelled off below 1.3 K and 0.2 K respectively. This is associated with magnetic ordering at $T_N = 1.3$ K for the $x = 0.8$ alloy. For the $x = 1$ and 1.5 alloys AC susceptibility measurements indicate peaks at 0.24 K and 0.15 K respectively and it has been suggested [32] that these peaks may be related to the formation of magnetic clusters that are formed in these disordered systems by the competition between Kondo and RKKY interactions [24]. Power-law behaviour in C/T for the $x = 1$ and 1.5 alloys extends not higher than 3.5 K and 1.3 K respectively according to Scheidt *et al*, in contrast with the results of de Andrade where this description is valid up to 8 K (see table 1). For the $x = 1.5$ alloy it is reported that C/T exhibits a changeover from a $-\log T$ dependence at higher temperatures to a $1 - \sqrt{T}$ dependence at the lowest temperature in agreement with the predictions of Moriya and Takimoto [34]. Finally, it should be mentioned that the linear temperature dependence of the electrical resistivity

$$\rho(T) = \rho_0(1 - aT)$$

reported earlier for $UCu_{5-x}Pd_x$ alloys [12, 14] has recently been observed to extend down to as low as 50 mK [35].

A scaling analysis of the susceptibility of $Ce(Ru_{1-x}Rh_x)_2Si_2$ for samples that either exhibit Fermi-liquid behaviour ($x = 0.03$) or NFL behaviour ($x = 0.5$) was recently reported by

Table 1. Values of the λ-exponent for a Griffiths-phase model of non-Fermi-liquid behaviour in $UCu_{5-x}Pd_x$. The temperature region in which a power law $C/T \sim \chi \sim T^{\lambda-1} \sim T^{-\eta}$ is valid is indicated through a superscript. Values of the exponent η indicated in previous work are used to find an appropriate value of λ. Error assignments are given where available.

	Susceptibility			Specific heat			
x	This study ($B = 0.2$ T)	Andraka and Stewart [12] (0.01 T)	de Andrade *et al* [25] (0.5, 1 T)	Andraka and Stewart [12]	Vollmer *et al* [33]	de Andrade *et al* [25]	Scheidt *et al* [32]
0.8	0.720 ± 0.001[a]						
0.9	0.694 ± 0.002[b]						
1.0	0.734 ± 0.001[c]		0.72[d]	0.68[e]	0.65[f]	0.70[g]	0.71[h]
1.2	0.833 ± 0.002[i]						
1.5		0.73 ± 0.03[j]	0.78[k]	—[l]		0.81[m]	0.82[n]

[a] 1.7–20 K.
[b] 1.7–17 K.
[c] 1.7–22 K.
[d] Not available.
[e] 1–10 K.
[f] 1–3.5 K; logarithmic for 0.2–2 K.
[g] 0.6–8 K.
[h] 0.7–3.5 K; logarithmic between 0.2 and 2 K.
[i] 1.7–4 K.
[j] 1.6–12 K.
[k] Not available.
[l] Logarithmic for 0.3–10 K.
[m] 0.6–8 K.
[n] 0.2–1.3 K; logarithmic between 0.2 and 3 K.

Souletie *et al* [36]. The susceptibility is described in this work by

$$(\chi - \chi_D)T = C\left[1 + \left(\frac{T_K}{T}\right)^n\right]^{-\gamma/n} \tag{3}$$

