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Scaling of the magnetic entropy and magnetization in $YbRh_2(Si_{0.95}Ge_{0.05})_2$

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Abstract

The magnetic entropy of $YbRh_2(Si_{0.95}Ge_{0.05})_2$ is derived from low-temperature ($T \geqslant 18\,\mathrm{mK}$) specific heat measurements. Upon field tuning the system to its antiferromagnetic quantum critical point unique temperature over magnetic field scaling is observed indicating the disintegration of heavy quasiparticles. The field dependence of the entropy equals the temperature dependence of the DC-magnetization as expected from the Maxwell relation. This proves that the quantum-critical fluctuations affect the thermal and magnetic properties in a consistent way.

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The heavy fermion system $YbRh_2(Si_{0.95}Ge_{0.05})_2$ is located very close to an antiferromagnetic (AF) quantum critical point (QCP) [1]. A small critical magnetic field of $B_c \approx 0.027\,\mathrm{T}$ is sufficient to suppress very weak AF order from $T_N = 20\,\mathrm{mK}$ ($B = 0$) towards zero temperature. At magnetic fields $b > 0$, where $b = B - B_c$ denotes the difference between the applied and critical field, a heavy Landau Fermi liquid (LFL) state is induced below a characteristic temperature $T_0(b) = 1.09b\,\mathrm{T/K}$ that increases linearly with b. This cross-over between non-Fermi liquid and LFL behavior is accompanied by unique T/b scaling in thermodynamic and transport properties observed over nearly four decades in temperature over magnetic field [1]. It indicates that the characteristic energy of the heavy quasiparticles is governed only by the ratio of the thermal energy to the magnetic field increment b and vanishes upon approaching the QCP. Such a behavior is consistent with the *locally critical* scenario for an AF QCP, at which the heavy quasiparticles disintegrate [2,3].

In this paper, we derive scaling expressions for the magnetic entropy and magnetization valid

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both in the LFL and non-Fermi liquid region of the B–T phase diagram. We prove that both properties are fully consistent with each other and probe the same degrees of freedom related to the QCP.

Specific heat data for $18\,\mathrm{mK} \leqslant T \leqslant 2\,\mathrm{K}$ and $0 \leqslant B \leqslant 0.8\,\mathrm{T}$ [1] are used to calculate the magnetic entropy $S(T,B) = \int_0^T C(T',B)/T'\,\mathrm{d}T'$. At magnetic fields $B \geqslant 0.05\,\mathrm{T}$, for which a LFL state is well established at the lowest measured temperature, the specific heat has been extrapolated towards $T \to 0$, using $C = \gamma_0(B)T$ [1]. At smaller magnetic fields a constant specific heat coefficient is not yet reached above 18 mK. Since the different entropy curves at low magnetic fields $B \leqslant 0.1\,\mathrm{T}$ merge above 1 K, the unknown entropy contribution from the temperature interval $0 \leqslant T \leqslant 18\,\mathrm{mK}$ can be deduced with satisfactory precision (cf. error bars in the inset of Fig. 1).

Fig. 1 displays the temperature dependence of the magnetic entropy at different applied magnetic fields. At zero field, the entropy gain at the AF phase transition amounts to only $S(T_N) \approx 0.008R \log 2$, indicating extremely weak AF order. For undoped $YbRh_2Si_2$ the entropy at $T_N = 70\,\mathrm{mK}$ equals $0.03R \log 2$ [5]. Thus, the ratio between the ordering temperature and $S(T_N)$ remains unchanged.

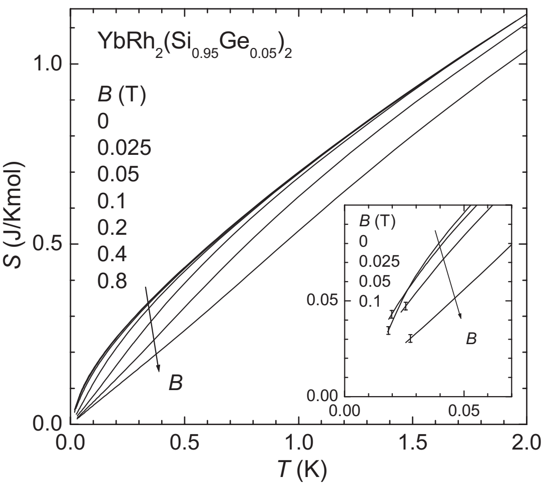

Fig. 1. Magnetic entropy $S(T)$ of $YbRh_2(Si_{0.95}Ge_{0.05})_2$ at various magnetic fields, obtained from integration of specific heat measurements [1]. Inset enlarges low-T behavior.

