

Pressure effect on superconductivity in $\text{CeCoIn}_{5-x}\text{Sn}_x$ studied by thermal expansion

J.G. Donath^{a,*}, P. Gegenwart^a, R. KÜchler^a, N. Oeschler^a,
F. Steglich^a, E.D. Bauer^b, J.L. Sarrao^b

^aMax-Planck Institute for Chemical Physics of Solids, D-01187 Dresden, Germany

^bLos Alamos National Laboratory, Los Alamos, NM 87545, USA

Abstract

We present low-temperature thermal expansion measurements on the Sn-substituted heavy fermion superconductor $\text{CeCoIn}_{5-x}\text{Sn}_x$ for $0 \leq x \leq 0.12$ in which T_c is rapidly suppressed from 2.3 K ($x = 0$) to 0.7 K ($x = 0.12$). The analysis of the superconducting transition anomalies reveals a drastic change of the uniaxial pressure dependences of T_c with Sn substitution. The hydrostatic pressure dependence of T_c is positive for Sn concentrations $x \leq 0.06$ and changes sign at larger x . A first-order superconducting transition, caused by Pauli limiting in magnetic fields that suppress T_c to below 0.7 K, is visible at $x \leq 0.06$.

Keywords: CeCoIn₅; Heavy fermion superconductivity; Quantum critical point

The tetragonal heavy fermion (HF) system CeCoIn_5 has attracted much interest because of its unusual normal and superconducting (SC) properties. An unconventional SC state below $T_c = 2.3$ K is indicated by power-law behavior in specific heat and thermal conductivity [1]. Its nodal structure obtained by thermal conductivity indicates most likely a d-wave nature [2]. Strong Pauli limiting leads to a first-order transition when superconductivity is suppressed by magnetic fields to temperatures below 0.7 K [3]. Furthermore, evidence for the formation of an inhomogeneous SC (FFLO) state has been found very close to $H_{c2} = 5$ T ($B \parallel c$) and 11.5 T ($B \perp c$) [3,4]. The normal state, which electronically due to the layered crystal structure is quasi-two-dimensional, shows pronounced non-Fermi liquid effects related to a magnetic field tuned quantum critical point $H_{\text{QCP}} \approx H_{c2}$ [5,6]. Remarkably, H_{QCP} and H_{c2} cannot be separated from each other by suppressing

superconductivity with Sn substitution in $\text{CeCoIn}_{5-x}\text{Sn}_x$ [7].

We use thermal expansion measurements to study the SC properties of $\text{CeCoIn}_{5-x}\text{Sn}_x$. Since the Sn atoms preferentially occupy the in-plane In(1)-site [8], this allows to investigate the evolution of the anisotropy in this system in a controlled way. The measurements on the same single crystals studied in Ref. [7] have been performed with the aid of a high-resolution capacitive dilatometer adapted to a dilution refrigerator.

Previous specific heat measurements have shown that the Sn-substitution leads to a drastic suppression of the SC transition with a rate $dT_c/dx = -0.6$ K/at% Sn [7]. Fig. 1 displays the linear thermal expansion measured along and perpendicular to the c -axis for different Sn concentrations. For measurements along the c -direction, the positive jump anomaly $\Delta\alpha_{\parallel} > 0$ at T_c , observed for $x = 0$, becomes suppressed with increasing Sn concentration, resulting in a pronounced negative anomaly at $x = 0.12$. This resembles the evolution of the c -axis expansion behavior in undoped CeCoIn_5 under magnetic fields [9]. For a quantitative analysis, the jump anomalies $\Delta\alpha_{\parallel,\perp}$ are

*Corresponding author. Tel.: +49 351 4646 2323;
fax: +49 351 4646 2360.

E-mail address: donath@cphys.mpg.de (J.G. Donath).

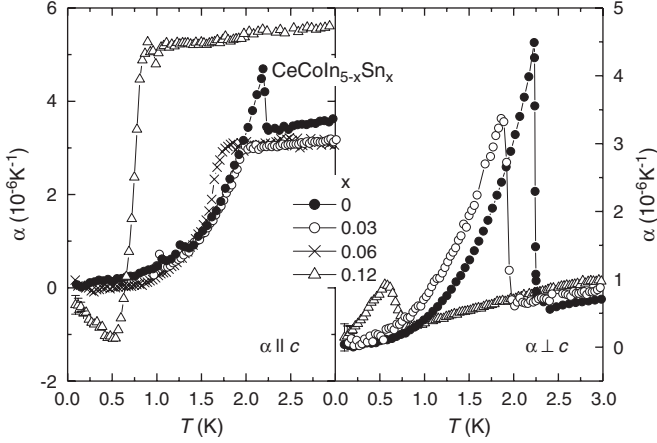


Fig. 1. Temperature dependence of the linear thermal expansion coefficient along (left) and perpendicular (right) to the c -axis for various concentrations of $\text{CeCoIn}_{5-x}\text{Sn}_x$.

