Eur. Phys. J. B **6**, 5–11 (1998)

THE EUROPEAN PHYSICAL JOURNAL B

Pressure-induced magnetically ordered Kondo lattice state in $YbCu_2Si_2$

K. Alami-Yadri[a], H. Wilhelm, and D. Jaccard

University of Geneva, DPMC, 24 quai Ernest-Ansermet, 1211 Geneva 4, Switzerland

Received: 29 December 1997 / Revised: 7 July 1998 / Accepted: 10 July 1998

Abstract. The effect of pressure on the electrical resistivity $\rho(T)$ of several $YbCu_2Si_2$ samples was investigated up to 25 GPa and for 30 mK $< T <$ 300 K. With increasing pressure the compound crosses from an intermediate valence state to a magnetic Kondo lattice state at a critical pressure $P_C \sim 8$ GPa. Below P_C, *i.e.* in the non-magnetic phase, $\rho = \rho_0 + AT^2$ is found at very low temperature, indicating the validity of the Fermi liquid description. On approaching the magnetic instability, the A coefficient and the residual resistivity ρ_0 increase strongly. Close to P_C, ρ_0 shows a pronounced maximum due to scattering by lattice defects. The pressure variation of the magnetic resistivity ρ_{mag} at high temperature is interpreted in the terms of a pressure induced change of the crystal field splitting.

PACS. 67.55.Hc Transport properties – 71.27.+a Strongly correlated electron systems; heavy fermions – 72.10.Fk Scattering by point defects, dislocations, surfaces, and other imperfections (including Kondo effect) – 75.30.Mb Valence fluctuation, Kondo lattice, and heavy-fermion phenomena

1 Introduction

In Kondo lattice systems the competition between the Kondo effect and the RKKY interaction is frequently described by the magnetic phase diagram of Doniach [1]. The Kondo temperature T_K and the magnetic transition temperature T_M are plotted as a function of the unit cell volume [2] or the exchange constant J of the $4f$ and conduction electrons [3] for some ternary CeM_2X_2 compounds with M = transition metal and X = Si or Ge. The RKKY interaction dominates over the Kondo effect for compounds with a large unit cell, like $CeAg_2Ge_2$, and the compounds show magnetic properties. The opposite situation is found for smaller unit cell volume, like for $CeNi_2Si_2$, with an intermediate valence (IV) character. Between these two extreme, compounds like $CeCu_2Si_2$, are situated and usually called heavy fermion (HF) compounds. On approaching the HF region from the magnetically ordered state, the magnetism vanishes at a critical point. The phase diagram of Doniach has been qualitatively confirmed for many Ce compounds using either external or chemical pressure. For example, $CeAu_2Si_2$ is magnetic at ambient pressure and enters the HF region at a critical pressure $P_C = 18.3$ GPa [4]. Other compounds, like $CeCu_2Ge_2$ [5], $CePd_2Si_2$ [6] and $CeRh_2Si_2$ [7], lose their magnetic character at P_C of 8, 2.7 and 0.9 GPa, respectively. The compound $CeCu_2Si_2$ [5] shows HF properties already at ambient pressure and enters the IV region at $P \sim 5$ GPa. At higher pressures the $4f$ electrons become completely delocalised. A similar classification for ternary YbM_2X_2 compounds is still not possible because there are only a few experimental results.

Ytterbium compounds are the subject of intensive studies because of the variety of physical properties observable in the IV region as well as in the Kondo lattice case. The physical properties of these compounds can be compared to the Ce-compounds using the electron-hole analogy. In this picture the missing $4f$ electron in the $4f^{13}$ configuration of the Yb^{3+}-ion can be interpreted as the presence of a $4f$-hole, analogously to the $4f$-electron in the Ce^{3+}-ion. The ternary $YbCu_2Si_2$ compound is of particular interest after the discovery of its pressure-induced magnetism [8]. At ambient pressure the Sommerfeld coefficient of the specific heat is $\gamma = 135$ mJ/molK^2 [9] and the valence of the Yb ion is close to 2.8 at $T = 4.2$ K [10]. Thus, $YbCu_2Si_2$ can be considered as a moderate HF and an IV compound. A Kondo temperature $T_K = 200$ K was determined from the thermal variation of a reduced $4f$ quadrupolar moment [11]. Both, the electrical resistivity and the magnetic susceptibility do not show any evidence of magnetic ordering down to 0.4 K at ambient pressure [9]. Using the electron-hole analogy the pressure effect on $YbCu_2Si_2$ can be explained qualitatively. Starting from an IV state, pressure drives $YbCu_2Si_2$ into the HF region and above a critical pressure P_C into a magnetically ordered phase with a weak Kondo effect. Furthermore, $YbCu_2Si_2$ is a promising candidate to test the recent discussion of the occurrence of non- Fermi liquid behaviour (NFL) in the vicinity of P_C, *i.e.* $\rho \propto T^n$, $n < 2$. At ambient pressure $\rho(T) \propto T^{1.3}$ was found for 1.2 K $< T <$ 10 K [8],

[a] e-mail: khalid.alami-yadri@physics.unige.ch

which could be considered as a sign of NFL behaviour. For $YbCu_{4.5}$ [12] and $YbCu_4Ag$ [13], no signs of magnetic order were found in the electrical resistivity even up to very high pressure ($P = 23.4$ and 19 GPa, respectively). For the latter a T^2 dependence of the resistivity at low temperature is present for all pressures. Because of the pressure-induced magnetic order in $YbCu_2Si_2$, it should be possible to approach the critical point by applying pressure and to study this region in more details. In this paper, we present electrical resistivity $\rho(T)$ measurements of $YbCu_2Si_2$ up to 25 GPa and down to 30 mK. Additionally, the magnetoresistivity was measured up to 8 Tesla in the magnetic phase.