where $n = 2$ for Fermi liquids and $n = 1$ in the NFL case. This equation is similar to the scaling equation describing magnetic phase transitions near a critical temperature T_c, but is applied outside its usual validity range with $T_c = -T_K < 0$ as described by Souletie *et al* [37]. In (3), χ_D is a small diamagnetic contribution and T_K denotes the Kondo temperature. It was illustrated in particular that (3) describes $\chi(T)$ well between 2 and 300 K for the NFL ($x = 0.5$) alloy. It thus seems as if (3) holds promise for providing a description of $\chi(T)$ for NFL Kondo systems from low temperatures up to temperatures approaching the asymptotically free Curie–Weiss limit. We investigated the suitability of (3) for fitting our data and indicate in figure 5 that the *low-field* $\chi(T, B = 0.2$ T) data are well fitted by (3) as indicated by a solid line. $\chi(T)$ data measured in high fields will also fit (3) at higher temperatures, but will deviate at low temperatures as should be evident from considering the results in figure 2. Fit parameters pertaining to least-squares fits of $\chi(T, B = 0.2$ T) data for the different alloys are given in table 2. There is little variation in T_K for the different compositions. We note that at sufficiently low temperatures for $T \ll T_K$, equation (3) approximately reduces to the temperature dependence given by (2) with $\gamma \simeq \lambda$. Comparison of the values of γ and λ for our alloys given in table 1 and table 2 indicates that this expectation is approximately observed.

Finally, scaling of M, B and T at low temperatures for the complete range of fields used up to 5 T is investigated following the *ansatz* of references [5] and [12]:

$$M = \frac{B}{T^\gamma} f\left(\frac{B}{T^{\beta+\gamma}}\right). \tag{4}$$

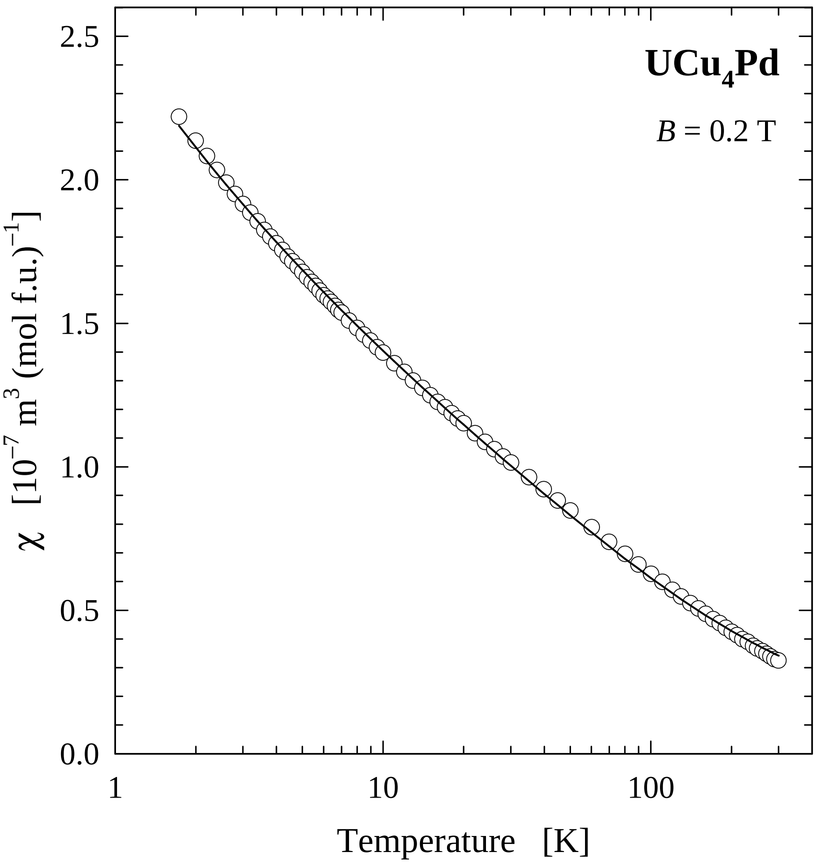

Figure 5. A least-squares fit of the scaling relation given in (3) to the $\chi(T \leqslant 300$ K, $B = 0.2$ T) data for the compound UCu_4Pd. The fitting parameters for this compound, as well as for other $UCu_{5-x}Pd_x$ compounds examined, are given in table 2.

