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Pressure dependence of the low-temperature magnetization of $YbRh_2Si_2$

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Abstract

We report DC-magnetization, $M(B)$, measurements on $YbRh_2Si_2$ under hydrostatic pressure of 0.64 GPa at magnetic fields up to 11.5 T and at temperatures down to 0.04 K. The evolution of low-T and low-B anomalies indicate that AF ordering is stabilized with pressure. The magnetic field at which the Yb-4f-electrons are completely localized is drastically reduced from 9.5 T at ambient pressure to 6.1 T at 0.64 GPa.

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High-pressure studies on heavy Fermion (HF) systems have contributed to a better understanding of interesting phenomena. Because of the low characteristic temperature scales in HF systems the experiments often need to be performed at temperatures well below 1 K.

Here, we report the first low-T ($T \geqslant 40$ mK) study of a DC-magnetization under hydrostatic pressure and in magnetic fields up to 12 T. We investigate the Yb-based HF system $YbRh_2Si_2$ which is located very close to a quantum critical point (QCP), related to a very weak antiferromagnetic (AF) order ($T_N = 70$ mK) [1]. A very small magnetic field of 0.06 T is sufficient to suppress the AF order and to tune the system towards a field-induced QCP [1]. Previous low-temperature isothermal DC-magnetization measurements have revealed two kinks at $B_c = 0.06$ T and $B^\star = 9.5$ T, related to the field-induced QCP and suppression of the Kondo state due to the complete localization of the 4f-electrons, respectively [1,2]. Zero-field electrical-resistivity measurements have revealed that T_N increases with hydrostatic pressure [3] as expected, because the ionic volume of the magnetic $4f^{13}$ Yb^{3+} configuration is smaller than that of the nonmagnetic $4f^{14}$ Yb^{2+} one. We thus expect an increase of B_c with pressure and, correspondingly, a decrease of

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the field scale $B^\star$ related to the suppression of the Kondo effect.

In order to investigate the DC-magnetization of $YbRh_2Si_2$ under hydrostatic pressure, both at low temperature and in high magnetic fields, we have mounted a miniature CuBe piston-cylinder pressure cell containing a 6.0 mg high-quality single crystal ($\rho_0 = 1\,\mu\Omega\,\mathrm{cm}$), on a high-resolution Faraday magnetometer [4]. The pressure has been determined by the difference between the superconducting transitions of two small Sn samples; one placed inside the pressure-transmitting medium (daphne oil) together with the $YbRh_2Si_2$ sample, the other one outside the pressure cell. The T_c values are determined using a commercial SQUID magnetometer. The piston is made from NiCrAl which has a relatively small magnetization among hard materials. We have measured the low-temperature magnetization of the pressurized sample together with the pressure cell and subtracted the contribution from the empty pressure cell with the NiCrAl piston which is temperature dependent and nonlinear in field. The ratio of the contribution from the empty cell divided by that from the sample is 58% at maximum in the entire field and temperature range.

In this paper, we present first results obtained at a pressure of 0.64 GPa. Fig. 1 shows the low-field regime of isothermal magnetization curves along the magnetic easy direction $B \perp c$ taken at different temperatures. At $T = 0.04\,\mathrm{K}$, a sharp kink is observed that corresponds to the suppression of AF order by magnetic field. In the susceptibility $\chi = M/B$ measured in a field of 0.1 T, a kink-like anomaly (cf. inset of Fig. 1) is observed at 0.21 K. (0.24 K in $\chi(T)$ at 0.05 T, not shown.) This T_N value is in perfect agreement with $T_N(p)$ derived from electrical resistivity [3].

Although the kink in the low-temperature magnetization curve broadens rapidly with increasing temperature, $M(B)$ exhibits a strongly nonlinear field dependence even for $T \geqslant T_N$. We ascribe this behavior to the polarization of fluctuating magnetic moments. Indeed, the temperature dependence of the susceptibility above T_N can be described by a Curie–Weiss law (dotted line in the inset of Fig. 1) with an effective moment $\mu_{\mathrm{eff}} =$

