Pressure effect on antiferromagnetism in $\mathrm{CeRhIn}_{5-x}\mathrm{Sn}_x$ studied by thermal expansion

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Abstract

We present low-temperature thermal expansion measurements on the Sn-substituted heavy fermion antiferromagnet $\mathrm{CeRhIn}_{5-x}\mathrm{Sn}_x$ for $0 \leqslant x \leqslant 0.36$ in which $T_\mathrm{N}(x)$ is linearly suppressed from 3.8 K at $x = 0$ to zero at $x_\mathrm{c} \approx 0.4$. The application of the Ehrenfest relation allows to calculate the initial uniaxial and hydrostatic pressure dependences $\mathrm{d}T_\mathrm{N}/\mathrm{d}P$ at various x. The observed non-linear variation with x is interpreted in terms of the Doniach diagram by an increase of the 4*f*-conduction electron hybridization induced by Sn-doping. As no traces of superconductivity are observed close to x_c, this system is ideally suited for the study of the magnetic quantum critical point.

Keywords: CeRhIn_5; Heavy fermion system; Quantum critical point; Antiferromagnetism

CeRhIn_5 [1] belongs to the family of "115" heavy fermion compounds CeMIn_5 (M = Rh, Ir, Co) which crystallize in a tetragonal layered structure giving rise to rather pronounced two-dimensionality in various physical properties. It shows antiferromagnetic (AF) order below $T_\mathrm{N} = 3.8$ K. The application of hydrostatic pressure leads to an abrupt suppression of T_N for pressures (P) above 1.5 GPa [1]. This quantum phase transition is masked by a "dome"-like superconducting (SC) region in the P–T phase diagram, with a maximum transition temperature of about 2.2 K. Recently, the interplay of AF order and superconductivity in this pressure-regime has been studied in great detail by specific heat measurements in magnetic fields [2]. Different regimes of coexistence and competition between superconductivity and AF order have been observed in temperature–pressure-field phase space.

In order to uncover the (zero-field) quantum critical point (QCP) in this system the superconductivity needs to be destroyed by disorder. For this purpose, we have studied the series $\mathrm{CeRhIn}_{5-x}\mathrm{Sn}_x$. The Sn-substitution of the In-sites increases the 4*f*-conduction electron hybridization, leading to a suppression of AF order, similar as found e.g. in cubic $\mathrm{CeIn}_{3-x}\mathrm{Sn}_x$ [3]. In this paper, we use thermal expansion measurements in order to follow the evolution of $T_\mathrm{N}(x)$ for single crystals with $0 \leqslant x \leqslant 0.4$ grown by a flux method [4]. Furthermore, we estimate the initial pressure dependences $\mathrm{d}T_\mathrm{N}/\mathrm{d}P$ (both uniaxial and hydrostatic). The thermal expansion coefficient $\alpha(T) = \mathrm{d}(\Delta L(T)/L)/\mathrm{d}T$ has been determined with the aid of a high-resolution capacitive dilatometer, attached to a dilution refrigerator.

Fig. 1 shows the temperature dependence of the linear thermal expansion along and perpendicular to the *c*-axis for various different Sn concentrations. Clear second-order phase transition anomalies are observed at the respective Néel temperatures (cf. arrows in Fig. 1) which are determined from equal-area (length conserving) constructions for the broadened steps in α vs T. For $x = 0$ perfect

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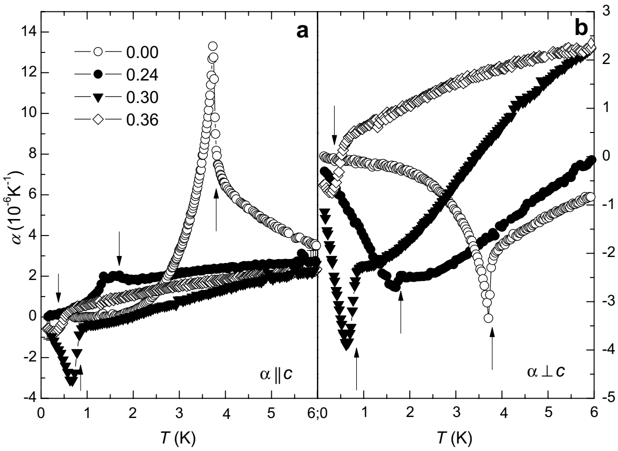

Fig. 1. Temperature dependence of the linear thermal expansion coefficient along (a) and perpendicular (b) to the c-axis for various concentrations of $\mathrm{CeRhIn}_{5-x}\mathrm{Sn}_x$. Arrows indicate Néel temperatures.

