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Angle-dependent electron spin resonance of $YbRh_2Si_2$ 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 $YbRh_2Si_2$ 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 $YbRh_2Si_2$ 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 $YbRh_2Si_2$ are discussed.

1. Introduction

The tetragonal heavy-fermion metal $YbRh_2Si_2$ shows pronounced magnetic anisotropy [1–3] 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 $YbRh_2Si_2$, the details of the magnetic order are highly interesting in context of the peculiar properties of $YbRh_2Si_2$. However, due to major experimental challenges in commonly used methods such as neutron scattering [6], the magnetically ordered phase of $YbRh_2Si_2$ 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 $YbRh_2Si_2$. Multiple ESR investigations on $YbRh_2Si_2$ have been performed [7–11], 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 $YbRh_2Si_2$. As the ESR response of $YbRh_2Si_2$ 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 [14–16] for $YbRh_2Si_2$ to overcome the limitations of conventional ESR spectrometers: as such resonators [17–20] can be operated with a multimode measurement technique [14,21–23], they can simultaneously address multiple ESR frequencies and thus multiple magnetic fields in the phase diagram [14], and they can also be employed at mK temperatures [23,17,24–27].

2. Experiment

We performed microwave measurements on $YbRh_2Si_2$ inside a ^{4}He-cryostat equipped with a superconducting electromagnet. The arrangement of microwave probe and sample is shown in Fig. 1a): the flat $YbRh_2Si_2$ sample is kept at a small distance parallel to the microwave resonator chip (see Fig. 1a)) and is mounted (see Fig. 1c)) 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

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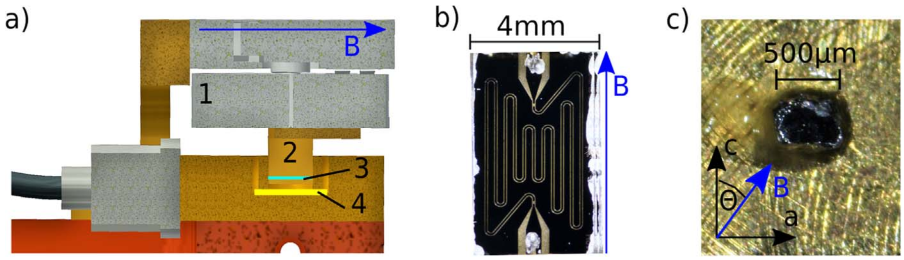

Fig. 1. Probe and sample mounting for ESR measurements and orientation of static magnetic field B. a) Construction inside the sample box with piezoelectric rotator (1), brass stamp (2), sample (3) and coplanar microwave resonator (4). b) Superconducting Nb resonator on sapphire substrate, with fundamental frequency of 1.5 GHz. c) Sample of $YbRh_2Si_2$ on a brass stamp, with angle Θ indicating the orientation of magnetic field B with respect to crystallographic axes a and c.

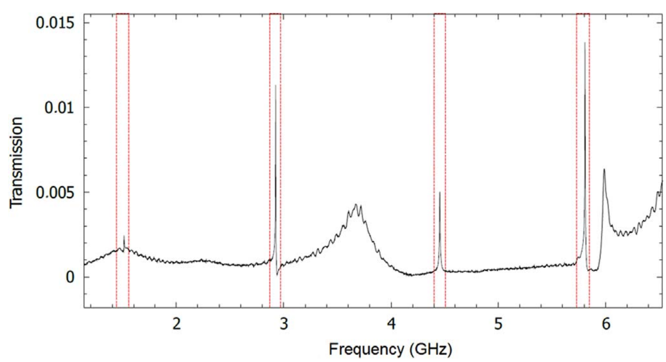

Fig. 2. Transmission spectrum of the superconducting Nb resonator with equidistant resonance peaks. Frequency ranges that are used to investigate the resonances are indicated. Additional features in the transmission might be due to box modes of the resonator mounting.

superconducting Nb resonator (see Fig. 1b)) 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 $YbRh_2Si_2$ 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 $YbRh_2Si_2$ 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 $YbRh_2Si_2$ 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) Δf_n:

$$Q_n = \frac{f_n}{\Delta f_n} \tag{1}$$

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 [17,30–33] and due to the microwave charge response of the heavy fermions [14,26,34–36], and additionally it has a dip at the resonance magnetic field B_0, indicating ESR absorption and thus the spin response of $YbRh_2Si_2$. As can be seen in Fig. 3, the resonance field B_0 increases if the angle Θ between the external magnetic field and the crystallographic c-axis is decreased from 90° (ab-plane) towards the c-axis.

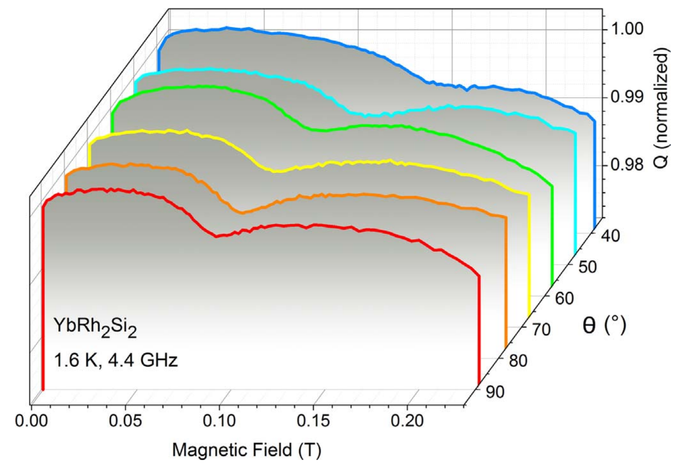

Fig. 3. ESR in $YbRh_2Si_2$ at 1.6 K and 4.4 GHz. The quality factor Q as a function of external magnetic field and normalized to the zero-field value, shown for several angles Θ between the external field and the symmetry axis c of the crystal, exhibits a pronounced minimum at the ESR field B_0.

After subtraction of the background the resonance magnetic field B_0 and ESR line width ΔB 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]

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

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

$$g = \frac{h\nu}{B_0 \mu_B} \tag{3}$$

Fig. 4 shows the ESR g-factor of the angle-dependent measurement at 1.6 K and 4.4 GHz between $\Theta = 104°$ and $\Theta = 36°$. There is a maximum around $\Theta = 90°$, 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].