2 Experimental

Polycrystalline $YbCu_2Si_2$ samples were prepared using a sealed melting method because of the high evaporation pressure of ytterbium. Stoichiometric amounts of the elements were sealed in an evacuated tantalum tube and melted for several minutes by resistance heating. The melting temperature was estimated to be ~1200 °C. Analysis by SEM showed the existence of a layered structure and it was attributed to the crystallographic (001) plane by comparison with other compounds which also crystallise in the tetragonal $ThCr_2Si_2$ structure type. The samples studied under pressure were selected by X-ray diffraction analysis and residual resistivity measurements at ambient pressure.

High pressure measurements were performed using the Bridgman anvil cell technique. The anvils are made of tungsten-carbide or sintered diamond and have surface diameters of 3.5 mm and 2 mm, respectively. With this technique, pressures up to 10 GPa and 25 GPa can be reached. The two opposite anvils are held in the so-called pressure clamp, and in between a pyrophyllite gasket is placed [14,15]. Disks of steatite served as pressure transmitting medium. The electrical resistivity was measured with the dc four-probe technique. The pressure was deduced from the critical temperature T_C of a thin Pb foil [16] closely placed to the sample. To obtain a sample, first a bar was cut from a large ingot and then it was polished down to obtain dimensions ($25\times80\times500{-}1200\,\mu m^3$) adapted to the pressure cell. For the large anvils, *i.e.* pressures up to 10 GPa, the resistance was measured at two parts of the sample allowing to control the homogeneity of the sample.

3 Results

The results presented here were obtained on four samples in different pressure experiments. They gave all the same $\rho(T)$ dependencies and therefore no distinctions between them will be made. Results at ambient pressure have been published elsewhere [8]. Before presenting the $\rho(T)$-curves the procedure used to obtain the magnetic part of the resistivity is described. At high temperature the total resistivity $\rho(T)$ in the presence of the Kondo effect can be written as:

$$\rho(T) = \rho_0 + \rho_{mag}(T) + \rho_{ph}(T) = \rho_1 - c\ln T + aT \quad (1)$$

where ρ_0, $\rho_{mag}(T)$, and $\rho_{ph}(T)$ describe the scattering of imperfections, spins, and phonons, respectively. In this equation, a and c are constants, and ρ_1 is the sum of ρ_0 and the spin disorder resistivity associated to the Kondo exchange interaction [17]. Fitting the right hand side of equation (1) to the $\rho(T)$-data at high temperature, a pressure-independent phonon contribution ($a = 0.067\,\mu\Omega$cm/K) is found. It corresponds well to the high temperature resistivity ($T > 20$ K) of the iso-structural and non-magnetic $LuCu_2Si_2$ compound [18]. Subtracting this contribution from $\rho(T)$ gives the residual and magnetic part $\rho_0 + \rho_{mag}(T)$ of $YbCu_2Si_2$, which is shown in a semi-logarithmic plot in Figure 1 at selected pressures up to 25 GPa. We point out that the linear approximation of the phonon contribution is less reliable below 20 K ($\Theta_D =$ 221 K [9]). However, at low temperature this phonon contribution represents a negligible part of the total resistivity, and therefore does not change qualitatively the low temperature dependence of the curves shown in Figure 1. At low pressure (Fig. 1a) the curves show the general behaviour of IV compounds characterised by a maximum

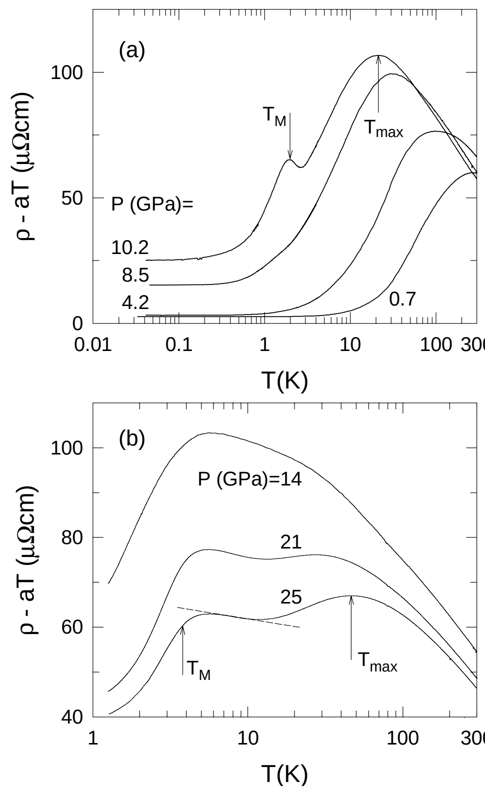

Fig. 1. Temperature dependence of the residual and magnetic contribution ($\rho_0 + \rho_{mag}$) to the total resistivity $\rho(T)$ of $YbCu_2Si_2$ at representative pressures plotted in a semi-logarithmic scale. (a) Above T_{max}, a logarithmic slope is present. At $P = 10.2$ GPa a clear sign of a magnetic phase transition is visible at $T_M \sim 1.9$ K. (b) Above 14 GPa a second logarithmic slope develops at low temperature.