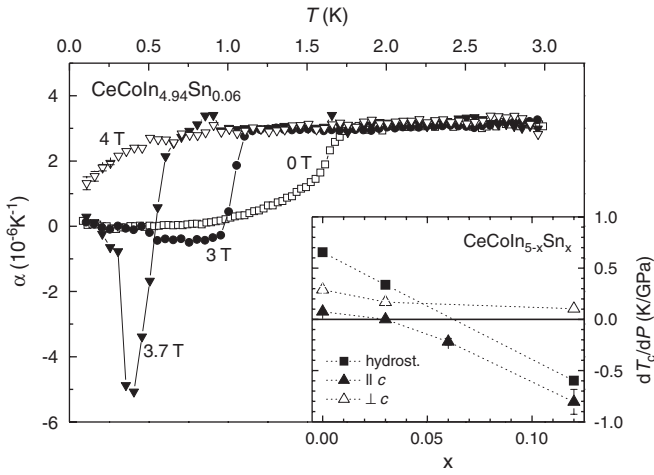


Fig. 2. Temperature dependence of the c -axis linear thermal expansion of $\text{CeCoIn}_{4.94}\text{Sn}_{0.06}$ at various magnetic fields applied along the c -axis. Inset: x -dependence of hydrostatic and uniaxial pressure dependences of T_c in $\text{CeCoIn}_{5-x}\text{Sn}_x$ for the limit of vanishing pressure.

estimated as usual by equal-areas construction. The uniaxial pressure dependences of T_c in the zero-pressure limit are obtained by using the Ehrenfest relation, $\partial T_c / \partial P_{\parallel, \perp} = V_{\text{mol}} T_c \Delta \alpha_{\parallel, \perp} / \Delta C$, where V_{mol} denotes the molar volume and ΔC the jump anomaly in specific heat [7]. The hydrostatic pressure dependence is then obtained by calculating $\partial T_c / \partial P = \partial T_c / \partial P_{\parallel} + 2 \partial T_c / \partial P_{\perp}$.

As shown in the inset of Fig. 2, the so-derived hydrostatic and uniaxial pressure dependences of the SC transition show a pronounced concentration dependence. The positive hydrostatic pressure dependence of undoped CeCoIn_5 indicates that the system is located on the left side of the maximum of the “dome” found in the T_c vs. P diagram [10]. The partial substitution of In by Sn leads to

an increase of the f -conduction electron hybridization, evidenced by a substantial increase of the characteristic maximum temperature in the electrical resistivity [11]. Our data indicate a strong decrease in the hydrostatic pressure dependence with Sn substitution. $\partial T_c / \partial P$ becomes negative for $x \geq 0.06$. This indicates that the system is driven towards the right side of the SC dome in accordance with measurements of the electrical resistivity of $\text{CeCoIn}_{4.88}\text{Sn}_{0.12}$ under hydrostatic pressure [12]. Most interestingly, it is the c -axis uniaxial pressure dependence which is most drastically changed in $\text{CeCoIn}_{5-x}\text{Sn}_x$ although the Sn atoms preferentially occupy the in-plane In(1) site. This supports our previous conclusion that the HF properties in CeCoIn_5 are most sensitive to c -axis strain, counterintuitive to viewing this system as a 2D HF system [9].

Finally, we discuss the effect of Sn substitution to the first-order SC transition in magnetic fields close to H_{c2} which is caused by strong Pauli limiting [3]. As shown for $\text{CeCoIn}_{4.94}\text{Sn}_{0.06}$ in Fig. 2, with increasing magnetic field, the SC transition anomaly changes from a step-like decrease at low fields to a sharp, almost divergent behavior indicative of a first-order transition for fields near H_{c2} . A similar observation has been made in CeCoIn_5 [9]. For larger Sn concentration, the first-order transition is suppressed by disorder. We also note that specific heat experiments on $\text{CeCoIn}_{4.94}\text{Sn}_{0.06}$ show no first-order transition [13].

To summarize, the substitution of In by Sn in $\text{CeCoIn}_{5-x}\text{Sn}_x$ leads to a drastic change in the pressure dependence of the SC transition in this system. Although the Sn atoms preferentially occupy the in-plane In(1) site, they most effectively increase the f -conduction electron hybridization along the c -axis. The detailed analysis of the normal state thermal expansion behavior of $\text{CeCoIn}_{5-x}\text{Sn}_x$ will be published elsewhere [14].

References

- [1] R. Movshovich, et al., Phys. Rev. Lett. 86 (2001) 5152.
- [2] K. Izawa, et al., Phys. Rev. Lett. 87 (2001) 057002.
- [3] A. Bianchi, et al., Phys. Rev. Lett. 89 (2002) 137002; A. Bianchi, et al., Phys. Rev. Lett. 91 (2003) 187004.
- [4] H. Radovan, et al., Nature 425 (2003) 51.
- [5] A. Bianchi, et al., Phys. Rev. Lett. 91 (2003) 257001.
- [6] J.P. Paglione, et al., Phys. Rev. Lett. 91 (2003) 246405.
- [7] E.D. Bauer, et al., Phys. Rev. Lett. 94 (2005) 047001.
- [8] M. Daniel, et al., Physica B 359–361 (2005) 401.
- [9] N. Oeschler, et al., Phys. Rev. Lett. 91 (2003) 076402.
- [10] V.A. Sidorov, et al., Phys. Rev. Lett. 89 (2002) 157004.
- [11] E.D. Bauer, et al., Physica B 359–361 (2005) 35.
- [12] S.M. Ramos, et al., Physica B 359–361 (2005) 398.
- [13] E.D. Bauer, et al., unpublished results.
- [14] J.G. Donath, et al., to be published.