Low-temperature electrical resistivity of slightly Ge-doped $YbRh_2Si_2$

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Quantum criticality in single crystalline $YbRh_2(Si_{1-x}Ge_x)_2$ with $x \approx 0.01$ is investigated by electrical resistivity measurements down to 15 mK at various magnetic fields applied parallel and perpendicular to the c-axis. Compared to undoped $YbRh_2Si_2$ with $T_N = 75$ mK (from the onset of the resistive signature), the slightly Ge-doped sample exhibits a reduced Néel temperature of 53 mK. In contrast to the recent report on nominally $YbRh_2(Si_{0.95}Ge_{0.05})_2$, we do not observe evidence for a non-Fermi liquid regime at $T \to 0$ over an extended magnetic field range. The obtained phase diagrams rather resemble the case of undoped $YbRh_2Si_2$.

The tetragonal $YbRh_2Si_2$ is one of the prototype heavy fermion (HF) systems, which displays pronounced non-Fermi liquid (NFL) behavior related to a magnetic quantum critical point (QCP).[1)] The latter is realized by suppression of a very weak antiferromagnetic (AF) state below $T_N = 70$ mK at a critical magnetic field B_c of 0.06 T (0.7 T) perpendicular (parallel) to the tetragonal c-axis.[2)] The observed thermodynamic, transport and magnetic properties are in contradiction with the predictions for an itinerant AF QCP.[3–5)] Different alternative theoretical scenarios have been proposed for $YbRh_2Si_2$, i.e. a breakdown of Kondo screening,[6–9)] the vicinity to a quantum tricritical point,[10)] a critical valence transition[11)] or a fermion condensation quantum phase transition.[12)]

One crucial question concerns the evolution of the Fermi surface across the QCP, since a destruction of Kondo screening would lead to a decomposition of the heavy quasiparticles into conduction electrons and local magnetic moments. In such case, an additional energy scale, often labeled $T^\star$, related to the formation of a Kondo screened HF state, is expected to vanish at the QCP. Indeed, measurements of the Hall coefficient and various other transport and thermodynamic properties have proven the existence of such an energy scale $T^\star(B)$ in the $T - B$ phase diagram of $YbRh_2Si_2$, which terminates at the field-induced QCP.[13,14)] The extrapolation of the broadened crossover in the Hall-effect towards $T \to 0$ suggests a step-like change of the Hall coefficient. This is interpreted as a collapse of the heavy quasiparticle Fermi surface at the QCP.[15)]

It has been found, that $T^\star(B)$ and $T_N(B)$ could be separated from each other under hydrostatic[16)] or chemical pressure.[17)] Negative chemical pressure, achieved by either partially replacing Rh with larger Ir[17)] or Si with larger Ge,[18)] results in a finite field range, in which the system neither orders magnetically, nor forms a Fermi liquid ground state. Such a NFL phase could indicate a novel fractionalized Fermi liquid state.[19)]

Below, we focus on Ge-doped $YbRh_2Si_2$. The isoelectronic substitution of Si with Ge weakens the Kondo interaction and leads to a reduction of the Néel temperature to 20 mK in nominally $YbRh_2(Si_{0.95}Ge_{0.05})_2$ which in fact has a Ge-content of 2% only.[3)] This large discrepancy between the nominal and actual Ge concentration results from a reduced solubility of Ge compared to Si in the In flux. We have performed a new growth of $YbRh_2(Si_{1-x}Ge_x)_2$ with a nominal Ge-content of $x = 0.1$ using a flux of 75% In and 25% Sn. Different single crystalline pieces have been obtained and characterized by X-ray diffraction (XRD), electron microprobe energy dispersive x-ray (EDX) and electrical resistivity measurements between 4 and 300 K. Unfortunately, XRD, due to the very small effect on the lattice parameters, and EDX, because the Yb-L and Ge-K lines overlap, could not be used to determine the exact Ge concentration. The effect of Ge-doping can be observed as a slight shift of the electrical resistivity maximum temperature $T_{\max}$ which equals 125 K for undoped $YbRh_2Si_2$ towards higher temperatures.[20)] To roughly estimate the Ge content of the different new single crystals we have measured their $\rho(T)$ behavior. The crystal with the largest shift of $T_{\max}$ has been studied by tomographic atom probe, revealing a Ge concentration of only $x = 0.015$. Thus, the problem with the solubility of Ge has not been solved using the different flux. The single crystalline piece studied in this paper has a lower shift of $T_{\max}$ and displays a smaller residual resistivity (ρ_0). Accordingly, its Ge-concentration is considerably lower and will not exceed 1%. In the following, we label the single crystal as $YbRh_2(Si_{0.99}Ge_{0.01})_2$. The low-temperature electrical resistivity has been measured in a dilution refrigerator using the four-terminal ac technique on a thin plate-like single crystal with the current flowing in the plane perpendicular to the c-axis.

