

Quantum Critical Behavior and Superconductivity in new multi-site Cerium Heavy Fermion Compound $\text{Ce}_3\text{PtIn}_{11}$

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Abstract. We discuss the results of thermodynamic and transport measurements at ambient and under hydrostatic pressure of the recently discovered heavy fermion superconductor $\text{Ce}_3\text{PtIn}_{11}$. At $p = 0$ superconductivity emerges in the complex antiferromagnetic state below $T_c = 0.32$ K. Both phenomena coexist in a wide range of the $p - T$ phase diagram. The critical pressure where $T_N \rightarrow 0$ and T_c is maximum equals $p_c = 1.3$ GPa. Here, the resistivity follows $\rho(T) \propto T^n$ with $n = 0.90 \pm 0.05$ suggesting a local moment-type of quantum critical point. The presence of a maximum structure in the susceptibility and the unusual pressure dependence of T_c hint to an understanding of properties of $\text{Ce}_3\text{PtIn}_{11}$ in the view of distinct different Kondo screened sublattices. Therefore, we analyze the magnetic entropy S_{mag} within the spin-1/2 Kondo model while accounting for the fact that $\text{Ce}_3\text{PtIn}_{11}$ unit cell possesses two inequivalent Ce-sites, Ce1 and Ce2. We employ an extreme case scenario of non-interacting sublattices where the Ce1-sublattice is paramagnetic and only Ce2-sublattice orders magnetically and discussed its consequences.

1. Introduction

In the past decade, condensed matter research has come to a point of convergence. The appearance of superconductivity in several classes of strongly correlated electron systems such as cuprates, organics, heavy fermions and the more recently discovered iron pnictides cover a putative quantum critical point (QCP). Here, these systems undergo a phase transition at zero temperature and critical fluctuations associated with the order parameter of the phase transition enhance the interaction between electrons in a similar way as phonons do in conventional superconductors leading to the observed superconducting dome [1]. This is probably best explored in heavy fermion (HF) materials where many different non-phononic pairing mechanism associated with different types of QCPs have been proposed [2]. Most notably, in numerous HF materials, superconductivity has been reported to emerge at the border of a magnetically ordered state and a paramagnetic state indicative of magnetically mediated superconductivity [3].

The vast majority of the cerium HF compounds studied to date have been compounds which have only one crystallographic site for the cerium ions. The ground state of these materials depends on the competition between the magnetic inter-site interaction, i. e., the indirect RKKY exchange interaction, and the demagnetizing on-site Kondo interaction. This competition is well illustrated by the Doniach diagram [4]; the ground state depends on the relative value of the



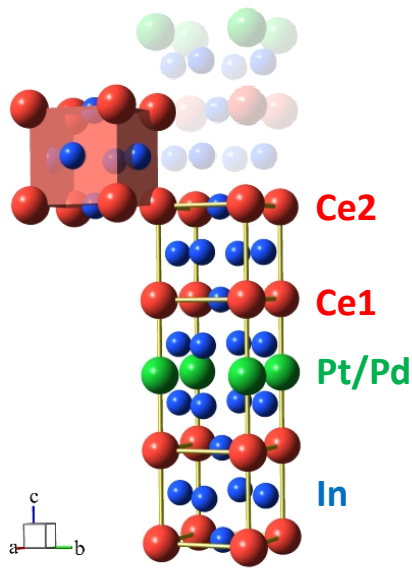


Figure 1. The crystallographic unit cell of $\text{Ce}_3\text{TIn}_{11}$ (Ce: red spheres; Pd or Pt: green spheres; In: blue spheres). The two inequivalent Cerium sites Ce1 and Ce2 are marked, respectively. The CeIn_3 environment of the Ce2-site is shown explicitly. The lattice parameters yield $a = 4.6874(4)$ Å and $c = 16.8422(12)$ Å for the Pt compound and for $a = 4.6896(11)$ Å and $c = 16.891(3)$ Å for the Pd-analogue.

respective RKKY and Kondo energies, $k_B T_{\text{RKKY}} \sim |N_F J_{\text{cf}}^2|$ and $k_B T_K \sim \exp[1/|N_F J_{\text{cf}}|]$, with N_F being the conduction band density of states at the Fermi level and J_{cf} the coupling constant (hybridization) between $4f(\text{Ce})$ and conduction electrons. Because of the extended nature of the Ce $4f$ wave-function, J_{cf} depends strongly on the local environment of the Ce-ion. This has been capitalized on, for example, investigating quantum critical phenomena in these HF compounds, where by either applying hydrostatic pressure or chemical substitution a formerly magnetic ground state (small values of $|J_{\text{cf}}|$) undergoes a transition at a QCP into a non-magnetic ground state where the Kondo effect dominates (large values of $|J_{\text{cf}}|$).