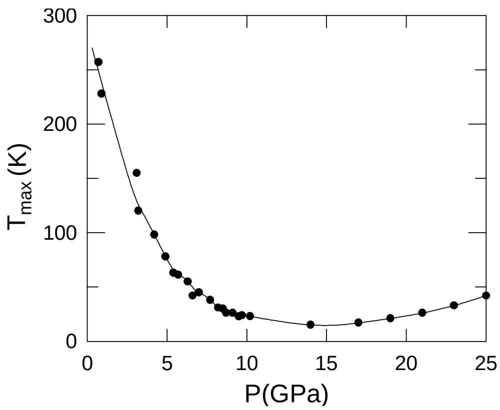

Fig. 2. Pressure dependence of T_{max} of $YbCu_2Si_2$, *i.e.* the temperature where the magnetic resistivity $\rho_{mag}(T)$ shows a maximum. $T_{max}(P)$ pass through a minimum at $P \sim 14$ GPa.

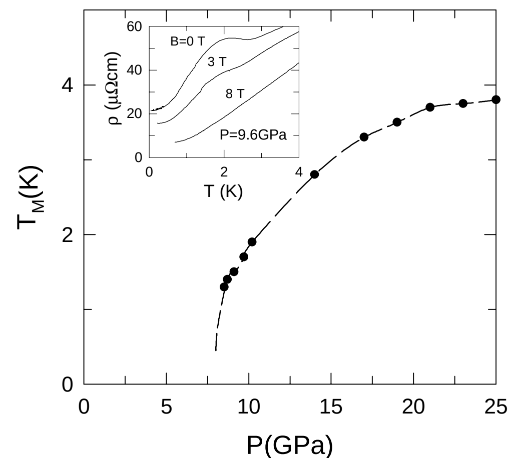

Fig. 3. Pressure dependence of the magnetic transition temperature T_M in $YbCu_2Si_2$. At $P = 8.5$ GPa a magnetically ordered state exists below $T_M \sim 1.3$ K. With increasing pressure T_M increases up to 3.8 K at 25 GPa. The influence of the magnetic field on $\rho(T)$ above P_C is shown in the inset for $P = 9.6$ GPa. The feature at T_M present in $\rho(T)$ for $B = 0$ and 3 T has disappeared at $B = 8$ T.

at T_{max} close to 300 K and a pronounced decrease of $\rho(T)$ towards lower temperature corresponding to the coherence state. With increasing pressure, T_{max} decreases and a negative logarithmic slope at high temperature appears, indicating incoherent Kondo scattering processes on the excited crystal field (CF) levels. An anomalous curvature starts to develop at about 8 GPa at $T_M \sim 1$ K, which is a signature of the magnetic transition. It is clearly visible at 10.2 GPa. Both, T_M and T_{max} can not be separated at 14 GPa (Fig. 1b) and a second logarithmic slope develops at low temperature, as can be seen from the curves recorded at 21 and 25 GPa. This second slope can be attributed to the Kondo effect on the ground state of the CF according to the Cornut and Coqblin model [17]. The temperature dependence of the resistivity at 25 GPa is similar to that of Kondo systems like $CeCu_2Ge_2$ [5]. At low temperature the residual resistivity ρ_0 remains unchanged for low pressures, increases one order of magnitude at intermediate pressures, and then starts to decrease at very high pressure ($P > 14$ GPa). This point will be examined in more detail in the discussion.

In Figure 2 the pressure variation of T_{max} is plotted. It strongly decreases with pressure and shows a minimum at about 14 GPa. An interpretation for the strong decrease at low pressure can be given in the picture where T_{max} is of the order of the Kondo temperature $T_K \propto \exp(-1/|JN(E_F)|)$, with J the exchange coupling constant and $N(E_F)$ the density of sates of the conduction electrons at the Fermi level. Assuming that $N(E_F)$ is not affected or only weakly affected by pressure, the enormous decrease of T_{max} (or T_K) can be interpreted by a reduction of the exchange coupling J, in good agreement with the Doniach description [1]. However, this description cannot explain the relatively weak increase of T_{max} for $P > 14$ GPa, also found for $YbCu_{4.5}$ at high pressure [12]. In the model of Cornut and Coqblin [17], T_{max} is rather related to the high Kondo temperature T_K^H, corresponding to the Kondo scattering on the excited CF levels. Hence, T_{max} depends not only on T_K, but also on the CF splitting [19]. As T_K is low at high pressure, the increase of T_{max} above 14 GPa is probably due to a CF effect and/or an interaction of the RKKY type.

