Thermopower Evolution in $\text{Yb}(\text{Rh}_{1-x}\text{Co}_x)_2\text{Si}_2$ Upon 4f Localization

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Abstract

We present thermopower measurements on $\text{Yb}(\text{Rh}_{1-x}\text{Co}_x)_2\text{Si}_2$. Upon cobalt substitution, the Kondo temperature is decreasing and the single large thermopower minimum observed for YbRh_2Si_2 splits into two minima. Simultaneously, the absolute thermopower values are strongly reduced due to a weaker exchange coupling between the 4f and the conduction electron states with increasing x . Pure YbCo_2Si_2 is considered a stable trivalent system. Nevertheless, we still observe two minima in the thermopower indicative of weak residual Kondo scattering. This is in line with results from photoemission spectroscopy revealing a tiny contribution from Yb^{2+} . The value at the high- T minimum in $S(T)$ is found to be proportional to the Sommerfeld coefficient for the whole series. This unexpected finding is discussed in relation to recent measurements of the valence and Fermi surface evolution with temperature.

Keywords Thermopower · Heavy-fermion system · Kondo interaction · Crystal electric field splitting

1 Introduction

Ce- and Yb-based heavy-fermion (HF) systems usually exhibit large absolute values of the thermopower S that have been attributed to the enhanced density of states

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at the Fermi level [1]. The temperature dependence $S(T)$ can be used to estimate the characteristic energy scales of these systems, namely the Kondo scale and the crystal electric field (CEF) splitting of the $4f$ multiplet. Both may generate large contributions to $S(T)$ via scattering processes. The CEF splitting is a result of the local symmetry at the $4f$ ion site: It partially lifts the degeneracy of the free-ion ground-state multiplet, leaving at least Kramers doublets in the case of Ce^{3+} and Yb^{3+} . Typically, the first excited CEF level of Ce and Yb systems lies at an energy $k_B T$ corresponding to $T = 20\text{--}200$ K above the CEF ground state. The thermal population or depopulation of higher CEF levels shows up in many physical properties in the respective temperature range, e.g., as a Schottky anomaly in the specific heat or as a deviation from Curie–Weiss-type behavior in the magnetic susceptibility upon lowering T . The Kondo interaction is an antiferromagnetic interaction between the local $4f$ moments of the Ce and Yb ions and the conduction electron moments. It leads to a delocalization of the $4f$ electron states via hybridization with the conduction electron states (the $4f$ shell becomes ‘unstable’) and to a screening of the $4f$ moments below the Kondo temperature T_K . The presence of Kondo interaction and CEF splitting in a Ce (Yb) system gives rise to two maxima (minima) in the thermopower $S(T)$: one around the Kondo temperature T_K due to scattering on the ground-state doublet [2–4] and one at higher T due to combined Kondo scattering on the ground state and thermally populated CEF levels. For a CEF level at $k_B T_{\text{CEF}}$ above the ground state, this second extremum is expected at about $0.3\text{--}0.6 T_{\text{CEF}}$ [4–6]. A single CEF extremum is usually found also in case of more than one excited CEF level due to the fact that thermal population of excited levels takes place over a considerable temperature range.

Chemical substitution is widely used to induce chemical pressure and to tune the ground-state properties of HF compounds, e.g., with the aim of driving the system to a quantum critical point (QCP) or an intermediate valence (IV) state. This is reached by changing the hybridization strength and the exchange coupling between the $4f$ and conduction electrons and consequently the magnetic coupling constant J upon substitution. The concomitant change of energy scales is reflected in the thermopower mainly as a shift of the maxima or minima as observed, e.g., in $\text{Ce}_{1-x}\text{La}_x\text{Ni}_2\text{Ge}_2$ [7]. If the Kondo and CEF energy scales get close, the two features may even merge into a single one, e.g., for $\text{Ce}(\text{Ni}_{1-x}\text{Pd}_x)_2\text{Si}_2$ [8] or $\text{Yb}(\text{Ni}_x\text{Cu}_{1-x})_2\text{Si}_2$ [9]. On the other hand, if J is strongly reduced, it is expected that the large thermopower values are reduced and the extrema eventually disappear. In this paper, we present an example for this situation, namely $\text{Yb}(\text{Rh}_{1-x}\text{Co}_x)_2\text{Si}_2$. We measured the thermopower of the series in order to trace how $S(T)$ changes upon $4f$ localization and to determine the sensitivity of the thermopower to a tiny residual hybridization as present in YbCo_2Si_2 . These results are also important as a comparison to theoretical calculations of the thermopower for varying exchange coupling.

