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Permalink

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Journal

physica status solidi (b), 247(3)

ISSN

0370-1972

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Publication Date

2010-03-01

DOI

10.1002/pssb.200983021

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Peer reviewed

The crossed-field and single-field Hall effect in LuRh$_2$Si$_2$

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The Hall effect of LuRh$_2$Si$_2$—the non-magnetic homologue of the heavy-fermion material YbRh$_2$Si$_2$—is studied with two different setups: In the conventional single-field geometry, the field dependence is analyzed in terms of the differential Hall coefficient. Beyond that, the recently developed crossed-field experiment allows to examine the linear-response Hall coefficient as a function of magnetic field. The results reveal the expected analogy between both experiments which corroborates the equivalent findings in YbRh$_2$Si$_2$. This emphasizes the applicability to investigate field-induced quantum critical points with both methods.
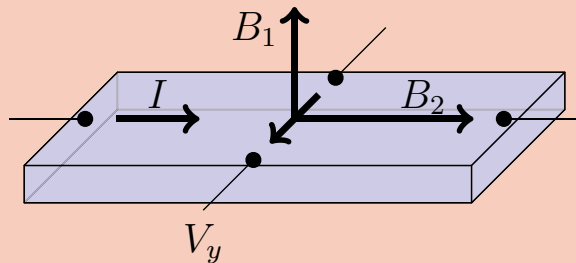
Setup of the crossed-field Hall-effect experiment.

1 Introduction Quantum critical points (QCPs) have recently attracted considerable interest [1]. They may arise via the suppression of a continuous phase transition to zero temperature by a non-thermal control parameter. For the proper description of QCPs in heavy fermion systems, two scenarios are available [2] predicting either a smooth (the spin-density-wave scenario) or a discontinuous (the Kondo-breakdown scenario) evolution of the Fermi surface at the QCP. Therefore, the experimental investigation of the Fermi surface is called for to identify the nature of a particular QCP [3]. This might be realized by using de Haas-van Alphen (dHvA) effect, photoemission spectroscopy or Hall effect. Currently, it is not possible to perform photoemission spectroscopy measurements at the low temperatures needed to track quantum criticality. The dHvA effect was already used to show a change of the Fermi surface in CeRhIn$_5$ [4]. However, dHvA studies are usually limited to high fields, which might in some interesting cases be beyond the QCP. Therefore, the Hall effect is presently the best-suited probe to investigate the Fermi-