The magnetic transition temperature T_M is determined from the extremum of the first temperature derivatives of the $\rho(T)$-curves and is plotted in Figure 3 as a function of pressure. This curve can be compared with that found for Ce compounds, *e.g.* $CeCu_2Ge_2$ [15] by considering the electron-hole analogy mentioned above. At very high pressure, T_M saturates at about 3.8 K in contrast to YbNiSn [20]. The extrapolation $T_M \rightarrow 0$ gives a critical pressure $P_C \sim 8$ GPa, slightly lower than $P = 8.5$ GPa, where the first sign of the magnetic order was found. The critical pressure was confirmed by resistivity and thermopower [21] as well as Mössbauer measurements [22]. In reference [8] an error of about 3 GPa was made in the pressure determination. All pressure values have to be shifted up by 3 GPa, yielding also $P_C \sim 8$ GPa. The T_M values reported in reference [8] are slightly higher than these shown in Figure 3. This is attributed to the fact that not the same sample was measured. The influence of the magnetic field on the transition temperature is shown in the inset of Figure 3, where the resistivity $\rho(T)$ at 9.6 GPa is plotted for two different magnetic fields. The pronounced resistivity bump corresponding to the magnetic transition at ~ 2 K in the zero field curve becomes a weak feature at $B = 3$ T and disappears completely at $B = 8$ T. The gradual decrease could be interpreted as an indication of an antiferromagnetic order. This is supported by Mössbauer spectroscopy results on one of our samples [22]. In the pressure range $8 < P < 8.9$ GPa, a complicated order was observed at $T = 1.8$ K and approximately half of the Yb-ions have a magnetic moment of $\mu = 1\,\mu_B$.

Figure 4 shows the magnetoresistivity $\Delta\rho(B)/\rho(0)$ at 9.6 GPa above and below the transition temperature

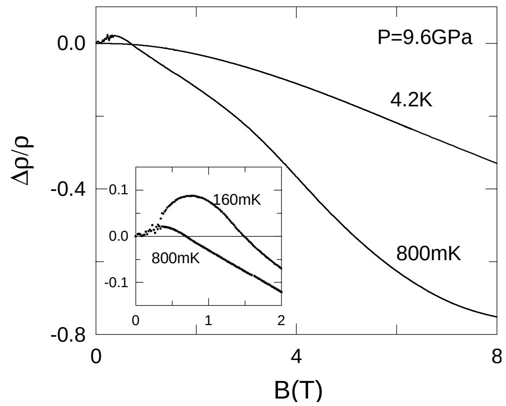

Fig. 4. Magnetoresistivity $\Delta\rho(B)/\rho(0)$ of $YbCu_2Si_2$ at 9.6 GPa for various temperatures. Always a negative magnetoresistivity is found in high fields reaching -35% for $T = 4.2$ K and even -75% for $T = 800$ mK. For the latter a positive magnetoresistivity is visible at low fields as is shown explicitly in the inset. This becomes more pronounced at 160 mK where the magnetoresistivity first reaches $+8\%$ at $B = 0.9$ T and then starts to decrease.

$(T_M \sim 2$ K). At $T = 800$ mK a large negative magnetoresistivity (-75% at 8 T) is found. It is still negative (-35%, $T = 4.2$ K) above the magnetic transition temperature. These large and negative values are similar to those reported for $YbCu_4Ag$ [13]. A positive magnetoresistivity is found at low fields and below T_M as is shown in the inset of Figure 4. The positive peak increases in magnitude and its position shifts down if the temperature increases. It is at $B = 0.75$, 0.5 and 0 T, for $T = 160$ mK, 800 mK and 4.2 K, respectively. This peak could be attributed either to a magnetic ordering, probably antiferromagnetic, or to a more complex field-induced electronic transition, as in other Kondo lattice compounds like YbNiSn [23] and YbNiAl [24].

At low temperature the electrical resistivity of Kondo lattice systems is usually described by $\rho(T) = \rho_0 + AT^n$, with $1 < n \leq 2$ for non-magnetic compounds and $2 \leq n \leq 4$ for magnetic compounds. If $n = 2$, $\rho(T)$ shows a Fermi liquid (FL) behaviour, as is usually the case for IV compounds. Close to the magnetic instability (around P_C), where spin fluctuations might influence the transport properties, an exponent $n < 2$ is often found. This deviation is described as a NFL behaviour [25]. Depending on the pressure, the above given power law can be fitted to the data with a fixed exponent n up to a temperature T_L. For various exponents the pressure dependence of T_L is depicted in Figure 5. In the non-magnetic phase, *i.e.* $P < P_C$, $n = 2$ is always found at low temperature. However, if the upper interval boundary is extended to higher temperatures, a power law with a smaller exponent can be fitted to the data. Neglecting minor deviations at low temperature, even a linear $\rho(T)$ variation is observed close to P_C. In the magnetic phase, n can take values between 2 and 3. For example at $P = 25$ GPa, a cubic $\rho(T)$ dependence up to 1.8 K and a quadratic one below $T_L = 2.3$ K was fitted to the data. The important result of this

