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Pressure effect on superconductivity in $CeCoIn_{5-x}Sn_x$ studied by thermal expansion

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Abstract

We present low-temperature thermal expansion measurements on the Sn-substituted heavy fermion superconductor $CeCoIn_{5-x}Sn_x$ for $0 \leqslant x \leqslant 0.12$ in which T_c is rapidly suppressed from 2.3 ($x = 0$) 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 $x \leqslant 0.06$ 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 $x \leqslant 0.06$.

Keywords: $CeCoIn_5$; 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 ($B \| c$) 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 $H_{QCP} \approx H_{c2}$ [5,6]. Remarkably, H_{QCP} and H_{c2} cannot be separated from each other by suppressing superconductivity with Sn substitution in $CeCoIn_{5-x}Sn_x$ [7].

We use thermal expansion measurements to study the SC properties of $CeCoIn_{5-x}Sn_x$. 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 $\Delta\alpha_\| > 0$ 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 $\Delta\alpha_{\|,\perp}$ are

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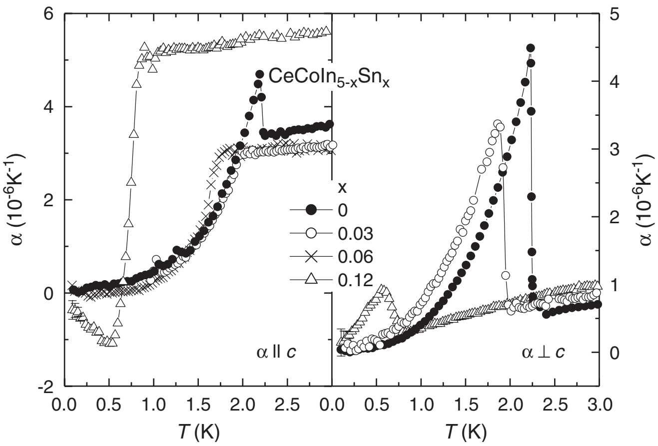

Fig. 1. Temperature dependence of the linear thermal expansion coefficient along (left) and perpendicular (right) to the c-axis for various concentrations of $CeCoIn_{5-x}Sn_x$.

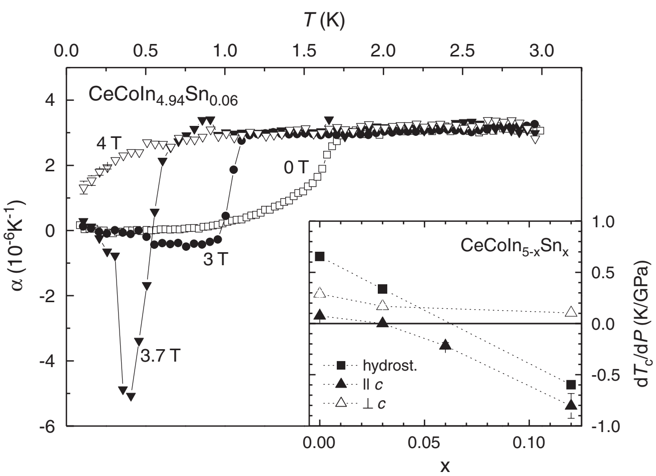

Fig. 2. Temperature dependence of the c-axis linear thermal expansion of $CeCoIn_{4.94}Sn_{0.06}$ at various magnetic fields applied along the c-axis. Inset: x-dependence of hydrostatic and uniaxial pressure dependences of T_c in $CeCoIn_{5-x}Sn_x$ for the limit of vanishing pressure.

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, $\partial T_c/\partial P_{\parallel,\perp} = V_{mol} T_c \Delta\alpha_{\parallel,\perp}/\Delta C$, 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 $x \geqslant 0.06$. This indicates that the system is driven towards the right side of the SC dome in accordance with measurements of the electrical resistivity of $CeCoIn_{4.88}Sn_{0.12}$ under hydrostatic pressure [12]. Most interestingly, it is the c-axis uniaxial pressure dependence which is most drastically changed in $CeCoIn_{5-x}Sn_x$ 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 $CeCoIn_{4.94}Sn_{0.06}$ 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 $CeCoIn_{4.94}Sn_{0.06}$ show no first-order transition [13].

To summarize, the substitution of In by Sn in $CeCoIn_{5-x}Sn_x$ 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 $CeCoIn_{5-x}Sn_x$ will be published elsewhere [14].

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