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Magnetic order and superconductivity in single-crystalline $CeCu_2Si_2$

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Abstract

Zero-field μSR measurements have been performed on $CeCu_2Si_2$ single crystals. Antiferromagnetic order shows in an initial rapid damping of the μ^+ polarization. In a single crystal exhibiting antiferromagnetic order and superconductivity, there exists clear evidence of phase separation of both phenomena with a first order transition from antiferromagnetism at higher temperature to superconductivity at low temperature.

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1. Introduction

The heavy-fermion compound $CeCu_2Si_2$ is located very close to a quantum phase transition at the disappearance of antiferromagnetic order. Hence, the ground state can either be antiferromagnetic order, called A-phase, sometimes coexisting with superconductivity, or A/S-type where superconductivity is thought to expel the A-phase, or only S(uperconducting). The availability of large high-quality single crystals of $CeCu_2Si_2$ with well defined thermodynamic properties renewed the interest in this prototypical heavy-fermion compound. Especially these crystals now allow us to perform microscopic measurements such as neutron scattering and muon-spin rotation/relaxation. The experiments are aimed to clarify the interplay between antiferromagnetism and superconductivity in the vicinity of the quantum phase transition in $CeCu_2Si_2$.

Recently we could identify the antiferromagnetic order by neutron diffraction on an A-type single crystal [1]. Below $T_N \approx 0.8\,K$ antiferromagnetic superstructure peaks have been detected with a propagation vector $\tau \approx$ (0.215 0.215 0.530) and an ordered moment $\sim 0.1\mu_B$. Further measurements on an A/S-type single crystal with $T_N \approx 700\,mK$ and a superconducting $T_c \approx 500\,mK$ yielded resolution limited magnetic Bragg peaks indicating the long-range nature of the magnetic order in this crystal. Extensive measurements, performed on the A/S-crystal also in magnetic fields, revealed that in this crystal antiferromagnetism and superconductivity seem to exclude each other on a microscopic scale. The magnetic Bragg peaks disappear at $T \approx 400\,mK$, i.e. $\approx 100\,mK$ below the onset of superconductivity [2]. However, the important questions remained open, if phase separation or coexistence of antiferromagnetism and superconductivity occurs around the antiferromagnetic-to-superconducting transition. This is quite important since it might have implications for the superconducting order parameter.

Muon-spin rotation/relaxation (μSR) is an ideal microscopic tool for probing the local environment around the muon stopping site and can detect even small local magnetic fields. Due to the different relaxation of the muon spin in magnetically ordered and paramagnetic environment, new light can be shed on the interplay between antiferromagnetism and superconductivity in $CeCu_2Si_2$. Several μSR experiments on $CeCu_2Si_2$ were performed in the past. Initial experiments gave first

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evidence for magnetic order in $CeCu_2Si_2$ [4], while later work began to study the interplay between superconductivity and antiferromagnetism [5–9] or focused on peculiarities of the A-phase magnetism [10]. However, all previous experiments were restricted to polycrystalline samples.

2. Experimental details

We performed zero-field (ZF) and transverse-field (TF) μSR measurements on A-, A/S-, and S-type $CeCu_2Si_2$ single crystals at temperatures below $T = 1\,K$ using the low temperature spectrometer LTF at the Swiss Muon Source, Paul Scherrer Institute in Villigen, Switzerland. In order to compare the results and relate the different methods the A- and A/S-crystals for the μSR measurements were identical to those used before in the neutron scattering experiments [1–3]. The S-type crystal shows a superconducting transition at $T_c \approx 600\,mK$ and no indications of antiferromagnetic order. This crystal is the only one which is platelike with dimensions of approximately $6 \times 5 \times 1\,mm^3$, while A- and A/S-type crystals are bulk samples with overall dimensions of a few millimeters. All crystals were mounted with the [1 1 0] axis parallel to the incident μ^+ beam which was longitudinally polarized (LP). Magnetic fields could be applied in $[1\bar{1}0]$ direction. 50 G TF measurements were used to determine the detector efficiency and for asymmetry corrections.