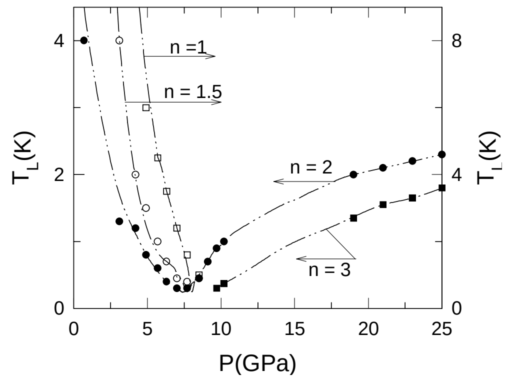

Fig. 5. The pressure dependence of the temperature limit T_L, up to which $\rho \propto T^n$ was fitted to the low temperature $\rho(T)$ data of $YbCu_2Si_2$. All the various $T_L(P)$ curves seem to point to the critical pressure region.

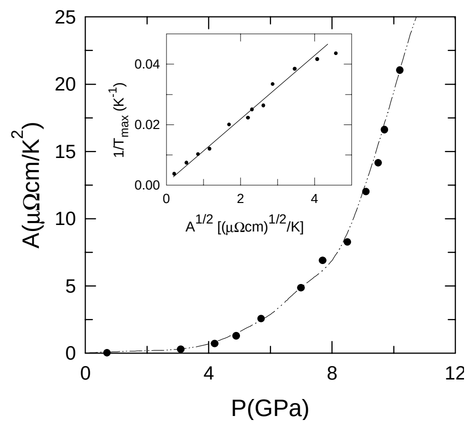

Fig. 6. The pressure variation of the A coefficient, obtained from a fit $\rho(T) = \rho_0 + AT^2$ to the data of $YbCu_2Si_2$. A strong increase of A with pressure is observed. In the inset $1/T_{max}$ is plotted *versus* $A^{1/2}$.

consideration is that all $T_L(P)$ curves seem to join in the vicinity of P_C.

In Figure 6 the A coefficient of a quadratic temperature dependence of $\rho(T)$ is plotted *versus* P. Below P_C, an increase of A from 0.042 $\mu\Omega\text{cm}/K^2$ at 0.7 GPa ($T_L = 4$ K) to 7 $\mu\Omega\text{cm}/K^2$ at 7.7 GPa ($T_L = 300$ mK) is found. This represents an enhancement by a factor 167, which should correspond to a decrease of $T_{max}(\sim T_K)$ by a factor 13 using the relation

$$T_{max} \sim T_K \propto 1/\sqrt{A}, \qquad (2)$$

valid in a FL picture. This proportionality is found up to 10.2 GPa, as shown in the inset of Figure 6.

4 Discussion

The region around the critical point between the magnetic and the non-magnetic phase in Doniach's diagram has been the subject of extensive studies. In the vicinity of this region, several compounds become superconducting at low temperature or a NFL behaviour occurs. The multichannel Kondo model introduced by Nozières and Blandin [26] describes the case of a magnetic impurity with more than one localised electron or hole. In this model, only the impurity spin S and the number of orbital channels i are the adjustable parameters. The classical Kondo effect corresponds to $i = 2S$, where the magnetic moment of the impurity is entirely screened at $T = 0$ K and results in a FL behaviour. If $i \neq 2S$ a NFL behaviour is expected, characterised at low temperature by a logarithmic divergence of the specific heat C/T and the $T^{1+\alpha}(\alpha < 1)$ dependence of the electrical resistivity. On the other hand, Moryia *et al.* [27] developed the self-consistent renormalised theory from the spin fluctuation theory in the case of the HF states which appear in the magnetic instability region. On approaching this region the model predicts a cross-over from a FL to a NFL behaviour for which the A coefficient diverges. At the critical point the resistivity is proportional to T^n with $n = 3/2$ or $5/3$ for antiferromagnetic or ferromagnetic spin fluctuations [25]. The existence of a quantum critical point for which $T_M \to 0$ is discussed for $CeNi_2Ge_2$, $CeCu_2Si_2$, UB_{13} and Yb_4As_3 [28]. A similar conclusion was reported for the alloys $CeCu_{6-x}Au_x$ [29]. In this solid solution the FL behaviour ($x = 0$) changes to a NFL one for $x_C = 0.1$ and a magnetic phase is reached at $x = 0.3$. Applying pressure ($P = 0.7$ GPa) to the latter compound drives it back into the NFL region. In a model proposed by Rosch *et al.* [30], three-dimensional conduction electrons are coupled to two-dimensional critical ferromagnetic fluctuations near the quantum critical point. A $\rho(T) \propto T^2$ behaviour for $T < T_1$ is predicted and a linear behaviour for $T > T_2 > T_1$. This is supported by the results presented in Figure 5. Regardless of the power n chosen, the limit temperature T_L extrapolates to a critical pressure $P_C \sim 8$ GPa. There is no evidence of a T^n behaviour with a well defined n between 1 and 2 as reported in the case of $CeNi_2Ge_2$ and $CeCu_2Si_2$ [28]. This confirms rather a FL description because there is always a T^2 dependence of the resistivity (Fig. 6) below a temperature T_L which scales with the Kondo temperature $T_K \propto T_{max}$.