We now turn to the unique T/b scaling that, as discussed in the introduction, hints at a locally critical QCP in $YbRh_2(Si_{0.95}Ge_{0.05})_2$. Previously, the scaling analysis of the specific heat has revealed $C(T,b)/T = b^{-1/3}\Phi(T/T_0(b))$ with $\Phi(x) \approx (\max(x,1))^{-1/3}$ [1]. This implies that the specific heat coefficient in the LFL state at $T \ll T_0(b)$ diverges as $\gamma_0(b) \propto b^{-1/3}$. Such a stronger than logarithmic mass divergence is clearly incompatible with the predictions of the Hertz–-Millis *itinerant* scenario [4]. The corresponding scaling behavior of the magnetic entropy is shown in Fig. 2a. Note that in the non-Fermi liquid regime $T \gg T_0(b)$, the entropy is nearly magnetic field independent and varies roughly as $S \propto T^{2/3}$. This corresponds to $C/T \propto T^{-1/3}$, observed very close to the critical field ($b \approx 0$) at temperatures below 0.4 K [1].

Fig. 2b proves that the derivative $\zeta = \partial S/\partial B$, experimentally deduced from the differential

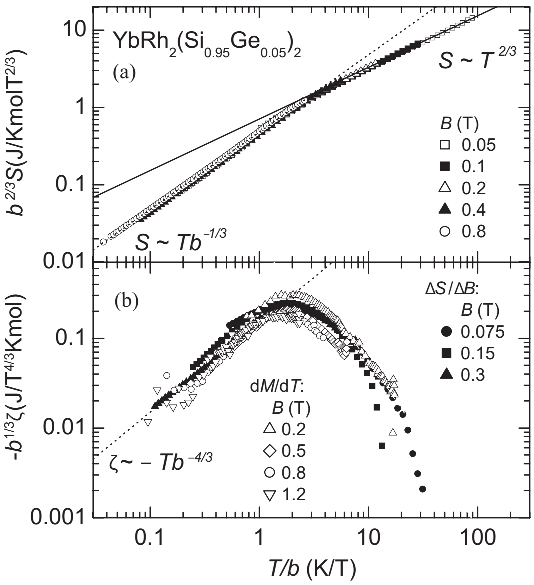

Fig. 2. T/b scaling for $YbRh_2(Si_{0.95}Ge_{0.05})_2$. Entropy S as $b^{-2/3}S$ vs. T/b on log–log plot (a). Dashed (dotted) line represents $S = 0.48\,\mathrm{JT}^{1/3}\,\mathrm{K}^{-2}\,\mathrm{mol} \times Tb^{-1/3}$ ($S = 0.71\,\mathrm{JK}^{-5/3}\,\mathrm{mol}^{-1} \times T^{2/3}$). Second derivative of free Energy $\zeta = \partial^2 F/\partial B \partial T = \partial S/\partial B = \partial M/\partial T$ as $-b^{1/3}\zeta$ vs. T/b on log–log plot (b). Open and closed symbols represent values obtained from differential quotient $\Delta S/\Delta B$ and slope $\mathrm{d}M(T)/\mathrm{d}T$ of isofield DC-magnetization measurements [6], respectively. Dotted line represents $\zeta = -0.15\,\mathrm{T}^{1/3}\,\mathrm{JK}^{-2}\,\mathrm{mol}^{-1} \times Tb^{-4/3}$.

quotient of the entropy data at different magnetic fields, equals the temperature derivative $\partial M/\partial T$ of isofield DC-magnetization measurements [6], as expected from the Maxwell relation. Both thermal and magnetic properties are thus influenced by the nearby QCP in a consistent way. In the LFL state ($T \ll T_0(b)$) $\zeta \propto -Tb^{-4/3}$ and the magnetic susceptibility can be derived using

$$\chi = \partial M/\partial B = (\partial/\partial B)\int_0^T \zeta(T', b)\,\mathrm{d}T' = \chi_0(b) + T^2 b^{-7/3}.$$

Thus, χ approaches the Pauli susceptibility

$$\chi_0(b) = \left.\frac{\partial M}{\partial B}\right|_{T=0}$$

with a T^2 temperature dependence and the coefficient of this term diverges strongly upon approaching the QCP at $b \to 0$. Such behavior has been observed in AC-susceptibility measurements on undoped $YbRh_2Si_2$ [7].

To summarize, we have analyzed the magnetic entropy of $YbRh_2(Si_{0.95}Ge_{0.05})_2$. At zero magnetic field, a tiny entropy of about $0.8\% R \log 2$ is related to the antiferromagnetic state. In the field-induced LFL state, the entropy scales as $S(T, b) \propto Tb^{-1/3}$ and its magnetic field dependence is consistent with the temperature dependence of the magnetization. This proves that specific heat and magnetic susceptibility probe the same degrees of freedom, related to the nearby locally critical QCP.

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