3. Results

We first present the results in the A-type $CeCu_2Si_2$ single crystals which can serve as a reference for the A/S-crystal. Fig. 1 displays the time dependence of the normalized polarization $G(t)$ in the A-type crystal at different temperatures in zero field. A rapid depolarizing component in $G(t)$ is detected below the ordering temperature $T_N \approx 850\,mK$ followed by a large tail. Just above the Néel temperature the μSR signal is only weakly damped. To analyze the data, the polarization $G(t)$ in the antiferromagnetic state has been fitted by a sum of a fast Gaussian damped signal with a depolarization rate Δ_m and a slow exponential depolarization with rate λ_m,

$$G_m(t) = \tfrac{2}{3}\exp\left(-\tfrac{1}{2}\Delta_m^2 t^2\right) + \tfrac{1}{3}\exp(-\lambda_m t).$$

Fits with $G_m(t)$ describe the data quite accurately as shown by solid lines in Fig. 1. The important parameter in $G_m(t)$ is the depolarization rate Δ_m which should reflect the order parameter of the incommensurate antiferromagnetic order. The temperature dependence of Δ_m is shown in Fig. 2. Δ_m vanishes at $T = 850\,mK$ and saturates below $T = 300\,mK$. This behavior is in agreement with thermodynamic measurements and neutron diffraction [1] revealing $T_N \approx 850\,mK$ and a magnetic Bragg intensity being constant at low temperatures [1]. In this A-type sample no indication of superconductivity has been found by μSR. However, very recent measurements of the electrical resistivity on this crystal yielded filamentary superconductivity below $\approx 450\,mK$. Bulk superconductivity can be ruled out due to the absence of an anomaly in the specific heat [11].

The most interesting sample is the A/S-crystal since here the interplay of superconductivity and antiferromagnetism can be studied. In contrast to the A-type crystal which fully orders magnetically and can therefore be described by $G_m(t)$, the depolarization of the A/S-crystal cannot be described by just one component. One has to introduce in addition a depolarizing component accounting for the paramagnetic (superconducting) volume. Hence, the polarization $G(t)$ has the form

$$G(t) = a_m G_m(t) + a_{pm} G_{pm}(t)$$

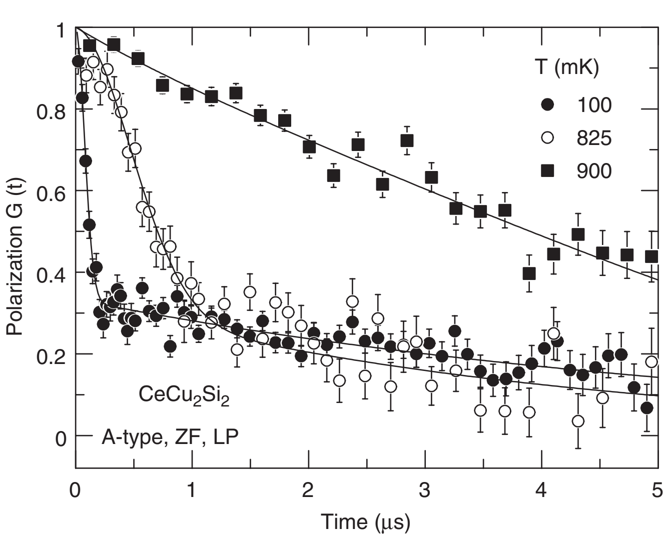

Fig. 1. Time dependence of the normalized muon polarization $G(t)$ in A-type $CeCu_2Si_2$ at different temperatures in zero field. Solid lines are fits to the data (see text).

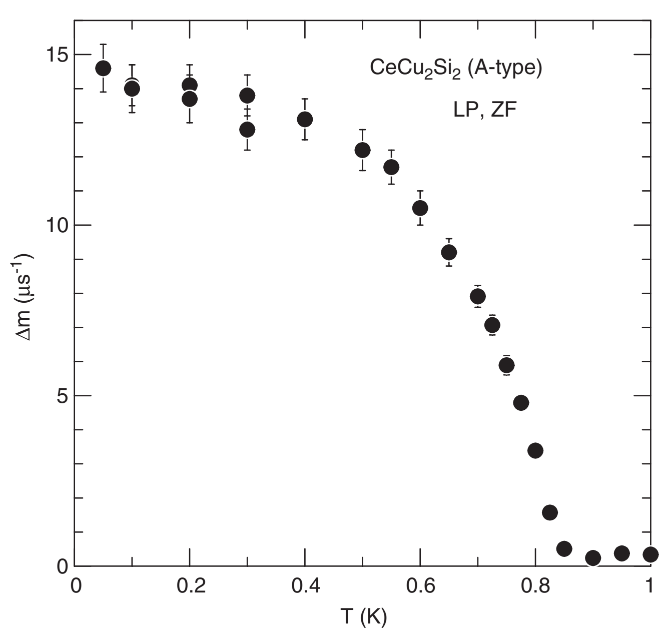

Fig. 2. Depolarization rate Δ_m of the μ^+ polarization versus temperature T in A-type $CeCu_2Si_2$ in zero field and longitudinal polarization.