surface evolution at the QCP [5]. Particularly, YbRh$_2$Si$_2$ has emerged as a prototypical material in which the control parameter—in this case the magnetic field—can be tuned continuously [6]. Moreover, a crossover of the Hall coefficient was observed which sharpens to an abrupt change at the QCP in the zero temperature limit [7]. This was considered evidence for the Kondo-breakdown scenario. In these experiments the magnetic field has a dual role: On the one hand, it generates the Hall response from which the Hall coefficient is extracted while on the other hand it tunes the ground state of the material through the QCP. This allows for two different setups: In the conventional, single-field experiment one magnetic field simultaneously performs both tasks (see inset of figure 1(a)). To extract the non-linear contributions of the Hall effect arising from the tuning through the QCP one has to examine the differential Hall coefficient. However, this separation is not straightforward as an additional term arises due to the Zeeman effect [7]. Therefore, the crossed-field setup was designed in which two perpendicular fields are utilized to separate the
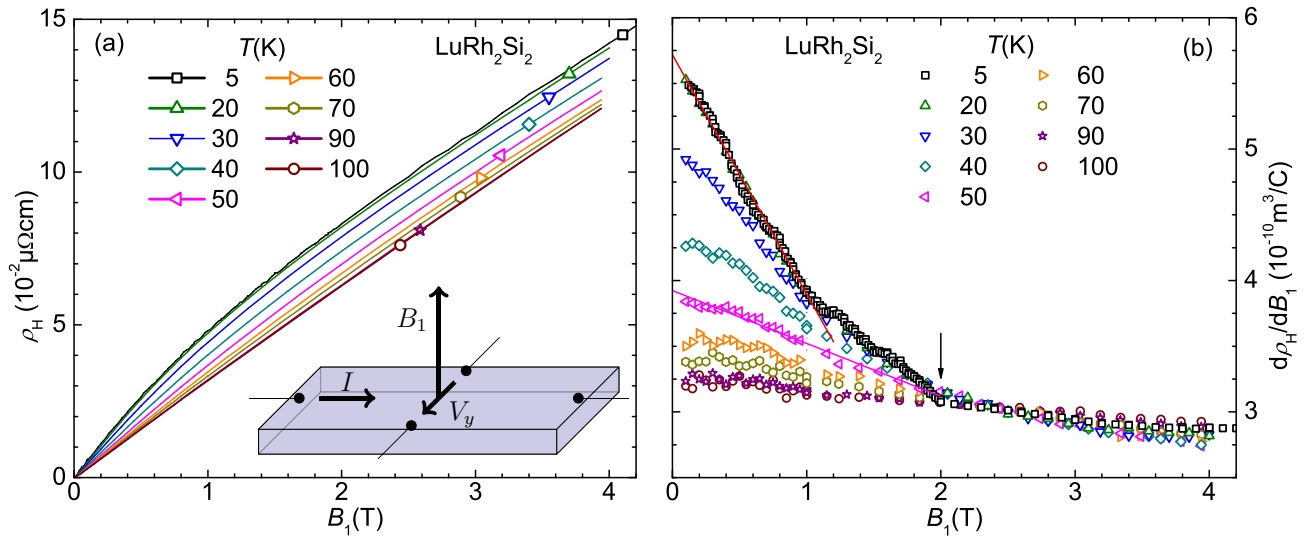
Figure 1 Hall resistivity (a) and differential Hall coefficient (b) of LuRh$_2$Si$_2$ at selected temperatures. Inset sketches the single-field setup. Solid straight lines in (b) are linear fits to the data at 5 K and 50 K for fields below 1 T. Arrow indicates the crossover field.

two effects: One field perpendicular to the current generates the Hall response, whereas the second field is oriented parallel to the current such that it only tunes the ground state (cf. inset of figure 2(a)).

Here, we report Hall-effect measurements on LuRh$_2$Si$_2$ —the non-magnetic homologue to YbRh$_2$Si$_2$—providing a crosscheck for the applicability of the two Hall effect setups.

2 Experimental Setup Single crystals of LuRh$_2$Si$_2$ were grown in an indium flux. Excess flux was removed with hydrochloric acid. The resistivity was measured to ensure In-free samples. The samples were polished to thin platelets with thickness $t < 60\,\mu$m. The current I flowed within the crystallographic ab plane. The magnetic field B_1 was applied along the c axis, generating the Hall voltage within the ab plane. This setup is henceforth called single-field setup and it is sketched in the inset of figure 1(a). The Hall resistivity ρ_{H} was calculated as the antisymmetric part of the transverse voltage V_y: $\rho_{\mathrm{H}} = t/2I * (V_y(B_1) - V_y(-B_1))$ to correct for misalignments of the contacts. Subsequently, the differential Hall coefficient was numerically calculated as $d\rho_{\mathrm{H}}(B_1)/dB_1$ for the single-field experiments. Single-field measurements were performed in a Quantum Design Physical Property Measurements System down to 5 K.

For the so-called crossed-field experiments an additional magnetic field B_2 parallel to the current was used (see inset of figure 2(a) for a sketch of the setup). This field cannot induce a Hall response as it is parallel to the current. In the case of the crossed-field experiment, the linear-response Hall coefficient $R_{\mathrm{H}}(B_2)$ was derived as the slope of linear fits to the Hall resistivity $\rho_{\mathrm{H}}(B_1)|_{B_2}$ at fixed

field B_2 for fields $B_1 \leq 0.4$ T as illustrated in figure 2(a). Crossed-field experiments were conducted in a ^{3}He/^{4}He-dilution refrigerator at temperatures $T \geq 20\,$mK.