YbRh_2Si_2 is a well-known and extensively studied HF system, which exhibits non-Fermi-liquid behavior close to an antiferromagnetic QCP [10–12]. Due to its very low magnetic ordering temperature of only 70 mK, it has served as a model system to study quantum criticality in HF systems [13,14]. Cobalt substitution on the rhodium site leads to a very strong reduction in the exchange coupling thus driving the system from the HF state in YbRh_2Si_2 to a stable trivalent state with extremely weak residual hybridization between the $4f$ and conduction electrons in YbCo_2Si_2 . The detailed

state of knowledge on the substitution series $\text{Yb}(\text{Rh}_{1-x}\text{Co}_x)_2\text{Si}_2$ makes it particularly suited to address specific problems. The focus of our study lies on the question how the successive suppression of the exchange coupling and the concomitant localization of the $4f$ moments with increasing Co content is reflected in the thermopower and whether the characteristic features from Kondo scattering and CEF splitting are still visible for YbCo_2Si_2 .

The characteristic Kondo and CEF scales are both significantly lower in YbCo_2Si_2 than in YbRh_2Si_2 : YbRh_2Si_2 has a ground-state Kondo scale T_K of about 25–30 K [15, 16] with a mean Yb valence of 2.93 at low T [17] and higher CEF doublets at 200–290–500 K, respectively [18]. YbCo_2Si_2 , has very weak Kondo interaction with a characteristic temperature of less or about 2 K [19, 20] and excited CEF doublets at 46–150–350 K [21]. Generally, YbCo_2Si_2 is considered a stable trivalent system. However, various experimental probes revealed a tiny residual hybridization between $4f$ and conduction electron states, such as photoemission spectroscopy (PES) [20], resonant X-ray emission spectroscopy, and angle-resolved PES (ARPES) [22]. Likewise, the Kondo-type increase in the electrical resistivity $\rho(T)$ toward low T and the slightly enhanced Sommerfeld coefficient $\gamma_0 = 0.13 \text{ J mol}^{-1} \text{ K}^{-2}$ point to a small Yb^{2+} contribution to the ground state [19].

The full substitution series $\text{Yb}(\text{Rh}_{1-x}\text{Co}_x)_2\text{Si}_2$ has been studied in detail in Ref. [20]. It exhibits a complex magnetic phase diagram with different magnetic phases below 2 K [20, 23, 24]. However, in our investigation we focus on the temperature region above 2 K. Substitution of Rh by Co has two major effects [20]: (1) With increasing Co content the exchange coupling between $4f$ and conduction electrons is strongly reduced. This was demonstrated by PES revealing a gradual lowering of the Yb^{2+} intensity with increasing x . It is confirmed by the concomitant lowering of the Sommerfeld coefficient γ_0 . (2) Simultaneously, the Kondo temperature is reduced. This is evidenced by an increase in the low- T entropy and the shift of the maximum in $\rho(T)$ toward lower T . In fact, above a Co concentration of about 50% the Kondo interaction is no longer the most relevant exchange interaction. Instead, RKKY interaction and the magnetic ordering of almost unscreened Yb^{3+} moments dominate the low- T properties. Following the notation in Ref. [20], we, therefore, use the term T_{4f} instead of T_K for the entropy-derived characteristic temperature.

In this paper, we present thermopower measurements on $\text{Yb}(\text{Rh}_{1-x}\text{Co}_x)_2\text{Si}_2$. As expected, the lowering of T_K with increasing Co concentration leads to the appearance of a low- T minimum in the thermopower, similar to the case of Lu substitution on the Yb place [16]. Simultaneously, the absolute thermopower values are rapidly reduced due to the lowering of the exchange coupling between $4f$ and conduction electrons. The value at the high- T minimum is found to be proportional to the Sommerfeld coefficient. For YbCo_2Si_2 , we still observe the characteristic temperature dependence with two minima in $S(T)$ as a result of a weak residual hybridization between $4f$ and conduction electron states.