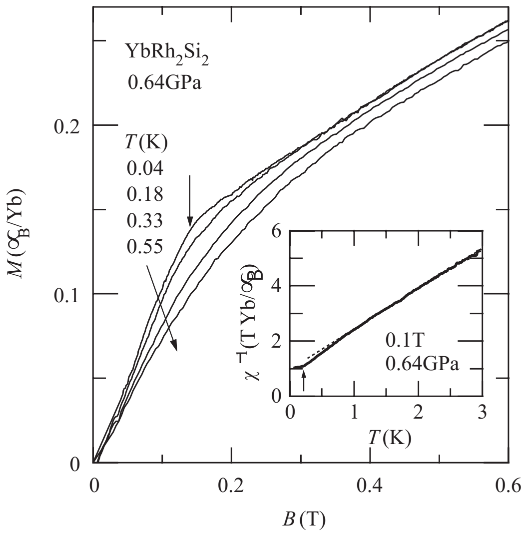

Fig. 1. Low-field magnetization $M(B)$ of $YbRh_2Si_2$ along the magnetic easy direction $B \perp c$ under hydrostatic pressure of 0.64 GPa at various temperatures. Vertical arrow indicates critical field $B_c = 0.14\,\mathrm{T}$. Inset shows temperature dependence of inverse susceptibility $\chi^{-1} = B/M(T)$ at $B = 0.1\,\mathrm{T}$. Broken line represents Curie–Weiss behavior, arrow indicates T_N.

$1.8\mu_B$ and Weiss temperature $\Theta = -0.69\,\mathrm{K}$. Compared to ambient pressure ($\mu_{\mathrm{eff}} = 1.4\mu_B$, $\Theta = -0.32\,\mathrm{K}$ [1]), the absolute sizes of both values increase because the Yb-4f-electrons become more magnetic under pressure and their AF coupling gets stronger. This tendency is also reflected in Fig. 2, where the isothermal magnetization curves at ambient pressure and 0.64 GPa are compared with each other. Note, that the kink at B_c has sharpened substantially under hydrostatic pressure.

At a magnetic field of $B^\star = 9.5\,\mathrm{T}$ the ambient pressure magnetization $M(B)$ shows a kink [2]. Above this field the HF state is destroyed and the Yb-4f-electrons are completely localized. Since this magnetic field corresponds to the Kondo scale of 25 K that decreases with pressure [3], we expect a decrease of $B^\star$ with increasing p. The inset of Fig. 2 displays the high-field $M(B)$ data at 0.64 GPa. A clear kink is observed at $B^\star = 6.1\,\mathrm{T}$. Thus, the characteristic field scale $B^\star$ is surprisingly sensitive to pressure. Future experiments at higher pressure will allow to study the magnetic properties near $B^\star \to 0$, i.e. in a state at which the Kondo-effect is suppressed already at zero-field.

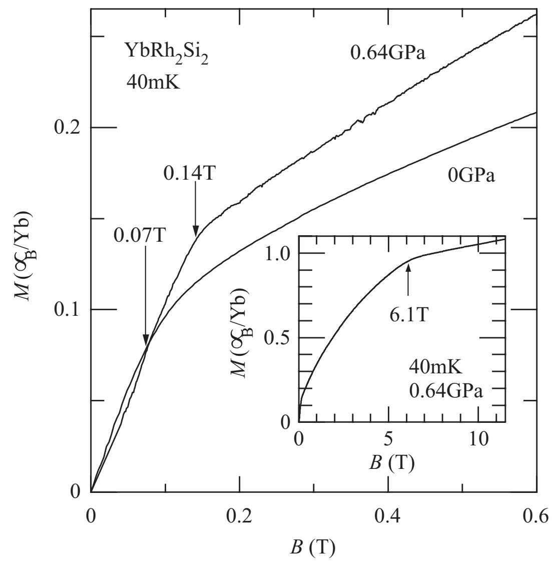

Fig. 2. Low-T magnetization $M(B)$ of $YbRh_2Si_2$ ($T = 0.04\,K$, $B \perp c$) at ambient pressure and at $p = 0.64\,GPa$. Arrows indicate critical fields B_c. Inset displays 0.64 GPa data on a larger field scale. Arrow indicates $B^\star = 6.1\,T$.

To summarize, we have reported the first pressure study of the low-temperature and high magnetic field magnetization on a HF system. The ambient-pressure magnetization curve of $YbRh_2Si_2$ shows two kinks, related to the suppression of (i) AF order at a critical field B_c and (ii) the Kondo effect at $B^\star \gg B_c$, respectively. Under hydrostatic pressure of 0.64 GPa, we observe a substantial increase of B_c and decrease of $B^\star$, indicating that the system becomes more magnetic with pressure.

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