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F. Weickert, Philipp Gegenwart, J. Ferstl, C. Geibel, F. Steglich

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Low-temperature electrical resistivity of $Yb_{1-x}La_xRh_2Si_2$

F. Weickert*, P. Gegenwart, J. Ferstl, C. Geibel, F. Steglich

Max-Planck Institute for Chemical Physics of Solids, D-01187 Dresden, Germany

Abstract

Substitution of Yb-atoms with La in $Yb_{1-x}La_xRh_2Si_2$ leads to an increase of the Kondo temperature and suppression of antiferromagnetic order. Here, we present low-temperature ($T \geqslant 20$ mK) electrical resistivity measurements on $x = 0.05$ and $x = 0.1$ single crystals at various magnetic fields. For $x = 0.05$, a linear temperature dependence is observed for $0 \leqslant B \leqslant 0.04$ T which turns into Landau Fermi liquid (LFL) behavior $\Delta\rho = AT^2$ at larger fields. For $x = 0.1$, LFL behavior is found already at 0.02 T. The evolution of $A(B)$ suggests $x = 0.05$ and $x = 0.1$ to be located on the magnetically ordered and LFL side of the quantum critical point, respectively.

Keywords: $YbRh_2Si_2$; Quantum critical point

$YbRh_2Si_2$ is a heavy fermion system situated very close to a magnetic quantum critical point (QCP) [1]. A very weak antiferromagnetic (AF) ordering below $T_N = 70$ mK is suppressed by a tiny critical magnetic field of 0.06 T applied in the easy-plane perpendicular to the tetragonal *c*-axis [2]. Pronounced non-Fermi liquid (NFL) effects like a stronger than logarithmic mass divergence and temperature over magnetic field scaling are incompatible with the itinerant spin-density-wave scenario for an AF QCP [3]. Furthermore, Hall-effect measurements suggest a dramatic change of the Fermi surface at the magnetic field tuned QCP [4]. The quantum critical fluctuations at magnetic fields well beyond 0.06 T have a dominating ferromagnetic component [5,6]. Therefore, it would be very interesting to compare the properties of such a magnetic field-driven QCP with the one at $B = 0$ in which the magnetic order is suppressed by an increase of the 4*f*-conduction electron hybridization g.

Hydrostatic pressure experiments on $YbRh_2Si_2$ have revealed an increase of T_N, as expected for Yb-systems, and allow to extrapolate to a negative critical pressure of $-0.3(1)$ GPa corresponding to a tiny 0.2% volume expansion [7]. A volume expansion could either be achieved by the partial substitution of Si-atoms with the larger Ge or by La-substitution on the Yb-site in $Yb_{1-x}La_xRh_2Si_2$. The attempt to grow Ge-doped single crystals in which the AF ordering is completely suppressed has failed due to problems in sample preparation [8]. On the other hand, $Yb_{1-x}La_xRh_2Si_2$ single crystals have been successfully prepared for $x \leqslant 0.3$ and their characterization down to 0.4 K has revealed a systematic evolution of the characteristic maximum in the electrical resistivity suggesting an increase of g with increasing La-concentration [8]. Indeed the specific heat coefficient has been found to saturate below 1 K for $x = 0.2$ at $\gamma = 0.38\,J/K^2$ mol, indicating heavy Landau Fermi liquid (LFL) behavior [8]. Here, we report electrical resistivity measurements on $x = 0.05$ (residual resistivity ratio $RRR = 12$) and $x = 0.1$ ($RRR = 8$) single crystals down to mK temperatures and at magnetic fields applied in the easy plane perpendicular to the *c*-direction.

Fig. 1(a) shows the low-temperature resistivity data of $Yb_{0.95}La_{0.05}Rh_2Si_2$. For $B \leqslant 0.04$ T and below 0.4 K a linear temperature dependence is observed, characteristic for NFL behavior. At larger fields, the low-T resistivity turns into a AT^2 dependence, as expected for a LFL. For $Yb_{0.9}La_{0.1}Rh_2Si_2$ (Fig. 1(b)) the zero-field data show power-law behavior $\Delta\rho \propto T^{\varepsilon}$ with $\varepsilon \approx 1.05$. This is in

*Corresponding author. Tel.: +49 351 4646 2323; fax: +49 351 4646 2360.

E-mail address: weickert@cpfs.mpg.de (F. Weickert).