2 Experimental Details

We investigated single crystals of $\text{Yb}(\text{Rh}_{1-x}\text{Co}_x)_2\text{Si}_2$ with $0 \leq x \leq 1$ grown by an indium-flux technique. Samples with $x > 0$ stem from the same batches as those characterized in Ref. [20]. The Co content x determined from energy-dispersive X-ray diffraction has a relative error of less than 1 at. % [20]. Data for pure YbRh_2Si_2 ($x = 0$) were taken from Ref. [16].

The thermopower was measured between 2 and 300 K using the thermal transport option of a commercial system (Physical Property Measurement System - PPMS). It applies a relaxation time method with a low-frequency square-wave heat pulse generated by a resistive heater. Two Cernox sensors are utilized for measurement of the temperature difference along the sample. In all measurements, the heat current was applied within the *ab* plane of the plate-like crystals.

Uncertainties in our measurement of $S(T)$ arise from 3 main sources: the temperature gradient along the sample, the thermal voltage, and the sample geometry. The calibration of the Cernox thermometers and the accuracy of thermopower measurements were checked using a Ni standard sample. The thermopower curve could be reproduced within $1 \mu\text{V/K}$. The sample geometry does not enter directly because thermal and electrical gradient are measured at the same contacts. However, the investigated crystals with a typical size of about $4 \times 2 \times 0.1 \text{ mm}^3$ were relatively small for a measurement with the thermal transport option. Repeated measurements on YbRh_2Si_2 showed that the absolute thermopower values varied within about 15%, while the shape of $S(T)$ and in particular the position of the maxima and minima was reproducible [16,25].

3 Results

The thermopower $S(T)$ of all investigated samples of $\text{Yb}(\text{Rh}_{1-x}\text{Co}_x)_2\text{Si}_2$ is shown in Fig. 1. Pure YbRh_2Si_2 exhibits a large negative thermopower with a single minimum around 80 K that was ascribed to combined Kondo scattering from the ground state and higher CEF levels [16,26]. Substitution of Rh by Co leads to a lowering of the absolute thermopower values around that minimum, while the minimum itself and its position are rather stable. A second minimum evolves, that shifts to lower T with increasing Co content. For $x \geq 0.68$, this minimum lies around or below 2 K. Its existence is confirmed by the fact that the thermopower must reach zero in the zero-temperature limit. At highest temperatures, a crossover to positive thermopower values is observed for samples with cobalt substitution. A positive thermopower is also found at intermediate temperatures for $x \geq 0.78$. These observations are probably due to a positive diffusion contribution to the thermopower from normal (light) charge carriers, which is typical for normal metals with hole-like charge carriers [27]. In fact, the non-magnetic reference of YbRh_2Si_2 , LuRh_2Si_2 , exhibits a small, positive thermopower [16].

The overall behavior of $S(T)$ of $\text{Yb}(\text{Rh}_{1-x}\text{Co}_x)_2\text{Si}_2$ can be most simply explained by a lowering of the ground-state Kondo scale T_K accompanied by a weakening of the Kondo interaction upon substitution of Rh by Co and an almost constant characteristic

Fig. 1 Thermopower of $\text{Yb}(\text{Rh}_{1-x}\text{Co}_x)_2\text{Si}_2$. Data for YbRh_2Si_2 ($x = 0$) have been published previously in Ref. [16] (Color figure online)

temperature for the CEF level splitting. In this picture, the increasing separation of the Kondo and CEF energy scales gives rise to the splitting of the single large minimum for YbRh_2Si_2 into two minima for $x \geq 0.195$. The position of the lower minimum is related to T_K , while the high- T minimum is caused by the CEF splitting. With further increase in Co concentration, the low- T minimum shifts to lower T as T_K is decreasing. The concomitant weakening of the Kondo interaction leads to the lowering of the absolute thermopower values, especially around the high-temperature minimum.

This simple picture ignores that the CEF splitting of the two end members YbRh_2Si_2 and YbCo_2Si_2 is rather different. YbRh_2Si_2 has CEF levels at 0–200–290–500 K [18]. Scattering from the three lower levels and probably even from the full multiplet is held responsible for the thermopower minimum at 80 K [16]. By contrast, YbCo_2Si_2 has a much lower overall CEF splitting with levels at 0–46–150–350 K [21], i.e., CEF excitations get relevant already at much lower T than in YbRh_2Si_2 . Therefore, it is rather surprising that the position of the high- T minimum in $S(T)$ does not change with substitution. However, the position of the thermopower minimum at elevated T is not directly related to the CEF splitting. To begin with, several excited levels contribute to the scattering responsible for the thermopower minimum. The respective effects cannot be simply added as, e.g., for the contributions to the specific heat. Moreover, the exact position of the thermopower minimum depends also on other parameters, in particular the position of the $4f$ level with respect to the Fermi level ϵ_{4f} .