In both, the single-field and the crossed-field setup, the Hall response is generated by the magnetic field B_1. A tuning effect to the ground state of the sample on the other hand may arise from both B_1 and B_2. A separation of the two effects may be achieved in the crossed-field setup if the tuning effect of B_1 is much smaller than that of B_2. In the case of YbRh$_2$Si$_2$, the strong magnetic anisotropy was utilized to ensure this condition. For the here presented measurements on LuRh$_2$Si$_2$ this condition will have to be surmised.

3 Results and Discussion
3.1 Single-field The Hall resistivity ρ_{H} measured in single-field setup and the thereof derived differential Hall coefficient $d\rho_{\mathrm{H}}/dB_1$ are presented in figure 1(a) and (b), respectively. Three temperature regimes are observed: In both the low temperature range below 20 K and in the high-temperature range above 70 K, no temperature dependence of the Hall resistivity is observed. Only at intermediate temperatures a crossover between the characteristics of the two limiting cases is seen as will be discussed below.

Within the low-temperature range, the field dependence of the Hall resistivity exhibits two regimes with different slopes: A large initial slope is observed below 1 T, followed by a crossover to linearity for fields above 2 T. In the intermediate temperature range, *i.e.* for $20\,$K $\leq T \leq 70\,$K, the different field regimes evolve differently: The high-field slope remains unchanged throughout the whole temperature range investigated. By contrast, the initial slope is found to decrease as the temperature is in-
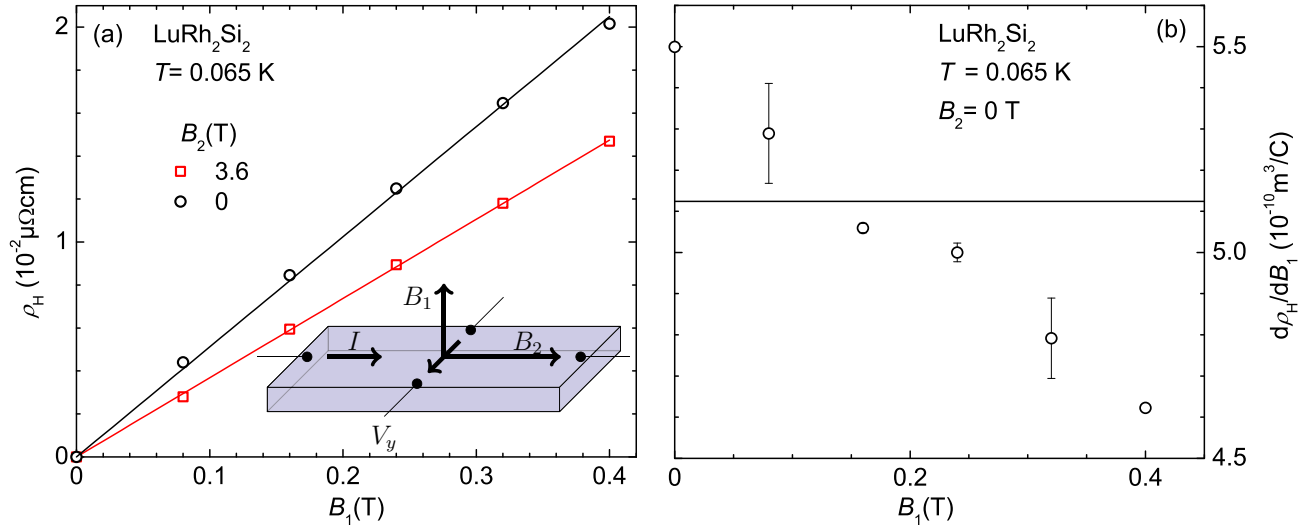
Figure 2 (a) Hall resistivity $\rho_H(B_1)|_{B_2}$ at a fixed temperature of $0.065\,\mathrm{K}$ for two selected fields B_2. Lines are linear fits to the data from which the Hall coefficient as shown in figure 3 was calculated. Inset sketches the crossed-field setup. Differential Hall coefficient of the $B_2 = 0\,\mathrm{T}$ curve of panel (a). Solid line corresponds to linear fit of panel (a) and directly reflects the Hall coefficient extracted (cf. figure 3).

creased. Upon approaching the high-temperature range, the low-field slope merges with that of the high-field regime. As a consequence, the crossover is absent at high temperatures, $T \geq 70\,\mathrm{K}$.