Another important point concerning this discussion is the role of the disorder which governs the low temperature resistivity. The pressure dependence of the residual resistivity ρ_0 obtained by extrapolating the resistivity to $T = 0$ K is reported in Figure 7. For all samples studied in this work, ρ_0 does not change at low pressure and increases rapidly on approaching the magnetic instability. This increase varies slightly from one sample to another. The nearly pressure independent ρ_0 obtained for the sample of reference [8] was not reproduced. At very high pressure ρ_0 decreases to a value well above that found at ambient pressure. A similar pressure behaviour of ρ_0 was observed for $YbCu_4Ag$ [13].

In a Kondo lattice with an ideal periodicity, the resistivity should vanish if $T \to 0$. Two kinds of disorder effects have to be taken into account. The first contribution results from lattice defects not affecting the Kondo lattice, as in normal metals. Secondly, due to the many body character of electron scattering in the coherent state ($T < T_K$) of the Kondo lattice, various types of defects should alter the Kondo resonance on a given site which will then act rather like a hole in the Kondo lattice. In other words, there is a hole Kondo effect in analogy to the case of a magnetic impurity in a non-magnetic matrix [31]. Neglecting the weak phonon contribution, we propose to approximate the resistivity at low temperature ($T < T_K$) by

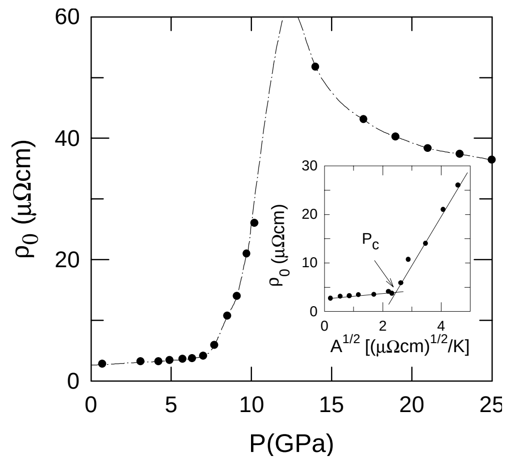

Fig. 7. Residual resistivity ρ_0 of $YbCu_2Si_2$ *versus* pressure. A strong enhancement of ρ_0 is observed in the vicinity of the critical pressure P_C. In the inset, ρ_0 is plotted as a function of $A^{1/2}$. At P_C a clear change of slope occurs.

$$\rho(P,T) = \rho_{0L} + A(P)T^2 + \rho_H(P,T), \qquad (3)$$

with an additional contribution ρ_H describing the disorder in the Kondo lattice. The static contribution ρ_{0L} is pressure and temperature independent and reaches values of typically 1–10 $\mu\Omega$cm for high quality crystals. The positive contribution $A(P)T^2$ describes the coherent scattering of the quasi-particles of the perfect Kondo lattice [32]. The coefficient A is related to $T_K \propto \gamma^{-1}$ by equation (2). The third term can be written as $\rho_H(P,T) = \rho_{0H} - BT^m$, with a temperature independent ρ_{0H} and a coefficient $B > 0$. If m is close to 2, the observed quadratic coefficient $(A-B)$ is clearly less than the value deduced from the empirical ratio $A/\gamma^2 = 10^{-5}\ \mu\Omega\text{cmK}^2\text{mol}^2/\text{mJ}^2$ [33] which was found for several Ce and U compounds. In particular, for $YbCu_4Ag$ [13] and $YbCu_{4.5}$ [14] A/γ^2 is in the range 0.02-0.03 $\times 10^{-5}\ \mu\Omega\text{cmK}^2\text{mol}^2/\text{mJ}^2$. The term $-BT^m$ seems to be very important in the case of alloys like $Yb(Ni_xCu_{1-x})_2Si_2$ [21], $Yb(Cu_xAl_{1-x})_5$ [34], and $Ce(Cu_xAl_{1-x})_2$ [35] and for compounds in which fluctuations of the composition appear, *e.g.* $CeCu_2Si_2$ [36]. On the other hand the term ρ_0 and hence ρ_{0H}, presents a maximum in the magnetic instability region as shown for $YbCu_2Si_2$ (see Fig. 7).

This correlation with the magnetic instability is the reason to attribute the term ρ_{0H} to an effect due to Kondo holes. These holes scatter like occupied Kondo sites. Thus, for a fixed number of scattering centers, we can assume that ρ_0 is proportional to the unitary limit ρ_u for the heavy quasi-particles and therefore to the product $m^* \sin^2 \delta$, where m^* is the effective mass of the quasi-particle and δ is the scattering shift [37]. In other words

$$\rho_0 \propto \sqrt{A}. \tag{4}$$

In the inset of Figure 7, ρ_0 is plotted as a function of $A^{1/2}$. The proportionality (4) is evident at low and high pressures and a clear change of slope at P_C occurs. This supports the idea that pressure weakens the $4f$-conduction electron exchange and enhances the Kondo hole scattering, which is probably represented at $T \neq 0$ by a more complicated relation than (4).