Figure 1 displays the electrical resistivity $\rho(T)$ of the investigated $YbRh_2(Si_{0.99}Ge_{0.01})_2$ single crystal at various magnetic fields $B \perp c$ (a) and $B \parallel c$ (b). Upon cooling from 1 K, an almost linear temperature dependence is found for all different curves, whereas significant changes in slope occur only below 0.2 K. At zero magnetic field, we observe a sharp decrease at the onset of the Néel ordering, similar as has been found for undoped $YbRh_2Si_2$.[2)] Taking the maximum in the temperature derivative $d\rho(T)/dT$, we estimate $T_N = (0.055 \pm 0.003)$ K for $YbRh_2(Si_{0.99}Ge_{0.01})_2$, which is about 0.02 K lower as in undoped $YbRh_2Si_2$. With increasing B we find a continuous suppression of $T_N \to 0$ towards critical magnetic fields B_c of (0.06 ± 0.005) T and (0.6 ± 0.1) T for $B \perp c$ and $B \parallel c$, respectively. At $B > B_c$, the low-T resistivity tends towards a T^2 dependence below T_{LFL}.

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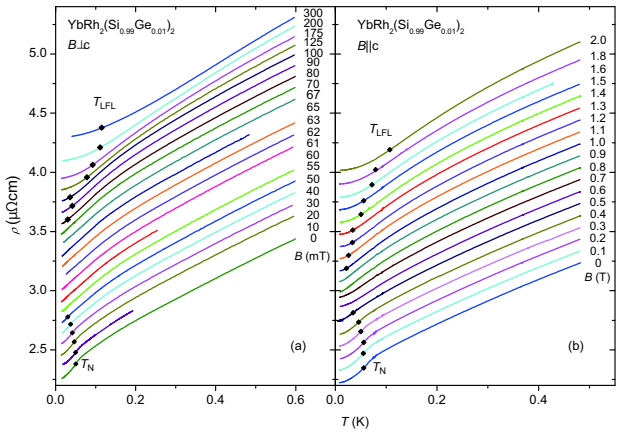

Fig. 1. Temperature dependence of the electrical resistivity of $YbRh_2(Si_{0.99}Ge_{0.01})_2$ at various magnetic fields applied perpendicular (a) and along the c-axis (b). For clarity, the curves at $B > 0$ are shifted by $0.1\mu\Omega$cm with respect to each other. T_N indicates AF transition temperature as determined from maxima in $d\rho/dT$, $T_{\rm LFL}$ marks upper boundary of $\rho(T) = \rho_0 + AT^2$ behavior.

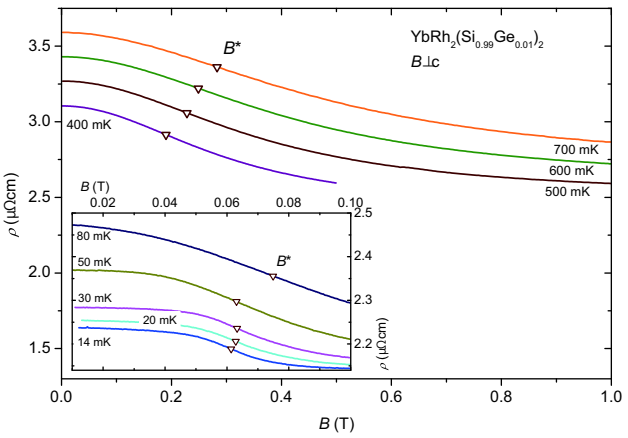

Fig. 2. Magnetoresistance of $YbRh_2(Si_{0.99}Ge_{0.01})_2$ at selected temperatures. The triangles indicate the positions of inflection points related to the energy scale $T^\star(B)$.

Complementary measurements of the magnetoresistance (MR) have been performed in the easy magnetic plane ($B \perp c$) only. As shown in Figure 2, an overall negative MR is found at low fields. Clear inflection points are found, whose positions shift towards higher fields with increasing temperature. A very similar signature has been found for undoped $YbRh_2Si_2$ at the low-energy scale $T^\star(B)$ determined from the Hall effect[13] and various thermodynamic measurements.[5,14] Compared to undoped $YbRh_2Si_2$, we do not observe any shift of $T^\star(B)$ like reported for low Ir- or Co-doped systems.[17]

Next, we turn to the analysis of the temperature dependence of the electrical resistivity. At those magnetic fields where the resistivity follows $\rho(T) = \rho_0 + A(B)T^2$, i.e. within the AF phase, as well as below $T_{\rm LFL}$ at $B > B_c$, the coefficient $A(B)$ has been determined (cf. Figure 3). Upon reducing the field