The almost constant position of the high- T thermopower minimum throughout the whole substitution series is still rather surprising. It may play a role that both YbRh_2Si_2 and YbCo_2Si_2 have the same Kramers doublet with Γ_7 symmetry as ground state [19,28] and that the leading CEF parameter changes smoothly along the series [20]. These facts are in line with the smooth evolution of the thermopower upon substitution. Moreover, NCA calculations have shown that an increase of ϵ_{4f} as expected for increasing Co concentration is accompanied by a weak shift of the thermopower minimum toward higher T [4]. This may compensate at least partially for the lowering of the overall CEF splitting upon substitution of Rh by Co. Nevertheless, in YbCo_2Si_2 CEF excitations should play a role at much lower T than in YbRh_2Si_2 . Taking a closer look at the thermopower, we find indeed some indication

Fig. 2 Thermopower (left axis) and derivative of the thermopower (right axis) on a logarithmic T scale of $\text{Yb}(\text{Rh}_{1-x}\text{Co}_x)_2\text{Si}_2$ for $x = 0.68, 0.78$, and 1 . The minimum in $S(T)$ is much broader for pure YbCo_2Si_2 than for the two samples with mixed Co/Rh content due to a low-lying CEF level. This differing behavior is also found in the derivatives of the thermopower on a logarithmic T scale. A clear minimum around 30 K is seen for $x = 0.68$ and 0.78 . By contrast, the curve for $x = 1$ exhibits a plateau at intermediate temperatures between two kinks or weak minima indicated by vertical arrows (Color figure online)

for this: Fig. 2 shows the thermopower curves for $x = 0.68$, $x = 0.78$, and $x = 1$ on a larger scale. In addition, we plot the corresponding derivatives $\partial S/\partial \log T$. We observe a significant broadening of the high- T thermopower minimum in YbCo_2Si_2 compared to the samples with mixed Rh/Co content: The high- T minima for $x = 0.68$ and $x = 0.78$ are rather symmetric (on a logarithmic T scale) in contrast to the one for $x = 1$. The corresponding derivatives for $x = 0.68$ and $x = 0.78$ fall almost on top of each other, while the one for pure YbCo_2Si_2 exhibits a broad plateau between 12 and 90 K . Most likely the CEF level at 46 K is responsible for the broadening of the thermopower minimum toward lower T , while the full multiplet is involved in the minimum at higher T .

Figure 3 shows the positions of the minima in $S(T)$ at low ($T_{\min}^{\text{LT}}$) and high ($T_{\min}^{\text{HT}}$) temperature in comparison with other characteristic temperatures taken from Ref. [20]: the temperature of the maximum in the (total) electrical resistivity $T_{\max}(\rho)$ and the temperature T_{4f} determined from specific heat measurements as twice the temperature where the magnetic entropy reaches $0.5R \ln 2$. This temperature is a measure of the magnetic exchange interactions acting on the CEF ground-state doublet and corresponds to T_K in case of dominating Kondo interaction. The value for T_{4f} of YbRh_2Si_2 is taken from Ref. [29]. The error bars for $T_{\min}^{\text{LT}}$ and for $T_{\min}^{\text{HT}}$ of YbCo_2Si_2 have been determined as the temperature range for which S deviates less than the scattering of the data from the value at the minimum. The uncertainty of $T_{\min}^{\text{HT}}$ of all other compositions is comparable to the symbol size. In addition, we also plot the extrapolated position of the low- T thermopower minimum determined for YbRh_2Si_2 from measurements on $\text{Lu}_{1-x}\text{Yb}_x\text{Rh}_2\text{Si}_2$ (open star) [16].

