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Effect of Ge-doping and pressure in the vicinity of the QCP of $YbRh_2Si_2$

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Abstract

We present electrical resistivity (ρ) and AC magnetic susceptibility measurements on Ge-doped single crystals of the NFL compound $YbRh_2Si_2$. Upon producing the volume expansion ($\Delta V \simeq +0.3\%$) necessary to tune this material to its QCP, the low-temperature $\rho(T)$ data of $YbRh_2(Si_{0.95}Ge_{0.05})_2$ are found to follow $\rho(T) = \rho_0 + bT$ over three decades in temperature. We compare the effect of ΔV to that produced by the application of hydrostatic pressure, and show that the linear temperature dependence is intrinsic to the proximity to the QCP and not due to disorder induced by Ge-alloying.

Keywords: Non-Fermi liquid; Quantum critical phenomena; $YbRh_2Si_2$

$YbRh_2Si_2$ is the first Yb-based, and one of the few stoichiometric f-electron compounds, situated already at ambient pressure and zero magnetic field very close to a magnetic quantum-critical-point (QCP) [1]. The electrical resistivity and the specific-heat coefficient of high-quality single crystals show a linear and a logarithmic temperature dependence, respectively, over more than a decade in temperature. These pronounced NFL effects are ascribed to quasi-2D spin-fluctuations related to a low-lying antiferromagnetic phase transition at $T_N =$ 65 mK, one of the lowest temperatures reported for the onset of magnetism in any strongly correlated f-electron compound. Upon applying hydrostatic pressure, T_N increases—as expected for Yb compounds—and allows one to determine for the QCP a critical pressure $p_c = -(0.3 \pm 0.1)$ GPa, which corresponds to a volume expansion of only $\Delta V \simeq +0.3\%$ [1]. This low value of ΔV suggests that T_N can be suppressed to $T \to 0$ by slightly expanding the crystal lattice, e.g., by alloying the Si-sites of the $ThCr_2Si_2$-structure with isoelectronic Ge. The evolution of the unit-cell volume of the series $YbRh_2(Si_{1-x}Ge_x)_2$ for $x > 0$ indicates that ΔV corresponds to a critical Ge-concentration of only $x_c =$ (0.06 ± 0.01). Correspondingly, doping $YbRh_2Si_2$ with Ge is, thus, expected to tune this material to its QCP without affecting its electronic properties and, due to the low value of x_c, without introducing significant disorder to the lattice. For this purpose single crystalline platelets of $YbRh_2(Si_{1-x}Ge_x)_2$ with nominal Ge concentrations $x = 0.05$ and 0.1 were grown from In flux as reported elsewhere [2]. The electrical resistivity (at $p = 0$ and in applied pressure) and the AC magnetic susceptibility were measured along the tetragonal plane using the experimental techniques described in Ref. [1].

The effect of Ge-alloying on the electrical resistivity of $YbRh_2Si_2$ is compared to the effect of pressure in Fig. 1. The steep decrease of $\rho(T)$ below 100 K is clearly shifted in an opposite way, either by the effect of the volume compression through the application of hydrostatic pressure or by the volume expansion produced by Ge-doping. This indicates that the characteristic high-temperature energy scale associated to the interaction between the 4f and the conduction electrons (commonly expressed by the lattice Kondo temperature) increases continuously for $x > 0$. Therefore, magnetic ordering is expected to be suppressed for $x \simeq x_c$. In fact, the $\rho(T)$ data of $YbRh_2(Si_{0.95}Ge_{0.05})_2$, i.e., for x very close to x_c, follows a linear temperature dependence above 10 mK, which extends up to 10 K, in a very large temperature

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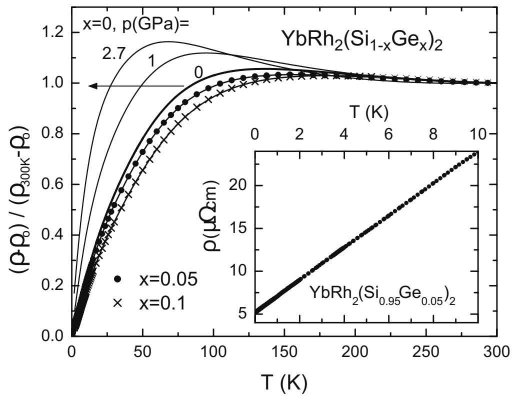