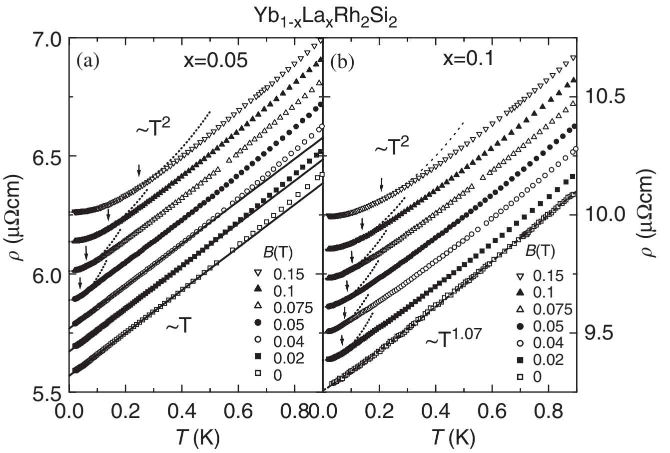

Fig. 1. Low-temperature electrical resistivity of $Yb_{1-x}La_xRh_2Si_2$ for $x = 0.05$ (a) and $x = 0.1$ (b) at varying magnetic fields applied perpendicular to the c-direction. For clarity, the different curves at $B>0$ are shifted subsequently by 0.1 μΩcm. Solid, dashed and dotted lines represent $\Delta\rho \propto T^{\varepsilon}$ with $\varepsilon = 1$, $\varepsilon = 1.07$ and 2, respectively. Arrows indicate upper limit of T^2 behavior.

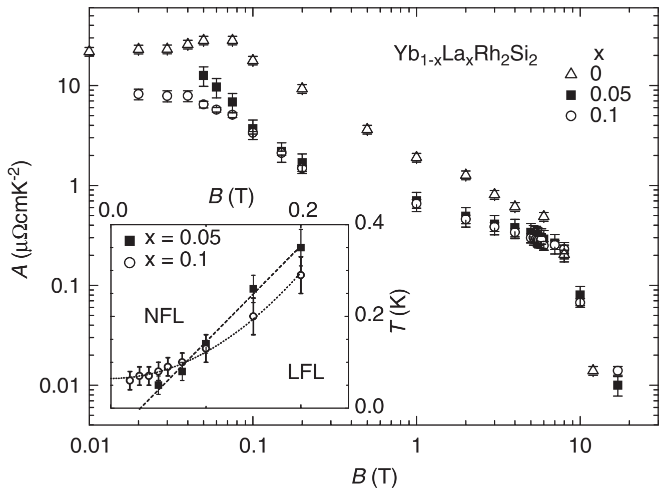

Fig. 2. Coefficient $A = \Delta\rho/T^2$ vs. field $B \perp c$ (on a double-log scale) for various concentrations x in $Yb_{1-x}La_xRh_2Si_2$. Inset: Temperature vs. field diagram with upper limit temperatures of $\Delta\rho = AT^2$ behavior (cf. arrows in Fig. 1), separating the non-Fermi liquid (NFL) regime from the LFL state. Dashed and dotted lines indicate linear and quadratic dependences, respectively.

accordance with the trend observed at $T \geqslant 0.4$ K, that the resistivity exponent increases with increasing La-substitution [8]. T^2 behavior is observed at $B \geqslant 0.02$ T.

To get further information on the ground state behavior in the two systems, we analyze the magnetic field dependence of the coefficient $A(B)$ which is a measure of the quasiparticle–quasiparticle scattering cross-section in the LFL state. In Fig. 2, $A(B)$ values extracted from the data shown in Fig. 1 are compared with corresponding results for undoped $YbRh_2Si_2$ [2]. We use a double-log representation for $A(B)$ since this allows to separate between three different cases: (i) for a divergence at a finite critical field B_c, like 0.06 T for the undoped system, an upwards curvature in $A(B)$ is observed upon reducing the field towards the critical field, (ii) for a zero-field QCP, a straight line would indicate a power-law divergence towards $B_c = 0$, whereas (iii) for a system located on the LFL side beyond the QCP, a saturation in $A(B)$ is expected at small fields. As shown in Fig. 2, the $A(B)$ data for the $x = 0.05$ system belong to case (i) and suggest a critical field slightly below 0.04 T, whereas the saturation of $A(B)$ observed for $x = 0.1$ indicates a LFL ground state in the latter system. The strong reduction of A for fields beyond 10 T, observed for all three different systems, is related to the field-induced suppression of the Kondo effect [9].

A finite critical field for $Yb_{0.95}La_{0.05}Rh_2Si_2$ is also consistent with the temperature-field diagram determined from the field-dependence of the upper limit of T^2 behavior shown in the inset of Fig. 2. The linear extrapolation of this cross-over towards zero temperature indicates a critical field $B_c \approx 0.03$ T for this system. In $Yb_{0.9}La_{0.1}Rh_2Si_2$ the boundary of the NFL–LFL cross-over extrapolates towards a LFL state at $B = 0$.

The fact that an AF transition in the $x = 0.05$ system cannot be resolved in the temperature dependence of the resistivity might hint at a transition temperature below 20 mK. Since the signature of the AF transition is very sensitive to disorder and has neither been observed for the first generation of $YbRh_2Si_2$ single crystals ($\rho_0 = 3$ μΩcm) [1], nor in $YbRh_2(Si_{0.95}Ge_{0.05})_2$ ($\rho_0 = 5$ μΩcm) [3] it is also very likely that the disorder introduced by La-substitution ($\rho_0 = 5.6$ μΩcm for $x = 0.05$) prevents the detection of the transition in the electrical resistivity.

To summarize, the analysis of the low-temperature electrical resistivity suggests a QCP in $Yb_{1-x}La_xRh_2Si_2$ for $0.05 < x < 0.1$. Further low-T experiments are needed to determine the nature of the zero-field QCP in this system.

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