Figure 3 demonstrates again that the low- T minimum in $S(T)$ shifts to lower T with increasing Co concentration, while the position of the high- T minimum is almost independent of x . Two additional observations are made: (1) $T_{\min}^{\text{LT}}$ roughly follows

Fig. 3 The positions of the high- T ($T_{\min}^{\text{HT}}$) and low- T ($T_{\min}^{\text{LT}}$) minima in $S(T)$ for $\text{Yb}(\text{Rh}_{1-x}\text{Co}_x)_2\text{Si}_2$ in comparison with the position of the maximum in $\rho(T)$ and with T_{4f} determined from the entropy as explained in the text (both taken from Ref. [20]). In addition, we plot data for $x = 0$: T_{4f} taken from Ref. [29] and the extrapolated position of the low- T thermopower minimum determined from measurements on $\text{Lu}_{1-x}\text{Yb}_x\text{Rh}_2\text{Si}_2$ (open star) [16]. The lines are guides to the eye (Color figure online)

T_{4f} . That is, the position of the low- T minimum in $S(T)$ is indeed a rough estimate of the Kondo scale in $\text{Yb}(\text{Rh}_{1-x}\text{Co}_x)_2\text{Si}_2$. (2) The maximum in the electrical resistivity shifts to lower temperatures with increasing Co content, similar to the low- T minimum in $S(T)$. However, for $x \leq 0.38$ it is observed at much higher T . This is at least partly due to the fact that the electrical resistivity contains a contribution from electron–phonon scattering. It is most relevant at elevated temperatures and was not subtracted in Ref. [20]. An exact evaluation of this component requires accurate knowledge of the sample and contact geometry, which is difficult for small single crystals. For the magnetic contribution to the electrical resistivity, we expect the maximum at somewhat lower T . Moreover, it appears that the electrical resistivity is less sensitive to CEF excitations in the presence of Kondo scattering than thermopower: While Kondo scattering from ground state and excited CEF levels leads to two separate minima in the thermopower (except for pure YbRh_2Si_2) only a single maximum is observed in the electrical resistivity. It is due to a combination of Kondo scattering and thermal population of CEF levels and found at some intermediate temperature. For $x \geq 0.58$, a weak hump appears in $\rho(T)$ at $T > T_{\max}(\rho)$ that has been related to the CEF splitting [20]. For the same concentration range, resistivity maximum and low- T thermopower minimum get close to each other.

Looking at Fig. 3, one might speculate that the maximum in ρ shifts to even lower T and ‘passes’ the thermopower minimum for higher x . However, measurements of $\rho(T)$ performed concomitantly with our thermopower measurements on the sample with $x = 0.78$ (not shown) suggest a maximum in $\rho(T)$ around 2 K, just below our measurement range and close to the anticipated thermopower minimum. Therefore, we suspect that both features remain close to each other also at higher Co concentration. For $x = 1$ magnetic ordering sets in before a maximum in ρ is reached.

Now we take a look at the lowering of the absolute thermopower values upon increasing Co content x . The effect is most obvious around the high-temperature min-

Fig. 4 **a** Value of the thermopower at the high- T minimum, $S_{\min}^{\text{HT}}$, vs. the Sommerfeld coefficient γ_0 taken from Ref. [20]. We find a proportionality $S_{\min}^{\text{HT}} \propto \gamma_0$. **b** For comparison, we also show $S_{\min}^{\text{HT}}$ vs. T_{4f} . The error bars for $x = 1$ illustrate the reproducibility of the thermopower values at the minimum for repeated measurements (Color figure online)

imum arising from Kondo scattering on the full $4f$ multiplet. This minimum is rapidly suppressed upon substitution. The pure Co system, YbCo_2Si_2 , exhibits only small absolute thermopower values that are similar in magnitude to those of LuRh_2Si_2 [16], the non-magnetic reference to YbRh_2Si_2 . Nevertheless, the minimum around 100 K is still present for YbCo_2Si_2 , which is in line with spectroscopic data revealing a tiny residual hybridization between $4f$ and itinerant states in the material [20,22]. In Fig. 4a, we plot the value at the high-temperature minimum in $S(T)$, $S_{\min}^{\text{HT}}$, vs. the Sommerfeld coefficient γ_0 taken from Ref. [20]. We find a surprisingly good proportionality between these two quantities. For comparison, we also show $S_{\min}^{\text{HT}}$ vs. T_{4f} (cf. Fig. 4b). In this case, the proportionality is less convincing, especially for large x .