In compounds with multiple inequivalent Ce sites, the local environment of these two- or more cerium sites will vary and consequently the respective Ce ion experiences different hybridization (different values for J_{cf}). This results in an interesting aspect; the ground state of such compounds might be a coexistence on microscopic scale of different electronic and magnetic states. For instance, it is quite conceivable that one Ce-site (Ce1) is magnetic, i. e., its sublattice orders magnetically, while the other Ce-site (Ce2) is non-magnetic as a results of dominant Kondo interaction. It was pointed out by Benlagra and co-workers [5] that in these compounds the inequivalent Ce sites (sublattices) do not act independently from each other. The onset of Kondo screening in one sublattice (Ce2-site in our example above) may boost or can reduce the onset of Kondo screening in the Ce1-sublattice. In particular with respect to quantum criticality and superconductivity this can have dramatic consequences as in a local moment scenario the Kondo scale breaks down at the QCP [6]. At present, the investigation of quantum critical behavior in these multi-site compounds is still rather an uncharted terrain. Two of the few examples in literature are Ce_7Ni_3 and $\text{Ce}_3\text{Pd}_{20}\text{Si}_6$. The first-mentioned compound crystallizes in the hexagonal Th_7Fe_3 structure (space group $P6_3mc$) in which the Ce-ions reside in three inequivalent sites, 1 Ce_I , 3 Ce_II and 3 Ce_III . The crystal structure is rather complex with the Ce_I surrounding being trigonal and the other two have monoclinic symmetry. Ce_7Ni_3 is a heavy-fermion antiferromagnet with $T_N = 1.8$ K. It was suggested by the entropy analysis of the specific heat and from magnetic studies that only the Ce_I sublattice orders. The Ce_II sublattice has been associated with heavy fermion (HF) behavior while the Ce_III one gives rise to intermediate valence contributions [7]. Under increasing pressure T_N decreases and vanishes near $p_c \approx 0.33$ GPa [8]. Non-Fermi-liquid (NFL) behavior appears at 0.4 GPa in both the specific heat and ac magnetic susceptibility, $C_{\text{el}}/T \propto \ln T$ and $\chi_{\text{ac}} \propto (1 - \alpha\sqrt{T})$, and has

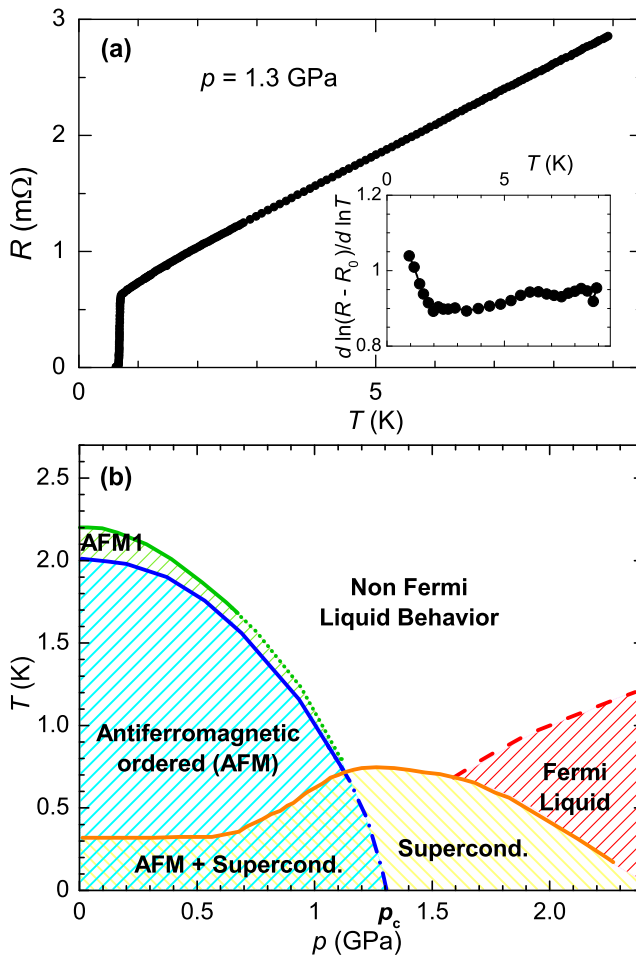


Figure 2. Summary of the properties of Ce_3PtIn_{11} (a) Observation of non-Fermi liquid behavior in the resistance R at the critical hydrostatic pressure of $p_c = 1.3$ GPa where $T_N \rightarrow 0$ [14]. Inset shows the corresponding resistance exponent in the normal state. (b) The $p - T$ phase diagram of Ce_3PtIn_{11} adapted from Ref. [14] showing the various ordered states.

been discussed in the frame of self consistent renormalization theory of spin fluctuations of heavy-fermion systems near an antiferromagnetic instability [9]. Above 0.62 GPa, the normal Fermi-liquid state is recovered. The latter compound, $Ce_3Pd_{20}Si_6$, is a so-called cage compound. $Ce_3Pd_{20}Si_6$ crystallizes in the cubic structure of space group $Fm\bar{3}m$. It harbors two different crystallographic Ce-sites, both with cubic symmetry but one with coordination 16 (tetrahedral 8c: all Pd) and one with coordination 18 (octahedral 4a: 12 Pd, 6 Si). At $T = 0.5$ K, $Ce_3Pd_{20}Si_6$ undergoes a quadrupolar phase transition and at $T_N = 0.31$ K a transition in an AFM ordered state [10, 11, 12]. The quadrupolar state has been linked to ordering of the 8c and the dipolar order to the 4a sublattice. Both ordered states coexist at low temperatures. The compound gained special attention displaying a field-induced QCP ($T_N \rightarrow 0$ for $B_c \approx 0.9$ T) of local moment (Kondo breakdown) type in a cubic system which separates the AFM and the AFQ state at $T = 0$ [13].

