Non-Fermi-liquid effects at ambient pressure in the stoichiometric heavy-fermion compound $YbRh_2Si_2$

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Abstract

Strong deviations from the properties of a heavy Landau Fermi-liquid already at ambient pressure and zero field are reported for single-crystalline $YbRh_2Si_2$. The low-temperature specific-heat coefficient and the electrical resistivity show a logarithmic and a linear temperature dependence, respectively, in more than a decade in temperature. This anomalous metallic state is ascribed to the proximity of a very nearby magnetic instability. Application of hydrostatic pressure induces anomalies in the electrical resistivity, indicating the onset of long-range magnetic order at a critical pressure $p_c \simeq 0.5$ GPa, which is so far the lowest required for the onset of magnetism in Yb compounds.

Keywords: Quantum critical phenomena; $YbRh_2Si_2$; Heavy fermion Yb compound

The study of quantum critical phenomena in f-electron-based systems attracts presently considerable attention since pronounced deviations from the properties of a Landau Fermi-liquid (LFL) were observed, mostly in Ce-based heavy-fermion (HF) metals, close to an antiferromagnetic (AF) quantum critical point (QCP) [1]. Generally, a control parameter like the degree of alloying or hydrostatic pressure is used to tune these materials through a magnetic instability at which the ordering temperature $T_N \to 0$. Up to now, the observation of “non-Fermi-liquid” (NFL) effects (see e.g. Ref. [1]) in *undoped* compounds at *ambient* pressure is restricted to only a few prototypical HF metals, e.g., normal-state UBe_{13}, $CeNi_2Ge_2$ and $CeCu_2Si_2$ [1]. However, only for the latter compound could a QCP be established so far [2]. Our investigation of high-quality single crystals of $YbRh_2Si_2$ shows that this is the first *stoichiometric* Yb-based intermetallic compound with pronounced NFL effects already at ambient pressure and zero field associated to the presence of a nearby magnetic instability.

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Single-crystalline platelets of $YbRh_2Si_2$ were grown from high-purity starting materials, using a molten–metal–solvent technique as described elsewhere (see e.g. Ref. [3]). X-ray powder-diffraction patterns showed single-phase samples crystallizing in the same tetragonal $ThCr_2Si_2$-type structure as the Ce-based homologues mentioned above [4]. Electron-microprobe analysis revealed neither any evidence of inhomogeneities, nor the incorporation of flux. All measurements were made using standard techniques on single crystals with typical residual resistivities $\rho_0 \approx 2$ μΩ cm (at $p = 0$) and a ratio $\rho_{300\,K}/\rho_0 \sim 35$; the latter being almost a factor of 10 larger than that of the polycrystalline sample previously investigated in Ref. [5].

A preliminary study of the magnetic susceptibility, specific heat and electrical resistivity showed that, in single-crystalline $YbRh_2Si_2$, paramagnetic Yb^{3+} moments form an ‘easy-plane’ square lattice with a strongly anisotropic magnetic response and without magnetic order above 1.8 K [4]. The strong magnetic anisotropy is evidenced by recent magnetization measurements which show that the low-T initial susceptibility $\chi = M/B$ is larger by a factor of 20 for B within the basal plane of the tetragonal structure, than for B applied along the c-axis

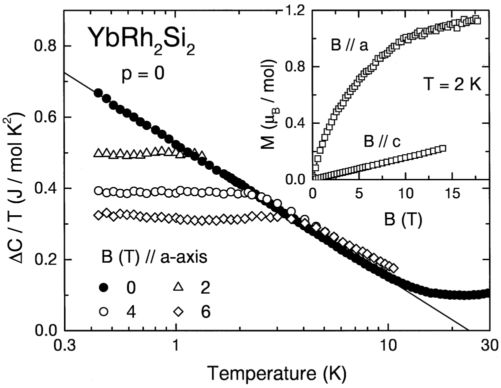

Fig. 1. Yb increment to the specific heat of $YbRh_2Si_2$ ($\Delta C = C_{YbRh_2Si_2} - C_{LuRh_2Si_2}$), plotted as $\Delta C/T$ in a log-T scale, at $p = 0$ and for differing applied magnetic fields. The solid line represents $\Delta C/T = \gamma'_0 \ln(T_0/T)$, with $\gamma'_0 = 0.17$ J/mol K^2 and $T_0 = 24$ K. Inset: Isothermal magnetization measured along *a*- and *c*-axis.