Table 2. Least-squares values of the fitting parameters pertaining to the magnetic susceptibility scaling relation given in (3), for samples in the $UCu_{5-x}Pd_x$ series. The analyses relate to $\chi(T, B = 0.2$ T) data.

x	χ_D (m^3 (mol f.u.)$^{-1}$)	C (m^3 (mol f.u.)$^{-1}$ K)	T_K (K)	γ
0.8	$(1.83 \pm 0.08) \times 10^{-8}$	$(9.1 \pm 0.1) \times 10^{-6}$	130.8 ± 0.1	0.728 ± 0.004
0.9	$(1.43 \pm 0.08) \times 10^{-8}$	$(6.9 \pm 0.1) \times 10^{-6}$	130.0 ± 0.1	0.706 ± 0.005
1.0	$(9.2 \pm 0.5) \times 10^{-9}$	$(9.92 \pm 0.09) \times 10^{-6}$	130.40 ± 0.06	0.759 ± 0.002
1.2	$(5.7 \pm 0.2) \times 10^{-9}$	$(1.32 \pm 0.01) \times 10^{-5}$	129.40 ± 0.02	0.767 ± 0.001

Equation (4) is an appropriate description for $T = 0$ quantum critical systems. $f(x)$ is a non-singular function for which Andraka and Stewart used the function $\ln x$ in their analysis. They observed a fairly satisfactory fit of their low-temperature isotherms to (4). Figure 6 illustrates our results from scaling the magnetization isotherms for the $UCu_{5-x}Pd_x$ compounds with $x = 0.8$, 0.9, 1.0 and 1.2. For the $x = 0.9$ and 1.0 alloys an excellent fit to the scaling function is obtained for all values of field for isotherms in the range 1.7–20 K. In the case of the $x = 1.2$