Until recently no superconductivity has been found in multi-site cerium (HF) systems. Our low-temperature experiments on newly discovered HF compounds Ce_3PdIn_{11} [15, 16] and Ce_3PtIn_{11} [16] revealed that both become superconducting [17, 14]. Ce_3PdIn_{11} and Ce_3PtIn_{11} belong to the Ce_nTIn_{3n+2} class of materials which comprises a numerous amount of compounds including $CeCoIn_5$, $CeRhIn_5$ and Ce_2RhIn_8 . The compounds crystallize with space group $P4/mmm$ (tetragonal structure) based on the $AuPt_3$ -type ($CeIn_3$ block) and $PtHg_2$ -type (TIn_2) units and possesses two non-equivalent Ce-sites labeled Ce1 (2 Ce-ions per f.u.) and Ce2 (1 Ce-ion per f.u.) as emphasized in Fig. 1. The advantage of both materials is that they are less complex from a crystallographic point of view than the examples mentioned before. Ce2

resides the Wyckoff $1a$ position which has local C_{4v} symmetry. The ion experiences CeIn₃-like environment. The Ce1-site occupies the $2g$ position (D_{4h} symmetry). Its surrounding is identical to Ce-atoms in Ce₂PdIn₈ and Ce₂PtIn₈. At ambient pressure, both compounds shows remarkable properties: in the absence of magnetic field, Ce₃PtIn₁₁ (Ce₃PdIn₁₁) undergoes two successive antiferromagnetic type of transitions at $T_1 = 2.2$ K and $T_N = 2$ K ($T_1 = 1.67$ K and $T_N = 1.53$ K in the case of Pd) and becomes superconducting below $T_c = 0.32$ K [14] (Pd: $T_c = 0.42$ K [17]).

1.1. Superconductivity in Ce₃PtIn₁₁ and Ce₃PdIn₁₁

We briefly summarize the superconducting properties of both compounds. Details can be found in the references mentioned above. Ce₃PtIn₁₁ and Ce₃PdIn₁₁ take a unique place in the Ce-based HF family of materials. In both compounds, superconductivity emerges out of a magnetically ordered state at ambient pressure. This, in fact, makes the compounds be the first known full inversion symmetrical stoichiometric heavy fermion material based on Ce exhibiting, most likely, a coexistence of magnetism and superconductivity already at ambient pressure. The superconducting transition temperatures are $T_c = 0.32$ K and $T_c = 0.42$ K, respectively, and the parameter $\Delta C/(\gamma_n T_c)$ yields for both ≈ 0.7 , being half of the expected value from BCS theory. The upper critical field for Ce₃PtIn₁₁ equals $B_{c2} = 1.4$ T and for Ce₃PdIn₁₁ $B_{c2} = 2.3$ T. The upper critical fields are orbital limited. The initial slope for the Pt-compound is $dB_{c2}/dT = -7.24$ T/K and for the Pd-analogue -8.6 T/K from which is evident that heavy quasiparticles, mass m^* , are involved in Cooper-pairing ($dB_{c2}/dT \propto (m^*)^2 T_c$). The superconducting phase in both has been linked to a nearby magnetic QCP.

1.2. Quantum critical behavior in Ce₃PtIn₁₁

So far quantum critical behavior has only been investigated on Ce₃PtIn₁₁ [14]. The application of hydrostatic pressure (p) reduces the temperature of magnetic ordering transitions as expected for a Ce-compound (see Fig. 2b). The magnetic transitions intersect with the superconductivity at $p \approx 1.1$ GPa. Upon increasing p , a pronounced region of non-Fermi liquid behavior has been observed above T_c which is characterized by an almost T -linear dependence of the resistance (R) up to temperatures even higher than $T > 5$ K. It was pointed out that the NFL behavior can be seen as indication of the presence of strong quantum critical fluctuations originating from a magnetic QCP hidden inside the SC dome. The position of the QCP where $T_N \rightarrow 0$ was traced by the maximum in T_c [1] and is located at a critical pressure of $p_c \approx 1.3$ GPa ($T_c = 0.7$ K). A fit to $R(T)$ at p_c gives $R = R_0 + AT^n$ with $n = 0.90 \pm 0.05$. Alternatively, the exponent has been determined using $n = d \ln(R - R_0)/d \ln T$, i. e., the temperature logarithmic derivative of the resistance measured relative to the residual low temperature value (Fig. 2a). From the value of exponent in the NFL-state it was suggested that the QCP might be of local moment type.

2. Results and analysis

this manuscript focusses on the analysis of the experimental data. The properties of Ce₃PdIn₁₁ and Ce₃PtIn₁₁ are very similar. In order to keep it transparent we will mainly discuss results of the latter compound.

