Angle-dependent electron spin resonance of YbRh$_2$Si$_2$ measured with planar microwave resonators and in-situ rotation

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Abstract

We present a new experimental approach to investigate the magnetic properties of the anisotropic heavy-fermion system YbRh$_2$Si$_2$ as a function of crystallographic orientation. Angle-dependent electron spin resonance (ESR) measurements are performed at a low temperature of 1.6 K and at an ESR frequency of 4.4 GHz utilizing a superconducting planar microwave resonator in a $^4$He-cryostat in combination with in-situ sample rotation. The obtained ESR $g$-factor of YbRh$_2$Si$_2$ as a function of the crystallographic angle is consistent with results of previous measurements using conventional ESR spectrometers at higher frequencies and fields. Perspectives to implement this experimental approach into a dilution refrigerator and to reach the magnetically ordered phase of YbRh$_2$Si$_2$ are discussed.

Keywords: heavy fermion, YbRh$_2$Si$_2$, anisotropy, electron spin resonance, microwave chip

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1. Introduction

The tetragonal heavy-fermion metal YbRh$_2$Si$_2$ shows pronounced magnetic anisotropy [1 2 3] and is an intensively studied model system for quantum criticality [4]. It exhibits antiferromagnetic order at temperatures below 70 mK and in-plane magnetic fields below 60 mT [3]. Its Néel temperature $T_N$ decreases with increasing field down to a quantum-critical point (with $T_N = 0$) induced by the external magnetic field of 60 mT (within the tetragonal $ab$-plane) or 660 mT (along the $c$-axis) [4 5]. Due to the presence of the quantum-critical point, the system shows pronounced non-Fermi-liquid properties [4 5]. As the antiferromagnetic state underlies the quantum-critical nature of YbRh$_2$Si$_2$, the details of the magnetic order are highly interesting in context of the peculiar properties of YbRh$_2$Si$_2$. However, due to major experimental challenges in commonly used methods such as neutron scattering [6], the magnetically ordered phase of YbRh$_2$Si$_2$ is not sufficiently investigated and understood yet. ESR could be a promising alternative method to elucidate details of the antiferromagnetic order, but conventional ESR spectrometers are limited in both temperature and magnetic field to energies much higher than the magnetic order of YbRh$_2$Si$_2$. Multiple ESR investigations on YbRh$_2$Si$_2$ have been performed [7 8 9 10 11], but they could not reach the mK temperature range that is required to address the regimes that are key to understanding the quantum-critical nature of YbRh$_2$Si$_2$. As the ESR response of YbRh$_2$Si$_2$ is a very interesting topic on its own [7] and as its possible relation to quantum criticality is not settled [12 13], ESR studies close to the quantum-critical point are also desired from a fundamental perspective of magnetic resonance. Planar microwave resonators can be used as ESR probes [14 15 16] for YbRh$_2$Si$_2$ to overcome the limitations of conventional ESR spectrometers: as such resonators [17 18 19 20] can be operated with a multimode measurement technique [14 21 22 23], they can simultaneously address multiple ESR frequencies and thus multiple magnetic magnetic fields in the phase diagram [14], and they can also be employed at mK temperatures [23 17 24 25 26 27].
2. Experiment

We performed microwave measurements on YbRh$_2$Si$_2$ inside a $^4$He-cryostat equipped with a superconducting electromagnet. The arrangement of microwave probe and sample is shown in Fig. 1(a): the flat YbRh$_2$Si$_2$ sample is kept at a small distance parallel to the microwave resonator chip (see Fig. 1(b)) and is mounted (see Fig. 1(c)) via a brass stamp to a commercial piezoelectric rotator [28], and thus can be rotated within the sample plane. The microwave chip with meander-type superconducting Nb resonator (see Fig. 1(b)) is installed in a brass box and connected via coaxial cables to the vector network analyzer for microwave transmission measurements.