Theoretical calculations for the thermopower of Kondo systems with CEF splitting agree to some extent with our observation [4]: In case of an excited level at splitting Δ above the ground state, a maximum (Ce) or minimum (Yb) in the thermopower is predicted at about $0.5 \Delta/k_B$. The absolute values at the extremum depend sensitively on the parameter choice: Both the hybridization strength and the position of the $4f$ level with respect to the Fermi level, ϵ_{4f} , are relevant, whereas a lowering of the hybridization and an increasing ϵ_{4f} lead to a lowering of the absolute thermopower over a large parameter range. The situation in $\text{Yb}(\text{Rh}_{1-x}\text{Co}_x)_2\text{Si}_2$ is more complicated due to the presence of several excited CEF levels. The hybridization strength may vary for different levels and the respective contributions to the thermopower do not simply add, as mentioned above. Even in case of only one excited CEF level, the clear proportionality between $S_{\min}^{\text{HT}}$ and γ_0 observed for $\text{Yb}(\text{Rh}_{1-x}\text{Co}_x)_2\text{Si}_2$ is not predicted by the calculations and rather surprising. In fact, we compare a quantity determined in the zero-temperature limit and in a magnetically ordered state with a value measured around 90 K. Several points may be relevant for this unexpected behavior: (1) Thermopower contributions from phonon drag and from the diffusion of light charge carriers are most probably small up to 100 K considering the small thermopower of LuRh_2Si_2 . Therefore, the thermopower of the whole series up to $T_{\min}^{\text{HT}}$

is dominated by the diffusion contribution from heavy charge carriers. (2) The position of the maximum in $S(T)$ is almost independent of x , i.e., we compare thermopower values taken at practically constant T . (3) Recent ARPES experiments on YbRh_2Si_2 revealed a temperature-independent Fermi surface up to about 100 K [30] and a significant hybridization between f and d states even up to at least 250 K [31]. In this sense, our thermopower minimum around 90 K is still lying in the low- T regime, and the charge carriers that participate in the transport at 90 K are related to those contributing to γ_0 taking into account thermal broadening. (4) Moreover, it has been demonstrated recently for a large number of Yb-based Kondo lattices, among them $\text{Yb}(\text{Rh}_{1-x}\text{Co}_x)_2\text{Si}_2$, that the deviation of the Yb valence ν_{Yb} from 3+ exhibits similar temperature dependencies independent of the respective characteristic ground-state Kondo scale [32]: The T dependence of the change in $(\nu_{\text{Yb}} - 3)$ normalized to the value of $(\nu_{\text{Yb}} - 3)$ at 0 K is almost the same for all materials. This observation is so far not understood. However, it means that the change in the Yb valence between 0 K (where γ_0 is defined) and 90 K (where $S_{\text{min}}^{\text{HT}}$ is determined) normalized to the deviation from 3+ at 0 K is the same for all Co concentrations x . Considering these points, the direct proportionality between $S_{\text{min}}^{\text{HT}}$ and γ_0 appears at least less amazing. The very special situation realized in our case might also explain, why the proportionality is not found in other $4f$ systems. However, we cannot exclude that its observation for $\text{Yb}(\text{Rh}_{1-x}\text{Co}_x)_2\text{Si}_2$ is just an accidental one. Despite this drawback, our measurements confirm nicely the expected reduction in the absolute thermopower values upon lowering of the exchange coupling by cobalt substitution, while the persistence of the two weak minima in YbCo_2Si_2 demonstrates the sensitivity of the thermopower to Kondo scattering.

4 Summary

We presented thermopower data on $\text{Yb}(\text{Rh}_{1-x}\text{Co}_x)_2\text{Si}_2$. The lowering of T_K with increase in Co concentration gives rise to a low- T minimum in the thermopower, while the absolute thermopower values are rapidly reduced due to the lowering of the exchange coupling between $4f$ and conduction electron states. YbCo_2Si_2 still exhibits two weak minima in $S(T)$ indicative of a residual hybridization. We find a linear correlation between the thermopower values at the high- T minimum and the Sommerfeld coefficient. The origin of this proportionality is not clear. However, it may be related to the recent finding of a rather stable FS up to temperatures of at least 100 K in YbRh_2Si_2 and to the similar T dependence of the Yb valence for the whole substitution series.

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