The two field regimes are more obvious in the differential Hall coefficient in figure 1(b): $\mathrm{d}\rho_H/\mathrm{d}B_1$ follows a linear decrease with increasing field B_1 for fields below $1\,\mathrm{T}$ with the highest slope observed in the low temperature range, $T \leq 20\,\mathrm{K}$. At fields above $2\,\mathrm{T}$, the differential Hall coefficient is almost constant at $3 \cdot 10^{-10}\,\mathrm{m}^3/\mathrm{C}$. In the intermediate temperature range, the low-field values and accordingly the slope of the linear field dependence are found to decrease with increasing temperature. As the high-temperature range is approached, the differential Hall coefficient $\mathrm{d}\rho_H/\mathrm{d}B_1$ converges to the high-field value. Consequently, the differential Hall coefficient depicts a unique field dependence without a crossover for temperatures above $70\,\mathrm{K}$. The decrease of the differential Hall coefficient at small fields reflects the decrease of the low-field Hall coefficient as a function of temperature between $20\,\mathrm{K}$ and $70\,\mathrm{K}$ [8].

The crossover field does not change as a function of temperature as clearly revealed by the differential Hall coefficient (figure 1(b)). This allows to rule out a low-field to high-field transition of the Hall effect expected at $\omega_c\tau \approx 1$ with the cyclotron frequency $\omega_c \propto B_1$ of the electron orbits and the scattering time $\tau \propto \rho^{-1}$ [9]. The transition field B_1 where the condition $\omega_c\tau \propto B_1/\rho \approx 1$ is fulfilled should increase with increasing resistivity ρ. The resistivity of $\mathrm{LuRh}_2\mathrm{Si}_2$ rises by a factor of 5 as the temperature is raised from $10\,\mathrm{K}$ to $100\,\mathrm{K}$. Consequently, the robustness of the observed crossover is incompatible with a low-field

to high-field transition. This is supported by an estimate of the transition field via $\omega_c\tau = B_1/(ne\rho_0) \approx 1$ with the residual resistivity $\rho_0 = 1.2\,\mu\Omega\,\mathrm{cm}$, the elementary charge e and the carrier density n from band structure calculations [10] yielding a transition field exceeding $70\,\mathrm{T}$, which is far beyond the accessed field range. One might speculate that the crossover is rather caused by the two-band behavior identified in the temperature dependence of $\mathrm{LuRh}_2\mathrm{Si}_2$ [10] as indicated by the fact that the high-field slope matches the initial slope at high temperatures. However, it remains to be understood why a field of $2\,\mathrm{T}$ has a comparable effect like warming up to $100\,\mathrm{K}$.

3.2 Crossed-field The tuning-field dependence of the Hall coefficient, $R_H(B_2)$, in the crossed-field setup is shown in figure 3. In the considered temperature range, *i.e.* below $1\,\mathrm{K}$, all curves are nearly identical which is a continuation of the temperature independence of the differential Hall coefficient observed in the low temperature range below $20\,\mathrm{K}$ (figure 1(b)). At zero field, a value of $5.2 \cdot 10^{-10}\,\mathrm{m}^3/\mathrm{C}$ is measured while R_H decreases linearly with increasing B_2 for fields up to $3\,\mathrm{T}$ (solid line in figure 3(a)). At higher fields slight deviations of $R_H(B_2)$ towards higher values compared to the low-field linearity are found.