2.1. Susceptibility at high temperatures

The temperature dependence of the susceptibility $\chi(T)$ for Ce₃PtIn₁₁ and Ce₃PdIn₁₁ $\chi(T)$ in field of $B = 1$ T applied perpendicular ($B \perp c$) and parallel c axis ($B \parallel c$) has been measured. Both compounds exhibit a weak magnetocrystalline anisotropy. The ratio $\chi^{\parallel c}/\chi^{\perp c}$ determined at $T = 3$ K yields 1.25 for the Pt-compound and 1.2 for the Pd-analogue [14, 17]. Figure 3a and b depicts the resulting inverse susceptibilities $1/\chi(T)$ for Ce₃PtIn₁₁ and for comparison

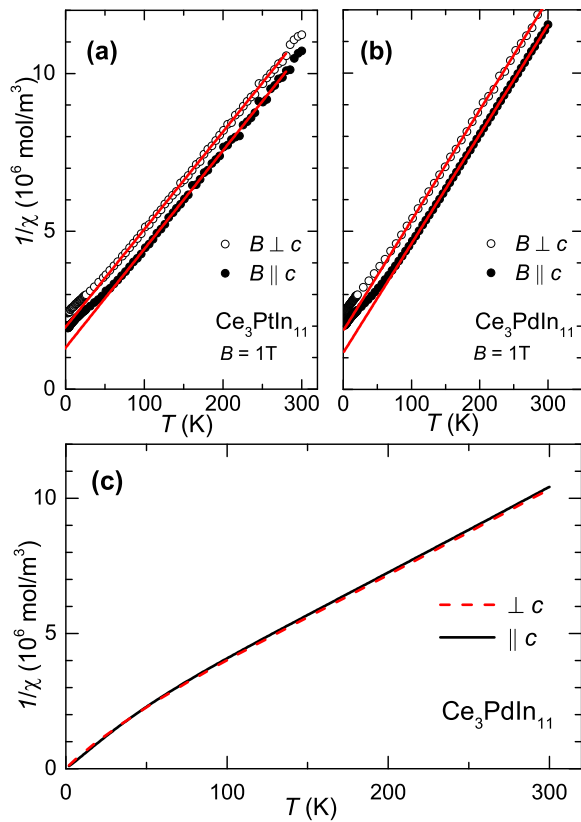


Figure 3. Temperature dependence of the inverse of the susceptibilities $1/\chi(T)$ (a) $\text{Ce}_3\text{PtIn}_{11}$ and (b) $\text{Ce}_3\text{PdIn}_{11}$ [17] for $B = 1$ T applied $\perp c$ (open) and $\parallel c$ (closed symbols). The solid (red) lines are Curie-Weiss fits to the data. (c) $1/\chi(T)$ of $\text{Ce}_3\text{PdIn}_{11}$ from first-principles calculations for $\parallel c$ (solid black line) and $\perp c$ (dashed red line), respectively.

$\text{Ce}_3\text{PdIn}_{11}$ [17], respectively. In higher temperatures $1/\chi(T)$ is fitted by a Curie-Weiss law (solid red lines) with values of the effective moment of $\mu_{\text{eff}} = 2.60\mu_{\text{B}}/\text{Ce}$ for both directions in case of $\text{Ce}_3\text{PtIn}_{11}$ and Weiss temperatures $\theta_p^{\perp c} = -64$ K and $\theta_p^{\parallel c} = -42$ K and $\mu_{\text{eff}} = 2.43\mu_{\text{B}}/\text{Ce}$ and $\theta_p^{\perp c} = -49$ K and $\theta_p^{\parallel c} = -33.5$ K for the Pd-compound. The effective moments are in good agreement with expected Hund's rule value for free Ce^{3+} -ion ($2.54\mu_{\text{B}}$) which indicates that all 3 Ce-ions in the unit cell are in Ce^{3+} -state. This is further supported by theoretical calculations. Figure 3c shows the results of first-principles calculations performed for $\text{Ce}_3\text{PdIn}_{11}$ based on density functional theory [18] from which we obtained the contribution to the susceptibility from each Ce-site separately when field applied along and perpendicular to c -axis. The high temperature $\chi(T)$ values are in qualitative agreement with experimental data and the figure reveals an almost isotropic behavior of $\chi(T)$. More specific, the susceptibility of the Ce1-site exhibits only a marginal magnetocrystalline anisotropy. Surprisingly, the Ce2-site shows a stronger anisotropy. $\chi^{\parallel c}(T)$ increases more upon decreasing temperature with respect to $\chi^{\perp c}(T)$. This increase in anisotropy is the origin of the crossing of $1/\chi^{\perp c}(T)$ and $1/\chi^{\parallel c}(T)$ in Fig. 3c. Note that in our experimental data such crossing has not been observed. A more detailed comparison with the experimental data, however, would require a correct description of the exchange interactions in the paramagnetic region $T > T_1$, including the exact crystal electric field level scheme of $\text{Ce}_3\text{PdIn}_{11}$ which is unknown. We can assume that first principle calculations on $\text{Ce}_3\text{PtIn}_{11}$ will give similar results. In the following we present results of $\text{Ce}_3\text{PtIn}_{11}$ only.