The Kondo hole effect seems also to be present in $\rho(T)$-curves in the magnetic phase of $YbCu_2Si_2$. Indeed, in reference [8] it is shown that $\rho(T) \propto T^3$ up to T_L which is close to T_M for a sample with a pressure independent ρ_0. In the view of the considerations mentioned above, there should no Kondo hole effect present in this particular case. However, for all samples investigated here, an increase of ρ_0 under pressure is observed. In these cases a cubic temperature dependence of $\rho(T)$ is found only at low temperature, well below T_M. This effect might also screen other phenomena like NFL behaviour or even superconductivity in $YbCu_2Si_2$. In $YbCu_4Ag$ [13] and $YbCu_{4.5}$ [12] the Kondo hole effect could have screened signs of a magnetic order in the electrical resistivity. Hence, $YbCu_2Si_2$ is up to now the only case where both the Kondo hole effect and a pressure-induced magnetic order are observed in the electrical resistivity.

In $YbCu_2Si_2$ the high temperature logarithmic slope c does not change with pressure (Fig. 1) as for other Yb compounds, *e.g.* $YbCu_{4.5}$ [12], $YbInAu_2$ and YbCuAl [21] in contrast to many Ce compounds [4]. The slope c is determined by contributions due to the $N(E_F)$, the s–f coupling constant J and the CF effect [17]. It was shown [38] that for Yb compounds the valence state +3, *i.e.* the magnetically ordered state, is favoured by the application of pressure. In the description of Doniach [1] the application of pressure is similar to a decrease of the product $JN(E_F)$. To get a pressure-independent logarithmic slope c, CF effects have to be considered. As was shown by Cornut and Coqblin [17], the ratio of the slopes of $\rho_{mag}(T)$ at high and low temperature is determined only by the effective degeneracy of the CF levels. This ratio is found to be 4.9 at 25 GPa, and is not far from the theoretical factor 63/15 for the CF scheme with a quartet ground state or a quasi-quartet ground state consisting of two energetically not-well-separated doublets and two doublets in the excited levels. The CF level sequence in $YbCu_2Si_2$ is 0-216-276-372 K at ambient pressure [39]. The appearance of the second logarithmic slope at about 10 K shows that pressure influences the CF in $YbCu_2Si_2$. Indeed from inelastic neutron scattering investigation up to 1.7 GPa [39] it was concluded that there is a weak reduction of the CF splitting with increasing pressure which was attributed to a redistribution of conduction electrons.

5 Conclusion

The electrical resistivity $\rho(T)$ of four $YbCu_2Si_2$ samples was investigated up to pressures as high as 25 GPa and in the temperature range 30 mK $< T <$ 300 K. A pressure-induced transition into a magnetic phase is observed at a critical pressure $P_C \sim 8$ GPa. The transition temperature $T_M = 1.3$ K at 8.5 GPa increases up to $T_M = 3.8$ K at 25 GPa. Hence, pressure drives $YbCu_2Si_2$ out of an intermediate valence state into a magnetic Kondo regime through a heavy fermion state. This crossing is accompanied by a strong decrease of T_{max}, where $\rho_{mag}(T)$ shows a maximum.

In the non-magnetic phase, a Fermi liquid behaviour ($\rho = \rho_0 + AT^2$) is found at very low temperature. Approaching the magnetic instability, the A coefficient increases strongly. No evidence of a non-Fermi liquid behaviour is found around the critical pressure in contrast with many other heavy fermion compounds. The pressure dependence of the low temperature resistivity was discussed in the context of the Kondo hole effect which leads to a pronounced maximum in the residual resistivity ρ_0 at the magnetic instability.

The magnetic Kondo regime (above P_C) is characterised by the development of a low temperature logarithmic slope in the magnetic resistivity which is attributed to the Kondo effect on the ground state of the crystal field. The pressure-independent high temperature logarithmic slope of the magnetic resistivity is correlated to a pressure induced reduction of the crystal field splitting.

We thank Prof. J. Sierro for many fruitful discussions, R. Cartoni for helpful technical assistance, and V. Pacheco for the X-rays analysis. This work was supported by the Swiss National Science Foundation.

References

1. S. Doniach, Physica B **91**, 231 (1977).
2. A. Szytula, in *Handbook of Magnetic Material* 6, edited by K.H.J. Buschow (North-Holland, Amsterdam, 1991).
3. T. Endstra, Ph.D. thesis, University of Leiden, 1992.
4. P. Link, D. Jaccard, Physica B **230-232**, 31 (1997).
5. D. Jaccard, P. Link, E. Vargoz, K. Alami-Yadri, Physica B **230-232**, 297 (1997).
6. F.M. Grosche, S.R. Julian, N.D. Mathur, G.G. Lonzarich, Physica B **223-224**, 50 (1996).
7. R. Movshovich, T. Graf, D. Mandrus, M.F. Hundly, J.D. Thompson, R.A. Fisher, N.E. Phillips, J.L. Smith, Physica B **223-224**, 126 (1996).
8. K. Alami-Yadri, D.Jaccard, Solid State Commun. **100**, 385 (1996).
9. B.C. Sales, R. Wiswanathan, J. Low. Temp. Phys. **23**, 449 (1976).
10. G. Neumann, J. Langen, H. Zahel, D. Plumacher, Z. Kletowski, W. Schlabitz, D. Wohlleben, Z. Phys. B **59**, 133 (1985).
11. K. Tomala, D. Weschenfelder, G. Czjzer, E. Holland-Moritz, J. Mag. Mag. Mat. **89**, 143 (1990).

