Tuning $YbRh_2Si_2$ to a non-magnetic state by La-doping

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Abstract

We grew single crystals of $Yb_{1-x}La_xRh_2Si_2$ with $x = 0.05$, 0.1, 0.2 and 0.3 and started a detailed investigation of their physical properties, e.g. their resistivity and specific heat. Our specific heat results show an increase of the Kondo temperature as well as a suppression of the antiferromagnetic order. The Fermi liquid state is already reached with 20% La-doping, after the QCP has been crossed.

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Recently the heavy fermion system $YbRh_2Si_2$ has attracted considerable attention because it is located very close to a quantum critical point (QCP) connected with the transition from a magnetically ordered ground state to a non-magnetic one [1]. At ambient pressure it orders antiferromagnetically at a very low-temperature of $T_N = 70\,\mathrm{mK}$. Upon applying a small magnetic field (60 mT) or a slight negative chemical pressure using Ge-doping [2], T_N disappears at a QCP where the effective mass of the quasiparticles diverges. The proximity to the QCP leads to pronounced non-Fermi-liquid (NFL) behavior in the resistivity $\rho(T)$ and the specific heat $C(T)$ even in pure $YbRh_2Si_2$ in zero field. In our study of the QCP, we faced strong difficulties in growing single crystals with a larger Ge-content. We tried the growth of La-doped single crystals, because La doping provides a further possibility for inducing a negative chemical pressure. According to experience in La-doped Ce-Kondo lattices, the disorder induced in the periodicity of the rare earth lattice does not seem to be detrimental as long as the La-doping is not too large. We could successfully grow single crystals of La-doped $YbRh_2Si_2$ up to a La concentration of 30% and are now investigating their properties in detail. Here, we present first results of this study.

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$Yb_{1-x}La_xRh_2Si_2$ single crystals with $x = 0.05$, 0.1, 0.2 and 0.3 were grown from In-flux, using the sealed Ta-crucible technique. The size of the platelets, grown perpendicular to the *c*-axis, varies from $3 \times 3 \times 0.2\,mm^3$ to $1 \times 1 \times 0.1\,mm^3$. The X-ray-powder diffraction pattern could be indexed in the $ThCr_2Si_2$ crystal structure. The increase of both lattice parameters with La content was weaker than expected from a simple Vegard-law. In contrast, the La-contents determined from microprobe measurements were slightly larger than the (nominal) starting concentrations. Because of the uncertainty of these methods, we shall use the nominal concentration for the presentation of the results. The electrical resistivity and the specific heat were determined in a commercial PPMS (Quantum Design) using an AC four contact technique and a relaxation method, respectively. In all La-doped samples, the resistivity (Fig. 1) keeps the typical Kondo lattice behavior observed in pure $YbRh_2Si_2$, with a constant or slightly increasing value below room temperature, a broad maximum around 100 K and a pronounced decrease below this maximum. As expected the residual resistivity increases continuously with increasing La-content, leading to a residual resistivity ratio of only 2.3 in the 30% La-doped sample. But even in that sample the onset of coherence, i.e. the pronounced decrease of $\rho(T)$ below the temperature of the maximum, is still clearly visible. One hallmark for the NFL behavior in pure $YbRh_2Si_2$ is a linear decrease of $\rho(T)$ with T below 10 K down to $T_N = 70\,mK$. In the La-doped samples, this linear temperature dependence is also kept, but with increasing La-content an upward curvature becomes visible in $\rho(T)$ at low temperatures, corresponding to an increase of the exponent n in a power law $\rho(T) = \rho_0 + AT^n$. Both n and the upper temperature limit of this positive curvature region increase with the La-content, evidencing an evolution towards a Fermi liquid. Measurements in the millikelvin range are under way to determine the behavior for $T \to 0\,K$.

Another hallmark for the NFL behavior in $YbRh_2Si_2$ is a continuous increase of $C(T)/T$ below 10 K, with a logarithmic T-dependence between 10 and 0.4 K. In Fig. 2 we show $C(T)/T$ of the La-doped samples, normalized to Yb-moles, on a logarithmic T-scale. The ln(T) behavior is kept until 10% La, with only a minor decrease of the normalized values at low T. However, preliminary data for the 5% La-doped sample down to 40 mK evidence the disappearance of the peak observed in pure $YbRh_2Si_2$ which is connected with the antiferromagnetic ordering, while the increase of $C(T)/T$ to low temperatures is similar to that observed in a nominal 5% Ge-doped sample. This suggests that the QCP related to the disappearance of the AF-state is located between 5% La and 10% La-doping. For the 20% and 30% La-doped samples $C(T)/T$ saturates below 1 K upon cooling to rather large values of

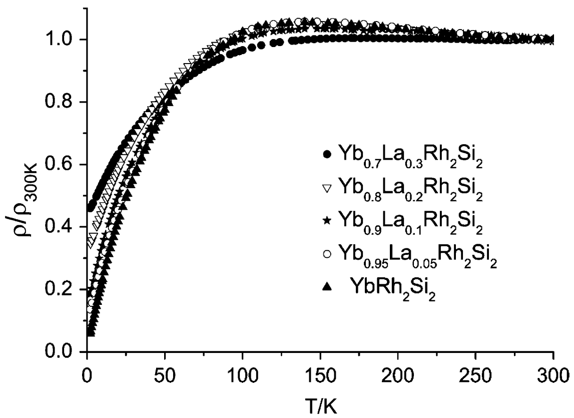

Fig. 1. Temperature dependence of the resistivity of all $Yb_{1-x}La_xRh_2Si_2$ samples.

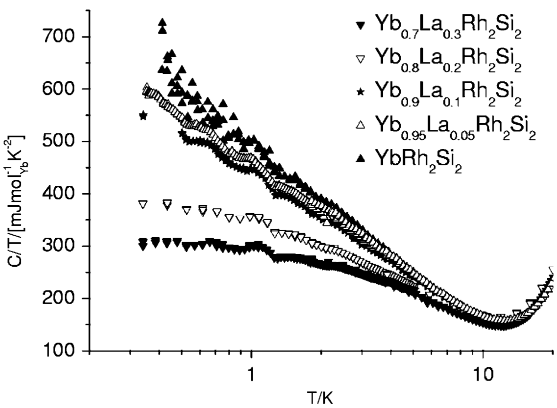

Fig. 2. Temperature dependence of the specific heat of the La-doped samples, normalized to the Yb-content, plotted as C/T versus T.

$\gamma = 380\,\mathrm{mJ/K^2\,mol}$ and $\gamma = 300\,\mathrm{mJ/K^2\,mol}$ for $x = 0.2$ and $x = 0.3$, respectively, indicating the transition to a heavy Fermi liquid behavior in the specific heat at these concentrations.

The overall decrease of the specific heat at low temperatures with increasing La-content implies that the recovery of the entropy contribution ($R\ln 2$) related to the doublet ground state is shifted towards larger temperature. Thus the Kondo temperature T_K (or characteristic 4f-temperature) increases as expected since the increase of the volume should lead to an evolution of the Yb from a trivalent towards a valence fluctuating state.

In summary, we have grown La-doped $YbRh_2Si_2$ single crystals and investigated their resistivity and specific heat. Our results evidence a transition to a heavy Fermi liquid in the specific heat for $x \geqslant 0.2$ and a continuous evolution in $\rho(T)$ from a linear in T increase towards a power law with $n > 1$. The critical concentration at which the AF-order disappears at a QCP seems to between $x = 0.05$ and $x = 0.1$.

References

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