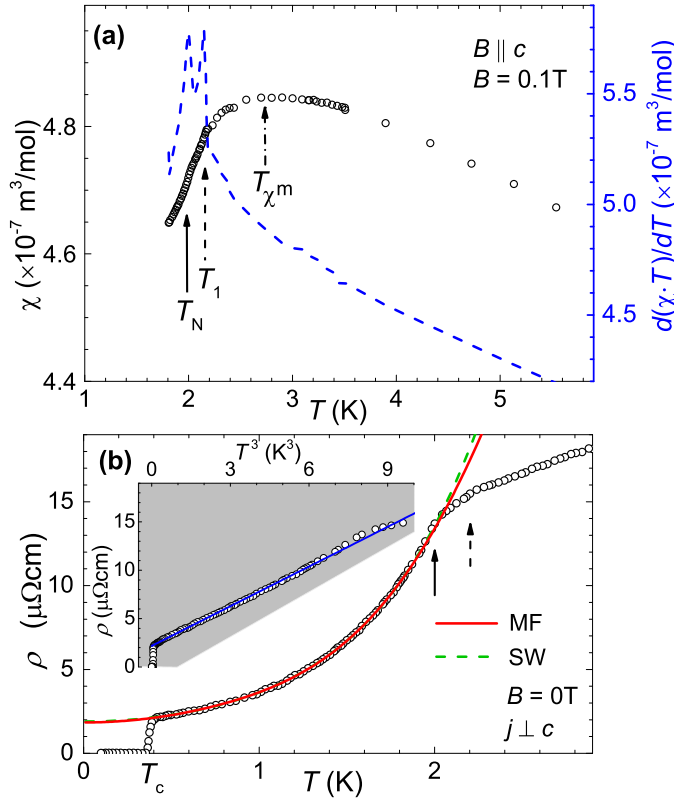


Figure 4. Low temperature susceptibility (χ) and resistivity (ρ) of $\text{Ce}_3\text{PtIn}_{11}$ in greater detail. (a) Left ordinate: χ vs T in field $B = 0.1$ applied $\parallel c$ -axis. Right ordinate: derivative $d(\chi \cdot T)/dT$ vs T in accordance to Ref. [19]. (b) Resistivity in $B = 0$ T and $j \perp c$ (symbols). The lines show the mean field (MF) and spin-wave (SW) fit for $T_c < T < T_N$ (see text). Solid and dashed arrows mark T_N and T_1 , respectively. The inset plots the $\rho(T)$ vs T^3 . The solid blue line is a fit $\rho \propto T^3$.

2.2. Susceptibility and resistivity at low temperatures

Figure 4 displays the ambient pressure susceptibility and transport properties of $\text{Ce}_3\text{PtIn}_{11}$ below 3 K. Two small anomalies can be identified in $\chi^{\parallel c}(T)$ (see Fig. 4a) which appear below a rounded maximum structure with vertex at $T_{\chi^m} = 2.8$ K. In accordance with work of Fisher [19] we attribute this maximum structure due to the presence of short-range magnetic correlations as precursor of a nearby AFM transition. In line with this work, the two anomalies which are inflexion points in $\chi^{\parallel c}(T)$ and appear as maximum in $d(\chi \cdot T)/dT$, hence correspond to T_1 and T_N (Fig. 4a right axis) yielding 2.15 K and 2 K. These values correspond well with those reported from specific heat being $T_1 = 2.2$ K and $T_N = 2$ K, respectively [14]. The antiferromagnetic-type of ordering at T_1 and T_N which we label AFM1 and AFM, is consistent with the observations in Fig. 5. Here we present C/T in field of $B = 3$ T applied along both crystallographic directions. Subtraction of phonon term has been omitted, because we are interested in the effect on the transitions only. For $B \parallel c$ both transitions temperatures shift to lower temperatures as expected in case of AFM ordering (Fig. 5a). Interestingly, along perpendicular direction the upper transition temperature T_1 remains unchanged while T_N decreased slightly being 1.97 K as seen in Fig. 5b. Equivalent has been observed in the Pd-analogue [17]. It suggests that the hard magnetic direction is perpendicular c -axis, which is in sharp contrast to other magnetic members of the $\text{Ce}_n\text{TIn}_{3n+2}$ group of compounds, i.e., CeRhIn_5 and Ce_2RhIn_8 [20]. The question arises whether or not the order-to-order transition at T_N is of first-order type, which then implies a symmetry change of the magnetic order parameter. At present we have no experimental evidence for this in form of, for instance, latent heat. It was pointed out in Ref. [14] that below T_N , C_{el}/T can be described by a second-order mean-field type expression (MF) or in equal matter by a simple spin-wave term (SW) for spin-waves with dispersion $\epsilon(q) \sim q$. The corresponding expected behavior of the resistivity is presented in Fig. 4b. The red solid line is a MF fit, $\rho(T) = \rho_0 + AT^2 + bT[1 + 2T/\Delta]e(-\Delta/T)$. The resulting parameters are

