NON-FERMI LIQUID EFFECTS CLOSE TO A QCP IN $CeIn_{3-x}Sn_x$*

J. Custers, T. Cichorek, P. Gegenwart, N. Caroca-Canales
O. Stockert, C. Geibel, F. Steglich

Max Planck Institute for the Chemical Physics of Solids, 01187 Dresden, Germany

P. Pedrazzini, and J.G. Sereni

Lab. Bajas Temperaturas, Centro Atómic Bariloche (CNEA)
8400 S.C. de Bariloche, Argentina

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Resistivity and specific heat measurements at low temperatures on $CeIn_{3-x}Sn_x$ samples with concentrations $x = 0.6, 0.65$ and 0.7 demonstrate that with increasing Sn-alloying, the antiferromagnetic ordering temperature decreases continuously down to $T = 0$ K and disappears at a quantum critical point. We observe non-Fermi liquid (NFL) behavior in the resistivity and the specific heat, however the temperature dependencies are different from the predictions for a spin density wave (SDW) scenario. The resistivity at the critical point shows *e.g.*, a linear temperature dependence, as expected for two dimensional fluctuations, which however can be excluded in the cubic structure of $CeIn_{3-x}Sn_x$.

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1. Introduction

In the presence of an antiferromagnetic (AF) quantum critical point (QCP) where $T_N \to 0$, clear deviations from the properties of a Landau Fermi liquid (LFL) have been observed mostly in Rare Earth-based heavy fermion systems (HF). Among the growing number of Ce-based HF compounds showing Non-Fermi liquid (NFL) effects $CeIn_3$ takes in a special position [1]. In contrast to many other NFL systems currently under investigation which have either orthorhombic, *e.g.*, $CeCu_{5.9}Au_{0.1}$ [2] or tetragonal, *e.g.*, $CeCu_2Si_2$ [3] and $CeNi_2Ge_2$ [4] crystal structure, in $CeIn_3$ the Ce-atom

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site has a cubic symmetry. According to today's theories, the dimensionality of the spin fluctuations plays a crucial role in the description of NFL behavior. Predictions have been made for transport and thermodynamical properties in case of 2D spin fluctuations, $\Delta\rho \propto T$ and $C/T \propto \log T$ and 3D fluctuations $\Delta\rho \propto T^{1.5}$ and $C/T \propto \gamma - b\sqrt{T}$, respectively [5,6]. Because of the cubic symmetry, $CeIn_{3-x}Sn_x$ is of great interest, being an outstanding candidate investigating the parameter "dimensionality" by comparison with other NFL-systems and known theoretical descriptions.

2. Resistivity and specific heat results

Resistivity and specific heat measurements were performed on polycrystalline samples with concentrations $x = 0.6, 0.65$ (only $\rho(T)$) and 0.7 in order to trace the vanishing of the AF transition and investigating the evolution of NFL-behavior. Due to the high Sn-doping needed to tune the systems towards the QCP the residual resistivity ratio (RRR= $\rho_{300\mathrm{K}}/\rho_{20\mathrm{mK}}$) is rather low, RRR ~ 1. In figure 1 $\rho(T)/\rho_{300\mathrm{K}}$ *versus* T is plotted for low temperatures. The $x = 0.6$ doped compound shows a kink in the resistivity at

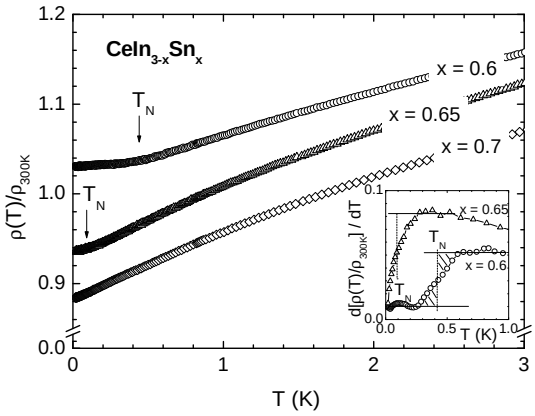

Fig. 1. Low-temperature zero field resistivity $\rho(T)$ *versus* temperature of $CeIn_{3-x}Sn_x$ with $x = 0.6, 0.65$ and 0.7. The arrow marks the Néel temperature estimated from an equal areas construction as shown in the inset.