In this arrangement of resonator and sample, precise ESR measurements on high-quality YbRh$_2$Si$_2$ single crystals [29] require sample dimensions of order one millimeter for the relevant surface, namely the $ac$-plane (or another plane that includes the $c$-axis). While such sample dimensions can readily be obtained for the $ab$-plane, growing a YbRh$_2$Si$_2$ crystal with millimeter dimension along the $c$-direction is challenging. This work is the first demonstration of an ESR measurement that combines a planar resonator and a YbRh$_2$Si$_2$ sample in $ac$-plane.
3. Results

Fig. 2 shows a typical transmission spectrum of the microwave resonator, and it clearly features sharp resonances of the first four harmonics with roughly equidistant resonance frequencies around 1.5, 2.9, 4.4, and 5.8 GHz. From such spectra, we determine the quality factor $Q_n$ of the $n$-th mode through a Lorentzian fit of the resonance peak in the transmission signal. $Q_n$ is defined as the ratio between resonance frequency $f_n$ and bandwidth (resonance width at half maximum) $\Delta f_n$:

$$Q_n = \frac{f_n}{\Delta f_n} \quad (1)$$

The transmission in the frequency range close to a resonance peak is measured as a function of magnetic field, and a pronounced change of the resonance peak can be observed. Thus we obtain the field dependence of the quality factor, which is shown in Fig. 3 for different sample orientations. $Q$ is generally decreasing with increasing field due to field-induced losses in the superconducting resonator [17, 30, 31, 32, 33] and due to the microwave charge response of the heavy
Figure 3: ESR in YbRh$_2$Si$_2$ at 1.6 K and 4.4 GHz. The quality factor $Q$ as a function of external magnetic field and normalized to the zero-field value, shown for several angles $\Theta$ between the external field and the symmetry axis $c$ of the crystal, exhibits a pronounced minimum at the ESR field $B_0$.

fermions $^{14, 26, 34, 35, 36}$, and additionally it has a dip at the resonance magnetic field $B_0$, indicating ESR absorption and thus the spin response of YbRh$_2$Si$_2$. As can be seen in Fig. 3, the resonance field $B_0$ increases if the angle $\Theta$ between the external magnetic field and the crystallographic $c$-axis is decreased from 90° ($ab$-plane) towards the $c$-axis.

After subtraction of the background the resonance magnetic field $B_0$ and ESR linewidth $\Delta B$ can be obtained through a fit of an inverse Dysonian function, which describes the absorbed power $P(B)$ at ESR in dependence of the magnetic field strength $^{37}$

$$P(B) = \frac{\Delta B + \alpha(B - B_0)}{4(B - B_0)^2 + \Delta B^2} + \frac{\Delta B - \alpha(B + B_0)}{4(B + B_0)^2 + \Delta B^2}. \quad (2)$$

The obtained $B_0$ is inserted into the ESR resonance condition to determine the ESR $g$-factor (with Planck constant $\hbar$ and Bohr magneton $\mu_B$):

$$g = \frac{\hbar \nu}{B_0 \mu_B}. \quad (3)$$
Figure 4 shows the ESR $g$-factor of the angle-dependent measurement at 1.6 K and 4.4 GHz between $\Theta = 104^\circ$ and $\Theta = 36^\circ$. There is a maximum around $\Theta = 90^\circ$, and $g$ continuously decreases when the crystal is rotated such that the orientation of the magnetic field moves from the $ab$-plane towards the $c$-axis. This evolution is consistent with data obtained previously at higher temperatures (5 K) and higher field with a conventional X-band spectrometer [8], which are shown as stars in Fig. 4 for comparison. The slightly higher absolute values of $g$ for the X-band measurement can be explained by the well-established decrease of the $g$-factor with decreasing temperature [7, 14].

4. Conclusions

The presented results prove that planar resonators are sensitive enough for ESR measurements of YbRh$_2$Si$_2$ for magnetic-field directions within the $ac$-plane. We performed the first ESR measurement using a superconducting coplanar microwave resonator in combination with in-situ sample rotation, and this
also includes the lowest temperature of any angle-dependent ESR measurement on YbRh$_2$Si$_2$ so far. Our results agree well with former results obtained by conventional techniques at higher frequencies and higher temperatures.

To investigate the magnetically ordered phase of YbRh$_2$Si$_2$ below 70 mK and 60 mT, this experimental approach for angle-dependent ESR measurements can now be implemented inside a dilution refrigerator. There the technical situation features additional challenges due to the smaller available cooling power (to be considered for the wiring and electrical power needed to drive the rotator). On the other hand, the generally increasing ESR intensity upon cooling promises strong signal for such an experiment.

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