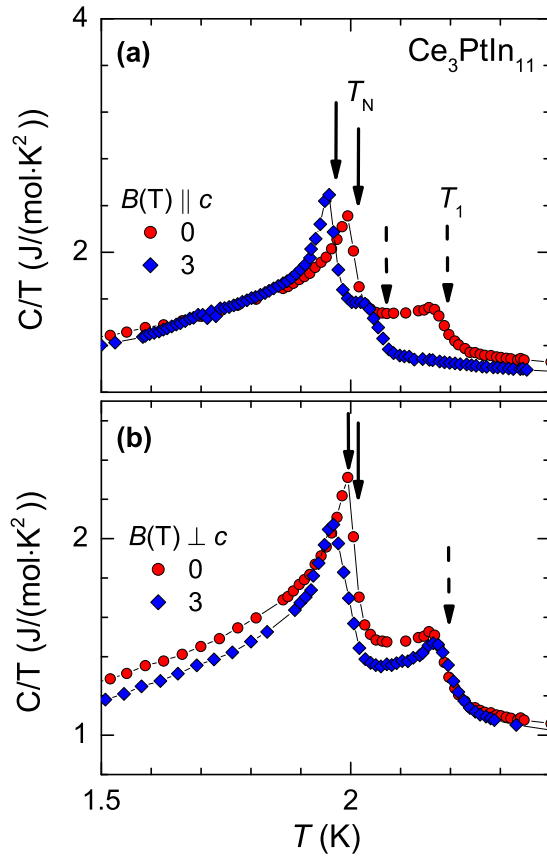


Figure 5. Comparison of the C/T vs T in zero field and in an applied field of 3 T for (a) $B \parallel c$ -axis and (b) $B \perp c$ -axis. Solid (dashed) arrows mark T_N (T_1).

$\rho_0 = 1.84 \mu\Omega\text{cm}$, $A = 1.76 \mu\Omega\text{cm}/\text{K}^2$, $b = 58.43 \mu\Omega\text{cm}/\text{K}$ and the gap $\Delta = 7.35$ K. The dashed green line plots the respective SW expression, $\rho(T) = \rho_0 + AT^2 + BT^5$, where the second term is Fermi liquid (FL) contribution and the third term is due to scattering off magnons. We obtain $A = 1.57 \mu\Omega\text{cm}/\text{K}^2$ and $B = 0.17 \mu\Omega\text{cm}/\text{K}^5$. Note that for both fits the FL contribution is very similar. Moreover, the necessity of the addition T^2 Fermi liquid term suggests that two types of scattering mechanisms are present. We can insert A in the Kadowaki-Woods relation [21] to determine the Sommerfeld coefficient, $\gamma = \sqrt{A/10 \mu\Omega\text{cm} \cdot \text{mol}^2 \cdot \text{K}^2 \cdot \text{J}^{-2}}$, and obtain a value of $\approx 0.4 \text{ J}/(\text{mol} \cdot \text{K}^2)$. It is still unclear whether this empirical relation holds for multi-site compounds. However, it is interesting to note that this value times 3 matches well with the normal state Sommerfeld coefficient from specific heat, $\gamma_n = 1.21 \text{ J}/(\text{mol} \cdot \text{K}^2)$ [14]. Finally, a single T^3 -behavior presented in the inset in Fig. 4c describes the resistivity data with similar quality, but such can only be explained by a more complex type of AFM ordering.

3. Discussion

The increase of T_c upon suppressing the magnetic transition temperatures T_1 and T_N as well as the observed NFL behavior the normal state in close vicinity around the critical pressure $p_c = 1.3$ GPa, strongly points to magnetic quantum fluctuations driving the SC state in $\text{Ce}_3\text{PtIn}_{11}$. The type of QCP is yet unclear. The exponent $n = 0.90 \pm 0.05$ in resistivity at p_c suggest a local moment-type scenario. However, in another compound of the $\text{Ce}_n\text{T}_m\text{In}_{3n+2m}$ layered class of materials, CeRhIn_5 , 2 dimensional-type (2D) spin fluctuations have been reported [22]. Hence, it is not unreasonable to assume that 2D spin fluctuations are present

in $\text{Ce}_3\text{PtIn}_{11}$ too. In that case, the resistivity data can be also explained within an AFM spin-density wave type of QCP. It predicts $R(T) \propto T^{d/z}$, where the dynamical exponent $z = 2$ and d is the effective dimensionality of the critical spin-fluctuation being 2 here [23]. More intriguingly, the pressure independency of the superconducting state for $0 < p < 0.6$ GPa observed in Fig. 2b seems to contradict the relationship between SC and QCP. It can be taken as a clue that SC and magnetism arise from different electrons in this part of the phase diagram. A possible explanation arises from the two Ce-sites (3 Ce atoms/f.u.: $2\text{Ce}_1 + 1\text{Ce}_2$) assuming one sublattice is responsible for magnetism and the other sublattice orders magnetically. Further support for this idea comes from Fig. 4b where the resistivity has been fitted by the sum of a T^2 -Fermi liquid expression and a T^5 -magnon term (green dashed line). In the following, we quantitatively discuss possible implications of this idea with respect to the thermodynamic properties.