$T_{\mathrm{N}} = 0.4$ K. The singularity in $\rho(T)$ is similar to those observed for lower Sn-concentrations at the transition from the paramagnetic to the antiferromagnetic ordered state indicating that this kink is indeed related to the antiferromagnetic transition. This is also confirmed by specific heat data which shows a broad anomaly around $T_{\mathrm{N}} = 0.4$ K (Fig. 2). At slightly higher content, $x = 0.65$ a small kink can still be resolved in $\rho(T)$ at $T_{\mathrm{N}} = 0.1$ K. The

transition temperature has been determined using an equal areas construction as shown in the inset. At a doping concentration $x = 0.7$ no indication of an AF transition could be found. The critical point therefore is localized between $0.65 \leq x_c \leq 0.70$. Figure 1 clearly shows that the exponent in the power law in the temperature dependence of $\rho(T)$ is well below 2. For $x = 0.6$ and $x = 0.65$ a best fit through the data for $T > T_N$ with $\Delta\rho \propto T^{\varepsilon}$ yields $\varepsilon \approx 0.8$, whereas for $T < T_N$ $\varepsilon \approx 1$ is found. In $CeIn_{2.3}Sn_{0.7}$ the resistivity decreases linearly upon decreasing temperature from $T \approx 0.8$ K down to the lowest investigated temperature. When applying a magnetic field we found in all samples a $\Delta\rho \propto AT^2$ behavior, meaning a LFL state is established. An analysis of the fitting shows a divergence of the A-coefficient towards $B \to 0$ T, while T^*, the temperature where the T^2-fit deviates from the measurement increases with increasing field.

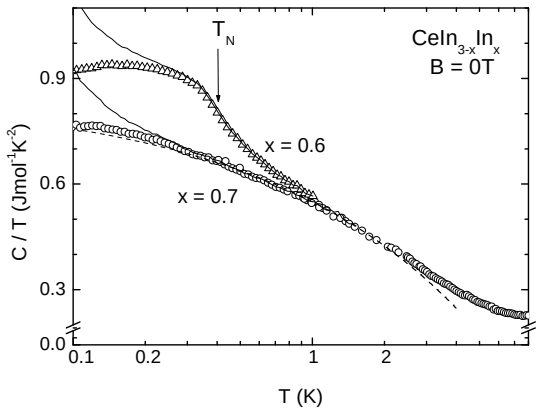

Fig. 2. Electronic specific heat of $CeIn_{2.4}Sn_{0.6}$ ($\triangle$) and $CeIn_{2.3}Sn_{0.7}$ (O) plotted as C/T *versus* $\log T$. The solid lines show the experimental data. Symbols present the data after subtraction of a nuclear contribution which has been estimated from the data below 0.1 K (see text). The dashed line is a $C(T)/T \propto \gamma_0 - b\sqrt{T}$-fit through the data.

The specific heat data for $x = 0.6$ and $x = 0.7$[1] are depicted in figure 2 in a C/T *versus* $\log T$ representation (solid line). Below 0.1 K, $C(T)$ is dominated by a large nuclear contribution of In, making the determination of the electronic contribution difficult. We estimated the nuclear contribution from the data below 0.1 K and subtracted a corresponding α/T^2-term from the data above 0.1 K (open symbols). We tried to fit the data for $x = 0.7$

[1] The high temperature specific heat data ($T > 0.4$ K) measured in a commercial Quantum Design PPMS has been multiplied by 1.05 in order to fall on top of the low C/T-measurement.

between $0.1 < T < 2$ K both with $C/T = a \log T$ and $C/T = \gamma_0 - b\sqrt{T}$. None of these fits where in good agreement with the experimental data. In the plot C/T *versus* $\log T$, the experimental data show a significant curvature in disagreement with a pure $\log T$-dependence, but the curvature is weaker than for the $C/T \propto \gamma_0 - b\sqrt{T}$ fit (dashed line).

3. Concluding remarks

Our results demonstrate that in $CeIn_{3-x}Sn_x$, the antiferromagnetic state disappears at a quantum critical point. The lowest transition we observed, $T_N = 0.1$ K, is two orders of magnitude lower than $T_N = 10$ K at $x = 0$, and at least one order of magnitude lower than the lowest T_N determined in experiments on pure $CeIn_3$ under pressure [7]. The NFL signatures do not agree with the prediction in the SDW-scenario [5] for a 3D-system. According to SDW-theory, the behavior in the resistivity would correspond to a 2D-system. Similar T-dependencies have been reported for many other NFL-systems. However, those systems show evidence for lower symmetry, *e.g.*, $CeCu_{6-x}Au_x$ for which a reduced dimensionality has been reported [8]. In cubic $CeIn_3$ the argument of lower dimensionality can be excluded. Furthermore, the linear behavior in resistivity violates even SDW-theory predictions including a large disorder effect. Here, an exponent $\varepsilon = 1.5$ in $\Delta\rho(T) \propto T^{\varepsilon}$ is expected, while for clean samples $\varepsilon \to 1$ [9]. Surprisingly, an exponent of $\varepsilon \approx 1.6$ has been observed in pure $CeIn_3$ with a low residual resistivity ratio ($RRR \sim 30$) when tuned towards the quantum critical point by pressure [7]. These results cast doubts on the applicability of the SDW-scenario.

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