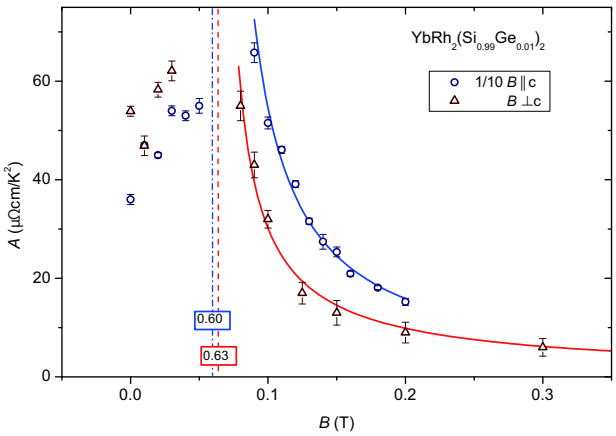

Fig. 3. Magnetic field dependence of the coefficient A derived from $\rho(T) - \rho_0 = AT^2$ for $YbRh_2(Si_{0.99}Ge_{0.01})_2$. The data for $B \parallel c$ have been divided by an anisotropy factor of 10.

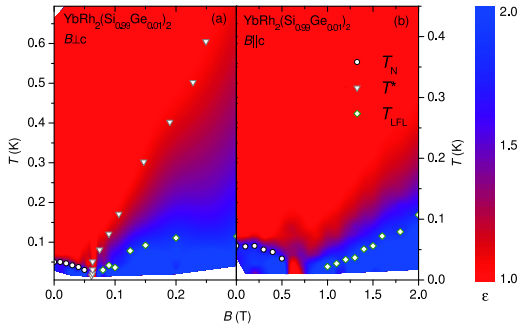

Fig. 4. Temperature versus magnetic field phase diagram for $YbRh_2(Si_{0.99}Ge_{0.01})_2$ for $B \perp c$ (a) and $B \parallel c$ (b). The circles, triangles and diamonds indicate T_N, $T^\star$ and T_{LFL} (see text). The color code reflects the exponent of the temperature dependence of the resistivity calculated as $\epsilon = d\log(\rho - \rho_0)/d\log T$.

from $B > B_c$ towards B_c, diverging behavior is found which could approximately be described by $A(B) \propto (B - B_c)^{-1}$ with $B_c = 0.6$ for $B \parallel c$ and $A(B) \propto (B - B_c)^{-0.85}$ with $B_c = 0.063$ for $B \perp c$, respectively. Similar behavior has been found for undoped $YbRh_2Si_2$.[2] Despite the 25% reduction of T_N in $YbRh_2(Si_{0.99}Ge_{0.01})_2$, the critical fields are not reduced compared to the pure system.

To get further information on a possible NFL phase in $YbRh_2(Si_{0.99}Ge_{0.01})_2$, we analyze the temperature dependence of the resistivity exponent ϵ as $\epsilon = d\log(\rho - \rho_0)/d\log T$, like it has been done for nominally $YbRh_2(Si_{0.95}Ge_{0.05})_2$.[3] As shown in Figure 4, for both field orientations no indication for an extended NFL phase at $T = 0$ could be found. Previously, Knebel et al. have claimed a T^2 dependence of the electrical resistivity in undoped $YbRh_2Si_2$ even directly at the field-induced QCP.[21] However, pure single crystals of $YbRh_2Si_2$ with $\rho_0 = 0.5\mu\Omega$cm have clearly shown a linear T-dependence at B_c down to 20 mK.[22] For the slightly Ge-doped single crystal studied in this paper, no indication for a

crossover to T^2 behavior is found for $B \perp c$ (cf. Fig. 1a) for fields between 0.055 and 0.065 T. For $B \parallel c$ only at 0.8 T a linear temperature dependence is found towards lowest temperatures, whereas at slightly smaller fields a significant curvature in $\rho(T)$ is found. We may speculate that a smearing of the AF transition due to the disorder introduced by the slight Ge-doping causes this behavior at fields applied along the hard direction. On the other hand, the *stronger* Ge-doped $YbRh_2(Si_{0.95}Ge_{0.05})_2$ (with actual composition of $x \approx 0.02$) studied previously, has displayed an extended $T \rightarrow 0$ NFL regime at $0 \leq 0.7$ T for this field orientation with no indication of curvature in $\rho(T)$ in the same temperature range.[18] Additional thermodynamic experiments in this field orientation are needed to prove the existence of an extended NFL phase.

To summarize, we have performed low-temperature electrical resistivity measurements on a $YbRh_2(Si_{0.99}Ge_{0.01})_2$ single crystal at magnetic fields applied parallel and perpendicular to the c-axis. Compared to the pure compound, a 25% reduction of the Néel temperature is found, whereas the critical fields and the field dependence of the A coefficient are almost unchanged. We do not find indications for a NFL regime at $T \rightarrow 0$ over an extended range in magnetic field, as reported for $YbRh_2(Si_{0.95}Ge_{0.05})_2$ (with actual composition of $x \approx 0.02$) at $B \parallel c$.[3] We conclude, that more than 1% Ge substitution is required for obtaining a NFL phase.

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