Fig. 1. Temperature dependence of the electrical resistivity normalized to $T = 300$ K after subtracting the value of the residual resistivity ρ_0, for $YbRh_2Si_2$ at $p = 0$ (thick line) and different values of hydrostatic pressure, as well as for $YbRh_2(Si_{1-x}Ge_x)_2$ crystals with $x = 0.05$ (•) and $x = 0.1$ (×). The effect of p (indicated by the arrow) is opposite to that of Ge-doping. Inset: Low temperature $\rho(T)$ data of $YbRh_2(Si_{0.95}Ge_{0.05})_2$ at $p = 0$.

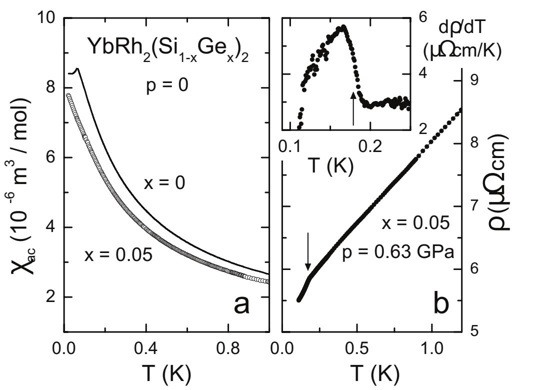

Fig. 2. (a) AC magnetic susceptibility of $YbRh_2Si_2$ and $YbRh_2(Si_{0.95}Ge_{0.05})_2$ at $p = 0$ as χ_{AC} vs. T, measured along the tetragonal plane. (b) Low-temperature electrical resistivity of $YbRh_2(Si_{0.95}Ge_{0.05})_2$ for $p = 0.63$ GPa. Inset: temperature derivative of $\rho(T)$. The arrows indicate the onset of magnetic order.

range of three decades in temperature (see inset of Fig. 1). This observation has so far not been made for any heavy-fermion metal at $p = 0$ and $B = 0$. As shown in Fig. 2a, the AC magnetic susceptibility of $YbRh_2(Si_{0.95}Ge_{0.05})_2$ shows no indication of a phase transition down to 10 mK, indicating that $YbRh_2(Si_{0.95}Ge_{0.05})_2$ lies extremely close to the QCP. A detailed discussion of the low-temperature electrical resistivity and magnetic susceptibility around x_c will be published elsewhere [3].

The value of the residual resistivity of the 5 at% Ge-doped sample, i.e., $\rho_0 \simeq 5$ μΩ cm (inset of Fig. 1), is only a factor of three larger than that of the best samples of undoped $YbRh_2Si_2$ [1], strongly suggesting that the extended linear behavior of $\rho(T)$ is, indeed, due to the proximity of $YbRh_2(Si_{0.95}Ge_{0.05})_2$ to the QCP and not an effect of disorder introduced by Ge-doping. In fact, upon applying hydrostatic pressure of only $p = 0.63$ GPa to this sample, the onset of magnetism is recovered, as shown in Fig. 2b. A well-defined second-order-type anomaly at $T_N = 0.185$ K (inset of Fig. 2b) is observed to develop from a linear temperature dependence of $\rho(T)$ above T_N [4]. This indicates that in $YbRh_2Si_2$ the delicate interaction between the 4f and the conduction electrons in the vicinity of the QCP can be controlled in a clean way by slightly doping with Ge as well as by applying pressure.

In summary, we observed that the volume expansion produced by Ge-doping drives the magnetic ordering temperature of $YbRh_2Si_2$ to $T \to 0$, opposite to the volume compression caused by the application of hydrostatic pressure. In the vicinity of the QCP, the electrical resistivity of $YbRh_2(Si_{0.95}Ge_{0.05})_2$ shows a linear temperature dependence over three decades in temperature. Upon applying hydrostatic pressure to this 5 at% Ge-doped crystal, the formation of magnetic order is recovered, showing that the pronounced NFL effects are intrinsic to the quantum critical behavior of $YbRh_2Si_2$ and not related to disorder caused by alloying.

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