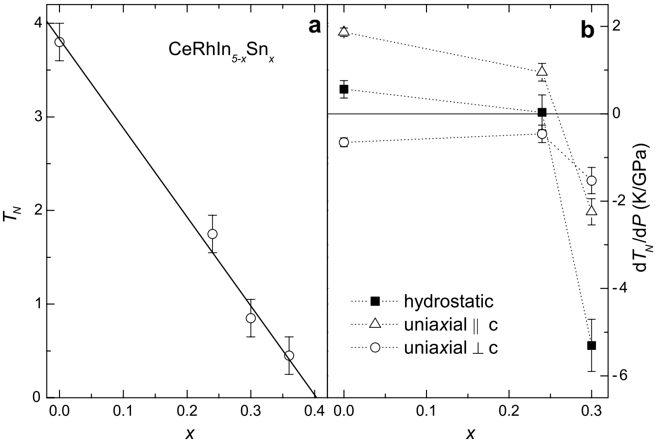

Fig. 2. Evolution of the Néel temperature $T_N(x)$ in $\mathrm{CeRhIn}_{5-x}\mathrm{Sn}_x$ (a). Note that for $x = 0.4$ no indication for AF order has been observed above 0.05 K. (b) Corresponding variation of the initial uniaxial and hydrostatic pressure dependences $\mathrm{d}T_N/\mathrm{d}P$.

agreement is found with previous thermal expansion measurements [5]. The same samples have also been studied by low-temperature specific heat measurements [4], revealing similar transition temperatures.

As displayed in Fig. 2a, we observe a linear suppression of $T_N(x)$, extrapolating to a QCP at $x_c \approx 0.4$. Detailed studies of the low-temperature thermal expansion and Grüneisen ratio at x_c will be presented elsewhere. Here, we focus on the thermodynamic analysis of the pressure dependences of the AF phase transition. The Ehrenfest relation, $\partial T_N/\partial P_{\|,\perp} = V_{\mathrm{mol}} T_N \Delta\alpha_{\|,\perp}/\Delta C$ (V_{mol}: molar volume) relates the step sizes $\Delta\alpha_{\|,\perp}$ and ΔC in thermal expansion and specific heat with the initial ($P \to 0$) uniaxial pressure dependences of the AF phase transition temperature parallel (∥) and perpendicular (⊥) to the c-axis. The initial hydrostatic pressure dependence follows then from $\partial T_N/\partial P_h = \partial T_N/\partial P_\| + 2\partial T_N/\partial P_\perp$. For CeRhIn_5 this results in a value of 0.6 K/GPa, in agreement with electrical resistivity measurements under hydrostatic pressure [1]. The evolution of hydrostatic and uniaxial pressure dependences with x is displayed in Fig. 2b with the values given in Table 1.

Table 1
Values for the superconducting transition temperature T_N and uniaxial and hydrostatic pressure dependences determined from the Ehrenfest relation, see text

x	T_N (K)	$\frac{\partial T_N}{\partial P_\|}$ (K/GPa)	$\frac{\partial T_N}{\partial P_\perp}$ (K/GPa)	$\frac{\partial T_N}{\partial P_h}$ (K/GPa)
0.00	3.8 ± 0.2	1.9 ± 0.1	−0.7 ± 0.1	0.6 ± 0.2
0.24	1.75 ± 0.2	1 ± 0.2	−0.5 ± 0.2	0 ± 0.4
0.30	0.85 ± 0.2	−2.2 ± 0.3	−1.5 ± 0.3	−5.3 ± 0.6
0.36	0.45 ± 0.2			

Whereas the in-plane pressure dependence $\partial T_N/\partial P_\perp$ is always negative, a sign change is observed for the pressure dependence along the c-axis, as well as for the hydrostatic pressure dependence at $x \approx 0.24$. Interpreting this observation in terms of the Doniach diagram suggests the $x = 0$ system to be located on the left side of the maximum in $T_N(P)$. Increasing the 4*f*-conduction electron hybridization with Sn-substitution of In shifts the system towards the non-magnetic side, thus yielding $\partial T_N/\partial P_h < 0$. Interestingly, the strongest effect of Sn-doping is observed for the c-axis uniaxial pressure dependence indicating that the ground state properties are most sensitive to changes of the c-axis parameter. A similar observation has also been made for $\mathrm{CeCoIn}_{5-x}\mathrm{Sn}_x$ [6].

To summarize, we have studied the HF antiferromagnet $\mathrm{CeRhIn}_{5-x}\mathrm{Sn}_x$ by low-temperature thermal expansion measurements. A linear suppression of $T_N(x)$ has been observed extrapolating to a QCP at $x_c \approx 0.4$. For the hydrostatic pressure dependence $\partial T_N/\partial P$, a sign change near $x = 0.24$ is found, compatible with the Doniach diagram and an increase of the 4*f*-conduction electron hybridization with x. $\mathrm{CeRhIn}_{5-x}\mathrm{Sn}_x$ is ideally suited to study the nature of the QCP in "115" systems, because no magnetic fields are needed to suppress superconductivity which covers the QCP in CeCoIn_5 ($P = 0$) and CeRhIn_5 close to its critical pressure.

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