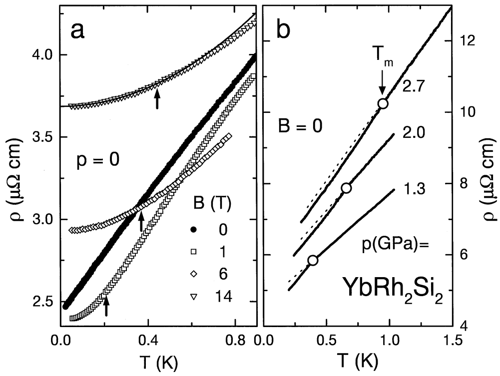

Fig. 2. (a) Low-T resistivity of $YbRh_2Si_2$ at $p = 0$ measured along the *a*-axis, for $B = 0$ and differing magnetic fields applied along *c*-axis. Arrows indicate the crossover temperature below which a T^2 law is recovered (cf. solid line for $B = 14$ T). (b) $\rho(T)$ at $B = 0$ for differing applied pressures. Circles indicate break in the slope of $\rho(T)$ at T_m, ascribed to the onset of long-range magnetic order. Dotted lines are guides to the eye.

(see inset of Fig. 1). No indication of metamagnetism up to $B \approx 15$ T is found down to 1.8 K. In addition, we have extended our specific-heat and resistivity measurements to lower temperatures and found strong deviations from the properties of an LFL at $p = 0$ and $B = 0$, as illustrated in Figs. 1 and 2a. Whereas $\Delta C(T)/T$ diverges logarithmically in the range 0.3 K $< T <$ 10 K, the $\rho(T)$ data can be described by a power law $\rho = \rho_0 + bT^{\epsilon}$, with $b = 1.8$ μΩ cm/K^{ϵ} and a temperature-dependent resistivity exponent ϵ that remains within (1 ± 0.05) below 10 K and saturates at $\epsilon = 1$ as T decreases down to 10 mK, without showing any evidence of a magnetic or superconducting phase transition at $p = 0$. In both cases, the application of a magnetic field leads to the recovery of the properties of a heavy LFL below a crossover temperature that increases with B, as observed in other systems showing NFL effects [1].

The present results clearly show that, at ambient pressure, $YbRh_2Si_2$ is situated at the *nonmagnetic* side of and close to a magnetic instability. Due to the hole–electron analogy between the $4f^{13}$–Yb^{3+} and the $4f^1$–Ce^{3+} electronic configurations, the application of hydrostatic pressure on Yb compounds is expected to produce the opposite effect to that in the case of Ce compounds [5]: It allows one to drive a *nonmagnetic* Yb system into a magnetically ordered state. Fig. 2b shows that application of hydrostatic pressure induces anomalies in $\rho(T)$, indicating the onset of long-range (presumably AF) order. The ordering temperature T_m vanishes close to a critical pressure $p_c \simeq 0.5$ GPa, which is, by far, the lowest p value for the onset of magnetic order in nonmagnetic Yb compounds known to date and, therefore, makes $YbRh_2Si_2$ a model system to study the physics near and at a QCP.

The distinct temperature dependences, $\Delta C(T)/T \propto -\ln T$ and $\rho - \rho_0 \propto T$, observed at $p = 0$ and $B = 0$ over more than a decade in temperature resemble those previously found in $CeCu_{5.9}Au_{0.1}$ (see e.g. Ref. [1]) and recently ascribed to quasi-2D spinfluctuations coupled to a 3D system of quasiparticles [6]. In the case of $YbRh_2Si_2$, further experiments are needed in order to elucidate the role which the strongly anisotropic 'easy-plane' magnetic structure plays in the microscopic nature of the relevant spinfluctuations and its relation with the observed NFL behavior.

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