The electronic specific heat coefficient γ_n of $\text{Ce}_3\text{PtIn}_{11}$ was reported to be 1.21 ± 0.05 J/(mol·K²) when extrapolated to zero temperature [14]. This large γ_n characterizes $\text{Ce}_3\text{PtIn}_{11}$ as heavy fermion compound. However, since there are two kinds of Ce-ions (Ce_1 and Ce_2) with different site symmetries and neighboring ions, it is quite likely that the two do not contribute equally to the density of states at the Fermi level, i.e., $\gamma_n = 1.21$ J/(mol·K²) is the sum of the individual contributions. The same argument accounts for the magnetic entropy S_{mag} which is depicted in the Fig. 6 (data taken from Ref. [14]). The value S_{mag} deliberated at T_1 equals $0.7R \ln 2$, that is one-fourth of the value expected for the ground state doublet of $\text{Ce}_3\text{PtIn}_{11}$ (three times $R \ln 2$). Thus there is a considerable reduction of the magnetic entropy. We relate the deficiency of $S_{\text{Ce}}(T_1)$ to the presence of the Kondo effect which partially lifts the twofold degeneracy above T_1 . In such case, it can be shown that $S_{\text{mag}}(T_1) = S_K(T_1/T_K)$, where $S_K(T_1/T_K)$ is the Kondo entropy at T_1 . [24] The relation holds if the first excited level $\Delta_{\text{CEF}} \gg k_B T_1$ and $\Delta_{\text{CEF}} \gg k_B T_K$. From earlier discussion we conclude that the former condition is satisfied in $\text{Ce}_3\text{PtIn}_{11}$ [14]. A value around $\Delta_{\text{CEF}} = 60$ K for the first excited state can be expected. Additionally, typical Kondo scales in the $\text{Ce}_n\text{T}_m\text{In}_{3n+2m}$ class of materials ranges between 2 and 10 K suggesting that also the second condition is fulfilled. Further, using the Bethe ansatz for spin-1/2 Kondo model, Desgranges and Schotte calculated the specific heat and corresponding magnetic entropy. [25] By inserting the experimentally found S_{mag} into the above relation we obtain the ratio T_1/T_K . The estimated Kondo temperature for $\text{Ce}_3\text{PtIn}_{11}$ hence yields 12 K, which is an average value, meaning we assume that the Kondo screening is equal for both Ce sites. Figure 6 compares S_{mag} (symbols) with the calculated values of the spin-1/2 Kondo model (S_{Ce} : green dashed line) [25]. The data agree fairly well suggesting that T_{K1} and T_{K2} are close. We observe that below T_1 the experimental data fall under the theoretical curve as expected (entropy is absorbed in the transition). For $T \gg T_1$ the S_{Ce} values exceed the calculated ones which is an indication for the presence of additional contributions to the specific heat, most likely originating from excited CEF levels.

In the extreme case of our scenario, the Ce_1 and Ce_2 sublattices do not interact and only one sublattice orders magnetically while the other sublattice is responsible for the observed HF behavior. Note that this is different from the discussion in Ref. [14] where the HF behavior is not allocated to a specific Ce-sublattice. Ideally, in this particular case the entropy well below the magnetic transition ($T \ll T_1$) is solely related to the second, paramagnetic sublattice. With this argument we can determine the paramagnetic sublattice Kondo temperature T_{K1} . We assume that the Ce_2 -sublattice orders magnetically, which is most plausible because of the CeIn_3 -like environment, and the Ce_1 -sublattice is paramagnetic. The matching of the low- T S_{Ce} data to the spin-1/2 Kondo model reveals a Ce_1 -sublattice Kondo temperature of $T_{K1} \approx 15.4$ K (see Fig. 6 red solid line). With the same model the entropy $S_{\text{Ce}_1}(T)$ of this Ce-sublattice above T_1 can be determined. The difference to the total entropy $\Delta S(T) = S_{\text{mag}}(T) - S_{\text{Ce}_1}(T)$ originates from the Ce_2 -sublattice and hence allows to estimate its Kondo temperature T_{K2} . In order to avoid the influence of magnetic fluctuations from the magnetic transitions as well as contributions arising