12. P. Link, K. Alami-Yadri, D. Jaccard, J. Sierro, E. Walker, Physica B **206-207**, 361 (1995).
13. T. Graf, R. Movshovich, J.D. Thompson, Z. Fisk, P.C. Canfeld, Phys. Rev. B **52**, 3099 (1995).
14. L. Spendeler, D. Jaccard, J. Sierro, M. François, A. Stepanov, J. Voiron, J. Low. Temp. Phys. **94**, 585 (1994).
15. D. Jaccard, E. Vargoz, K. Alami-Yadri, H. Wilhelm, Rev. High Pres. Sci. Technol. **7**, 412 (1998).
16. B. Bireckhoven, J. Wittig, J. Phys. E **21**, 84 (1988).
17. B. Cornut, B. Coqblin, Phys. Rev. B **5**, 4541 (1972).
18. D. Wohlleben, B. Wittershagen, Adv. Phys. **34**, 403 (1985).
19. K. Hanzawa, K. Yamada, K. Yosida, J. Mag. Mag. Mat. **47-48**, 357 (1985).
20. K. Drescher, M.M. Abd-Elmeguid, J.P. Sanchez, C. Meyer, J. Phys.-Cond. **8**, L65 (1996).
21. K. Alami-Yadri, Ph.D. thesis, University of Geneva, 1997.
22. H. Winkelmann, M.M. Abd-Elmeguid, J.P. Sanchez, K. Alami-Yadri, D. Jaccard, in *Proceedings of the SCES 98 Conference, Paris 1998* (to be published).
23. L. D'Onofrio, O. Hamzic, A. Fert, Physica B **171**, 266 (1991).
24. J. Diehl, S. Klimm, H. Davideit, E. Baur, S. Horn, U, Klinger, C. Geibel, F. Steiglich, E. Bauer, H. Kirchmayr, in *Proceedings of the International Conference on Physical Phenomena at High Magnetic Fields-II, Thallahassee, Florida, 1995*, edited by Z. Fisk, L. Gor'kov, D. Meltzer, R. Schrieffer (World Scientific, 1995), p. 185.
25. A. Huxley, S. Kambe, C. Pfleiderer, H. Suderow, C. Thessieu, A. Buzdin, J. Flouquet, L. Glemot, I. Fomin, J. P. Brison, J. Phys. Soc. Jpn B **65**, 1 (1996).
26. P. Nozières, A. Blandin, J. Phys. France **41**, 193 (1980).
27. T. Moriya, T. Takimoto, J. Phys. Soc. Jpn **64**, 960 (1995).
28. F. Steglich, P. Gegenwart, R. Helfrich, C. Langhammer, P. Hellmann, I. Donnevert, C. Geibel, M. Lang, G. Sparn, W. Assmus, G.R. Stewart, A. Ochiai, Z. Phys. B **103**, 235 (1997).
29. H.V. Löhneysen, J. Mag. Mag. Mat. **157-158**, 601 (1996).
30. A. Rosch, A. Schröder, O. Stockert, H.V. Löhneysen, Phys. Rev. Lett. **79**, 159 (1997).
31. J.M. Lawrence, J.D. Thompson, Y.Y. Chen, Phys. Rev. Lett. **54**, 2537 (1985).
32. D.L. Cox, N. Grewe, Z. Phys. B **71**, 321 (1988).
33. K. Kadowaki, S.B. Woods, Solid State Commun. **58**, 507 (1986).
34. E. Bauer, R. Hauser, L. Keller, P. Fischer, O. Trovarelli, J.G. Sereni, J.J. Rieger, G.R. Stewart, Phys. Rev. B **56**, 711 (1997).
35. E. Bauer, Adv. Phys. **40**, 417 (1991).
36. F. Steglich, B. Buschinger, P. Gegenwart, C. Geibel, R. Helfrich, P. Hellmann, M. Lang, A. Link, R. Modler, D. Jaccard, P. Link, in *Proceedings of the International Conference on Physical Phenomena at High Magnetic Fields-II, Thallahassee, Florida*, 1995, edited by Z. Fisk, L. Gor'kov, D. Meltzer, R. Schrieffer (World Scientific, 1995).
37. P. Schlottmann, Phys. Rep. **181**, 1 (1989).
38. G. Wortmann, K. Syassen, K.H. Frank, J. Feldhaus, G. Kaindi, in *Valence Instabilities*, edited by P. Wachter, H. Boppart (North-Holland, 1982).
39. U. Walter, E. Holland-Moritz, U. Steigenberger, Z. Phys. B **89**, 169 (1992).