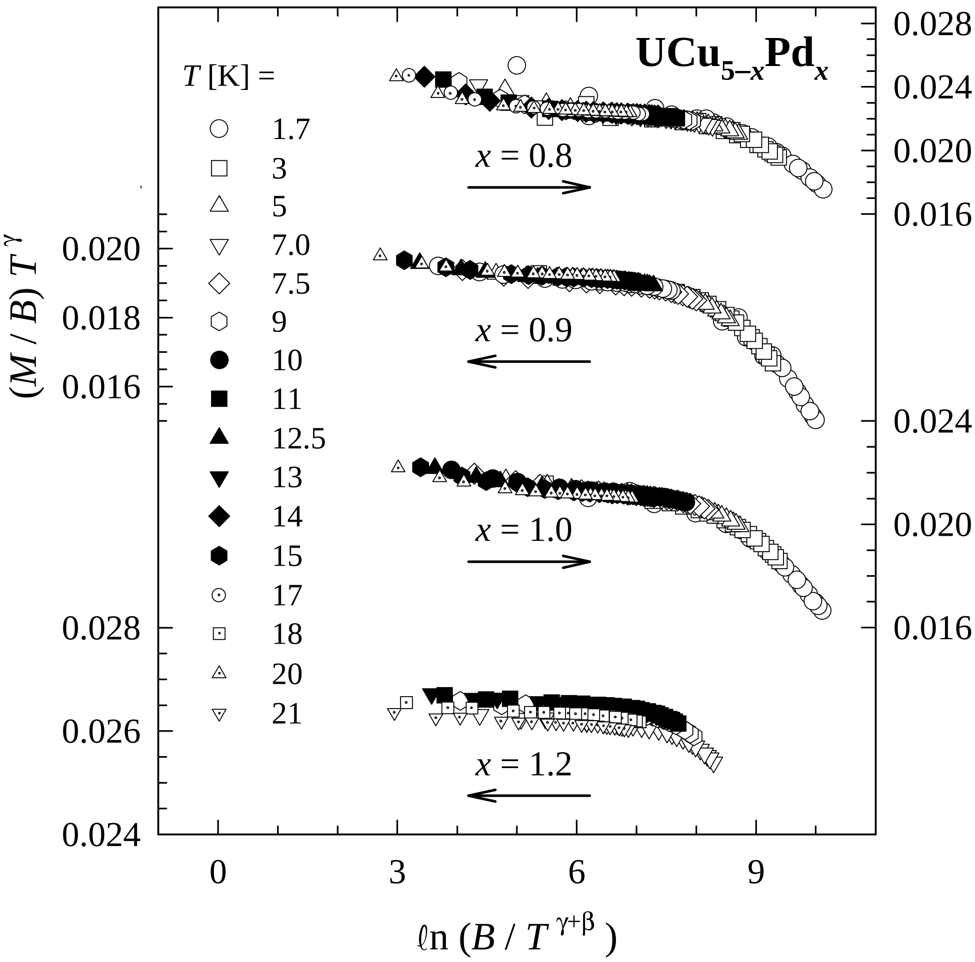

Figure 6. A comparison of a scaling analysis using (4) for the $UCu_{5-x}Pd_x$ compounds investigated. The values of the scaling exponents derived are given in table 3.

alloy, the number of isotherms that conform to the scaling is considerably reduced (see table 3 for details). Values of the exponents γ and $\gamma + \beta$ and the range of isotherms that conform to the scaling for the different alloys are given in table 3 and compared with the results obtained by Andraka and Stewart.

Table 3. The exponent values obtained in a scaling analysis of the magnetization for $UCu_{5-x}Pd_x$ compounds near the non-Fermi-liquid phase. The scaling relation is given in (4).

x	γ	$\gamma + \beta$	Scaling range (K)
0.8	0.288 ± 0.002	1.31 ± 0.01	1.7–20
0.9	0.305 ± 0.005	1.40 ± 0.05	1.7–20
1.0	0.280 ± 0.005	1.30 ± 0.05	1.7–20
1.2	0.27 ± 0.02	1.30 ± 0.05	7–21
1.5[a]	0.27 ± 0.03	1.3 ± 0.2	2.5–10

[a] Results for this compound were obtained by Andraka and Stewart [12].

4. Conclusions

The magnetization and susceptibility of several alloys of the $UCu_{5-x}Pd_x$ system near where the magnetism disappears have been studied with the purpose of establishing scaling relationships for these alloys. It has been observed that the low-temperature susceptibility in the small-field limit $\chi(T, B \to 0) \propto T^{\lambda-1}$. This power-law relation is valid over one decade of temperature. Such a description is in agreement with the theory of Castro Neto *et al* in which NFL behaviour in f-electron alloys is considered to originate from the interplay of disorder, RKKY interactions and Kondo interactions. It is furthermore shown that $\chi(T, B \to 0)$ conforms to a scaling relationship given by Souletie *et al* for the extended temperature interval $1.7 \leqslant T \leqslant 300$ K. It is indicated that the description given by Souletie *et al* effectively reduces to the power-law formulation of Castro Neto *et al* at low temperature. Scaling of M, B and T at low temperature and for a range of fields up to 5 T in accordance with a prescription given by Tsvelik and Reizer, for NFL behaviour associated with a $T = 0$ phase transition, has been observed.

In general, for all of the above cases of scaling investigated, the best agreement between our results and the particular scaling relationship was obtained for alloys with $x = 1$ and 0.9. Distinctly poorer agreement or a reduced temperature range of scaling is obtained for the $x = 1.2$ alloy. This may be related to the observation that antiferromagnetic correlations were found to be present at low temperature in the $x = 1$ alloy, but not in the $x = 1.5$ alloy [17]. Thus more comprehensive scaling is observed in the vicinity of the quantum critical point than for the alloys further away from the critical concentration where $T_N \to 0$.

An extension of the present measurements of $M(T)$ and $\chi(T, B)$ to lower temperatures in order to investigate the extent of the power-law description and to investigate possible antiferromagnetic or spin-glass ordering for a range of alloys will be of considerable interest.

Acknowledgments

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