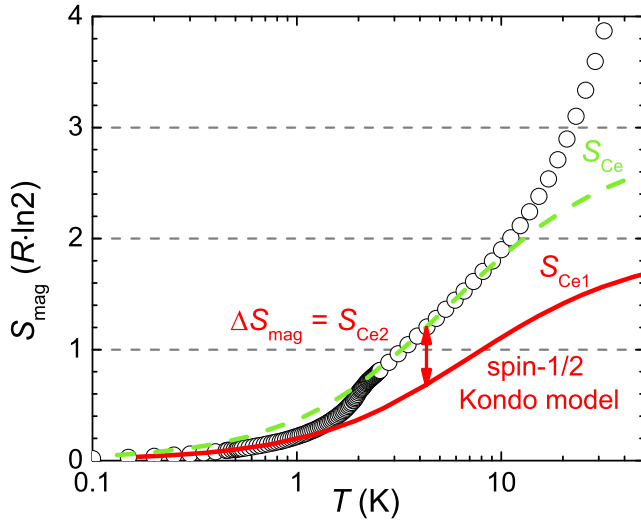


Figure 6. The magnetic entropy S_{mag} of $\text{Ce}_3\text{PtIn}_{11}$ in units of $R \ln 2$ (symbols). The green dashed line marked S_{Ce} shows the theoretical calculation of the spin-1/2 Kondo model [25] in case of $T_K = 12$ K and assuming all Ce-ions contribute equally to S_{mag} . The red curve (solid) depicts the contribution to the entropy arising from the Ce1-sublattice only (see text). The double arrow marks the difference $\Delta S_{\text{mag}} \equiv S_{\text{Ce2}} = S_{\text{mag}} - S_{\text{Ce1}}$ at $T = 4$ K which is the entropy associated with the Ce2-sublattice.

from CEF we determined T_{K2} from a single data point at 4 K. With $S(4\text{K})/R = 0.533$ we obtain $T_{K2} \approx 8$ K [25]. Note that this value is the lower limit of the Ce2-sublattice Kondo temperature. More realistic is a higher T_{K2} because some entropy of the Ce2-sublattice will be present below T_1 . The calculation, however, shows that even in the very extreme case both sublattice Kondo temperatures are of the same order of magnitude and similar to the values obtained in Ref. [14] being $T_{K1} = 15$ K and $T_{K2} = 3$ K, respectively. It promotes the view that in $\text{Ce}_3\text{PdIn}_{11}$ the two sublattice Kondo temperatures are mutually cooperative, meaning the set in of T_{K1} is expected to boost the lower Kondo scale T_{K2} [5].

We can further speculate about the implications of above scenario; with the Ce1-sublattice paramagnetic this would lead to a huge separation (16.891 Å) between adjacent magnetic Ce2-layers. Hence, one would expect a significant magnetically 2D behavior with for instance, a strongly reduced T_N . The observed maximum in $\chi(T)$ can be interpreted as a signature of this 2D-behavior [26]. Here, in a 2D-spin Heisenberg model for a spin-1/2 system the position of the maximum relates to $T_{\chi^m} \approx 0.93|J|$ which for $T_{\chi^m} = 2.8$ K gives $|J| = 3$ K. Any deviation from ideal 2D produces long-range order at $T_N \approx S(S+1)|J|/2 = 1.1$ K. This value is lower than the observed magnetic transition temperature but the model does not include Kondo interactions. These may suppress the fluctuations considerably shifting T_{χ^m} to lower temperatures. Assuming further that the fluctuations are stronger affected by the Kondo interaction than T_N which reduces for similar reasons could explain the discrepancy.

4. Summary and conclusion

A detailed analysis of the ambient pressure susceptibility, resistivity and the magnetic entropy of multi-site heavy fermion compound $\text{Ce}_3\text{PtIn}_{11}$ has been presented. The compound crystallizes in a tetragonal structure and possesses two inequivalent Ce-sites (Ce1 and Ce2). Despite the layered structure $\chi(T)$ exhibits a weak magnetocrystalline anisotropy. First principle calculations attribute this anisotropy to the Ce2-site. We employ an extreme scenario of non-interacting sublattices with the Ce1-sublattice being paramagnetic and solely responsible for heavy fermion behavior and a magnetic Ce2-sublattice. Within this scenario we discuss the magnetic entropy and analyze the data using the spin-1/2 Kondo model of Desgranges and Schotte [25]. The corresponding sublattice Kondo temperatures $T_{K1} = 15.4$ K and $T_{K2} = 8$ K have been retrieved. Although the scenario is a strong simplification of the real property of $\text{Ce}_3\text{PtIn}_{11}$, it in principle explains the fact of two contributions to the resistivity, i.e., a FL and a magnon term as well

as the possibility of existence of 2D magnetic fluctuations. The latter would be important to understand the nature of the QCP at $p_c = 1.3$ GPa. Inelastic neutron experiments are indispensable here. The observation of a pressure independent T_c in a large part of the $p - T$ phase diagram ($p < 0.6$ GPa) opens speculation that the ambient pressure SC state has different origin of Cooper-pairing than the SC-state around p_c . It complies, however, with our scenario. Here the heavy quasiparticles associated with the Ce1-sublattice form the Cooper-pairs. In fact, we may speculate that the gap-symmetry is s -wave. At higher pressures around p_c critical spin fluctuations linked to the suppression of magnetic order in the Ce2-sublattice enhance T_c and the SC state contains a mixture, or overlap, of distinct different SC order parameters resulting from different pairing mechanisms. Although this is still to be investigated, together with the unusual magnetic states and the question of the nature of the QCP makes Ce₃PtIn₁₁ (and Ce₃PdIn₁₁) an exciting compound for future studies.

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