Magnetization Measurements on YbRh$_2$Si$_2$ at Very Low Temperatures

E. Schuberth$^1$, M. Tippmann$^1$, M. Kath$^1$, C. Krellner$^2$, C. Geibel$^2$, T. Westerkamp$^2$, C. Klingner$^2$, and F. Steglich$^2$

$^1$ Walther-Meissner-Institute, D-85748 Garching, Germany
$^2$ MPI for Chemical Physics of Solids, D-01187 Dresden, Germany

E-mail: eschuber@ph.tum.de

Abstract. YbRh$_2$Si$_2$, a heavy fermion compound, is in the center of interest for its unconventional behavior around a quantum critical point (QCP) which can be tuned by a magnetic field. To study the system at the lowest possible temperatures, we have measured the dc magnetization in magnetic fields up to 60 mT and down to 1 mK using an rf SQUID magnetometer. Our fields were high enough to reach the QCP in the $B \parallel (a, b)$ crystal orientation. Both field cooled (fc) and zero field cooled (zfc) data were taken. We found a sharp transition to a low magnetization ground state at 2.2 mK and differences between the fc-zfc traces below 11 mK. In this temperature range down to 2.2 mK an additional increase of the magnetization is seen, just before the final drop sets in. These results will be discussed with respect to the nature of the ground state in low magnetic fields and its relation to the QCP.

1. Introduction
Compounds close to a Quantum Critical Point (QCP) have been in the focus of interest for many years. A QCP marks a continuous phase transition at $T=0$ in the vicinity of which pronounced deviations from the conventional Landau Fermi liquid state have been found. It can be reached, e.g., by suppressing magnetic order by pressure (including chemical pressure through doping) and in some cases by magnetic field. In YbRh$_2$Si$_2$ a weak antiferromagnetic phase was found below 70 mK [1] which can be driven to very low temperatures by a moderate magnetic field which is only 55 mT in the $B \parallel (a, b)$ crystal orientation and about 0.6 T in the $B \perp (a, b)$ direction. This way its QCP can be tuned by small magnetic fields.

The ordered moments in the 70 mK phase are less than one percent of $\mu_{Bohr}$ [2] and large spin fluctuations are left in the magnetic system leaving room for more magnetic interactions and possible transitions. To study the system at the lowest possible temperatures, we have measured the dc magnetization of YbRh$_2$Si$_2$ in magnetic fields up to 60 mT and down to 1 mK using an rf SQUID magnetometer.

2. Experimental
YbRh$_2$Si$_2$ single crystals of excellent quality have been grown in an Indium flux. The first two samples we studied were tiny with dimensions of about $2 \times 1 \times 0.08 \text{ mm}^3$ (\#1) and masses of 2.2 and 0.75 mg, respectively. Their resistivity ratios at 1.9 K were 28 and 27, respectively, which
corresponds to a residual resistance ratio of 150, among the highest values ever obtained for this compound. The data from these two crystals (oriented with $B \parallel (a, b)$) as well as from a third one with much bigger mass (30 mg) were all identical, when scaled for their masses, although they came from different batches and were mounted in different field orientations within the a,b plane.

The experiments were done in our nuclear demagnetization cryostat at the Walther Meissner Institute in Garching. We used a home made dilution refrigerator and a 0.9 mole PrNi$_5$ nuclear demagnetization stage with a final temperature of 0.4 mK. To reach 1 mK it was sufficient to precool the nuclear stage over night in a magnetic field of 2.2 T and to demagnetize it within 3 hours. Temperatures were measured by pulsed NMR on Pt and Cu rods thermally anchored at the nuclear stage. The samples were clamped in a 5N Ag rod screwed to the nuclear stage and extending into the pick-up coil of a conventional flux transformer which transferred the signal into an rf Nb SQUID. Since the electrical conductivity of the samples is high (of the order of 5000 Sm) we have no indication that their temperature deviates from that of the nuclear stage by more than a few tens of µK, at least above the new transition on which we report here.

3. Results

We find a drop of the magnetization below 2.2 mK ($B \parallel (a, b)$ orientation) which is largest for very small magnetic fields, of order of or below 0.1 mT, see Fig.1. The associated phase transition extends up to 23 mT, see Fig.2. Beyond this field it is suppressed to below 800 µK, and we cannot detect it any more. Obviously, below 2.2 mK there exists an ordered state, different from
Figure 2. Phase diagram of YbRh$_2$Si$_2$ as derived from the transitions at low temperatures. The different symbols display data from 3 different samples. The dashed lines mark the kink at 6 mT and show two possible extrapolations for temperatures below 1 mK.

the AF state at higher temperatures. An extrapolation of the new phase boundary to higher fields even leaves the possibility that it could extend all the way up to the QCP, 55 mT where it is definitely suppressed. A kink in this phase boundary around 6 mT is also remarkable.

We further studied the system under different cooling conditions, especially field-cooled (fc) and zero-field-cooled (zfc) states. Field-cooled and zero-field-cooled data start to deviate from each other below 11 mK. The field cooled data increase at first below this temperature and only show a drop of about 30% of their maximum magnetization below 2.2 mK. The zero field cooled data (with compensated earth field) had lowest start values in the "virgin state", i.e., when no other magnetic field was run in the cryostat except the field used for demagnetization. On warming from the lowest temperatures they begin near zero magnetization and are temperature independent below the new transition. On further warming a sharp increase with a peak at 2.2 mK is observed followed by a decrease until at 11 mK the field-cooled trace is met.

In applied fields of a few tenths of mT, the data look quite different (Fig. 3). Here the increase of M below 11 mK is much larger and even the zero-field cooled states do not start at zero but at some finite value $M_0$ which increases with field.

The drop at 2.2 mK is preceded by an uprise of $M(T)$ towards lower temperatures which can be fit with Curie law ($\Theta_{Weiss} = 0$) and with small magnetic moments of the order of 0.02 $\mu_{Bohr}$.

4. Discussion and Conclusion
Our results show that below 2.2 mK there is a new (ground) state of the heavy fermion compound YbRh$_2$Si$_2$ which is characterized by a pronounced drop of the magnetization. The
Figure 3. Magnetization of YbRh$_2$Si$_2$ in a series where the zero-field-cooled state was reached by demagnetization and the warm-up curve (lower trace) was followed by the field-cooled state in 0.1 mT. In lower magnetic fields the differences between fc and zfc states are even bigger. As in Fig. 1, zero magnetization is defined as $M(T_{\infty})$.

reduction is largest in magnetic fields below 100 $\mu$T. It is unlikely that this marks just a change in the antiferromagnetic order as there exists a large hysteresis between the zfc and the fc magnetization. On the other hand, the 2.2 mK transition is preceded by an upturn of $M$ towards lower temperatures which involves moments of similar magnitude as those which order below 70 mK [2]. Whether parts of the latter become free again at low temperatures which would indicate a weakened RKKY interaction, or whether new moments are showing up is yet unclear. We can exclude nuclear moments from the parameters of the Curie fit. Anyway, moments of a few percent of $\mu_{\text{Bohr}}$ are consistent with a suppression field of 30 mT for the new state. Although the origin of this new (ground) state of YbRh$_2$Si$_2$ is unknown so far, we have shown that the magnetism of this unique compound reveals a very rich phase diagram down to the lowest accessible temperatures.

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6. References
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