The comparison of the crossed-field results with those of the single-field experiment in figure 3 reveals that both obey a linear decrease at small fields in the low-temperature range. However, the scaling of the field axis of the single-field differential Hall coefficient by a factor of 4 reveals that the crossed-field Hall coefficient exhibits a 4 times smaller slope. Furthermore, the linearity is provided over an almost 4 times larger field range in the crossed-field experiment. This indicates a magnetic anisotropy
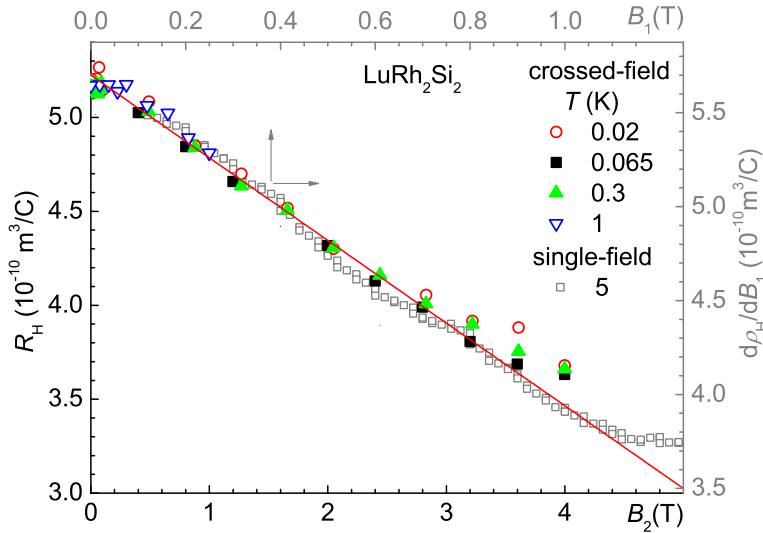
Figure 3 Crossed-field Hall coefficient of LuRh$_2$Si$_2$ as a function of the magnetic field B_2 at selected temperatures (left and bottom axes). The solid line represents a linear fit to all datasets for fields below 3 T. Single-field data at 5 K from figure 1(a) are replotted in gray (right and top scale) with the field axis scaled by $1/4$ and the ordinate shifted by $0.475 \cdot 10^{-10}$ m^3/C accounting for the reduction of R_{H} in the crossed-field experiment (see text).

requiring 4 times larger fields applied within the ab plane (crossed-field experiment) to obtain the same effect like for fields along the c axis (single-field experiment). This anisotropy would naturally explain both the decreased slope and an enlarged field range fulfilling the linearity. The deviations of $R_{\mathrm{H}}(B_2)$ from linearity above 3 T reflect the corresponding behavior of the single-field results at 1 T. The crossover towards constant R_{H} is expected at fields beyond the accessible range of our crossed-field measurements.

We note that the above discussed magnetic anisotropy of LuRh$_2$Si$_2$ is opposite to that of YbRh$_2$Si$_2$. Consequently, the tuning effect of B_1 is not negligible and leads to the slight deviations from linearity observed for the Hall resistivity $\rho_{\mathrm{H}}(B_1)$ presented in figure 2(a). This is more obvious in figure 2(b) as a decreasing differential Hall coefficient upon increasing field B_1. The low-field value is then in good agreement with the results of the single-field experiment (figure 1(b)). Furthermore, figure 2(b) illustrates the systematic deviations of the linear-slope Hall coefficient extracted in the crossed-field measurements compared to the differential Hall coefficient extracted in the single-field experiment: In the crossed-field case, the Hall coefficient was determined as the slope of the linear fits for fields B_1 up to 0.4 T (horizontal line in figure 2(b)) which represents an average over the differential Hall coefficient in this field range (data in figure 2(b)). The decrease of the differential Hall coefficient with increasing field, therefore, causes a reduction of the linear-slope Hall coefficient (crossed-field experiment) (figure 3(a)) with respect to the differential Hall coefficient (figure 1(b)). This reduction is accounted for by a shift of the ordinate in the direct comparison of both experiments in figure 3.

4 Conclusions In summary, we emphasize that the crossed-field and the single-field experiment yield consistent results: The field dependences of the Hall coefficient in both experiments is found to be in good agreement if the field axis of the single-field experiment is scaled by a factor of $1/4$. This scaling arises due to the fact that the tuning-fields are applied along different crystallographic directions for the different experiments strongly indicating a magnetic anisotropy of LuRh$_2$Si$_2$. The anisotropy is likely caused by the actual band structure which displays a pronounced anisotropy as expected for a tetragonal system. Our comprehensive study establishes both the single-field and the crossed-field experiment as a powerful tool to investigate field induced QCPs. In particular, it would be interesting to study an example for the spin-density-wave scenario which might be realized at the field-induced QCP in CeCu$_{5.8}$Au$_{0.2}$ [11].

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