μSR and low-temperature antiferromagnetism in the ordered non-Fermi-liquid compound $YbRh_2Si_2$

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Abstract

Muon spin relaxation experiments have been carried out at low temperatures in the non-Fermi-liquid heavy-fermion compound $YbRh_2Si_2$, to study antiferromagnetism in the vicinity of the quantum critical point $T = 0$, $H \approx 600$ Oe. The zero-field muon relaxation rate is found to be independent of temperature down to 100 mK, but increases substantially below ∼70 mK, indicative of the onset of static magnetism. The estimated internal field at a muon stopping site is ∼2 Oe, which suggests a very small ordered moment ($\mu_{\rm ord} \approx 10^{-3}$–$10^{-2}$ μ_B).

Key words: Heavy-fermion compounds; $YbRh_2Si_2$; μSR; non-Fermi liquids; quantum criticality.

$YbRh_2Si_2$ crystallizes in the tetragonal $ThCr_2Si_2$ structure. Thermodynamic and transport measurements [1,2] indicate a quantum critical point (QCP) at $T = 0$, $H_{ab} \approx 600$ Oe. The resistivity ρ and specific heat C follow the characteristic non-Fermi-liquid (NFL) forms $\Delta\rho = \rho(T) - \rho(0) \propto T$ and $C_{\rm el}/T \propto -\ln T$ over more than a decade in temperature [1]. Anomalies in the zero-field ac susceptibility and resistivity around 70 mK indicate an antiferromagnetic (AFM) transition, which can be suppressed by a small magnetic field of $H_c \sim 600$ Oe. For $H > H_c$ NFL behavior in $YbRh_2Si_2$ is suppressed and Landau Fermi-liquid behavior is recovered. A recent NMR study [3] ($H > 1.5$ kOe) revealed Korringa behavior ($1/T_1T =$ const.) below a crossover temperature which decreases with decreasing field down to ∼50 mK at 1.5 kOe.

In order to identify the character of the 70-mK anomalies and to characterize spin-fluctuations in this system, we have carried out muon spin relaxation (μSR) measurements on $YbRh_2Si_2$. The μSR technique gives unique information on local magnetic properties, especially in low fields. Positive-muon (μ^+) μSR experiments were carried out on $YbRh_2Si_2$ at the LTF facility of the Paul Scherrer Institute, Switzerland. A full report of this work, which will be published elsewhere [4], discusses the dynamic spin susceptibility in the low-temperature state, the muon stopping site, and the static susceptibility inhomogeneity in more detail.

Figure 1 shows the time dependence of the zero-field muon polarization $G(t)$ at 400 mK and 16 mK.

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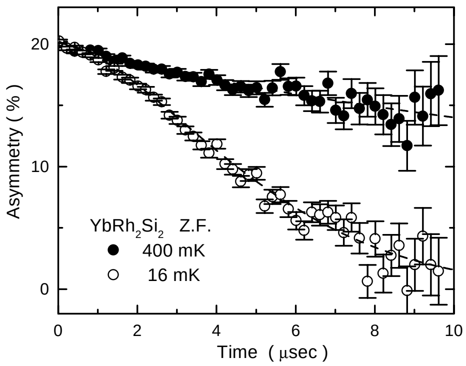

Fig. 1. Zero-field μ^+SR spectra in $YbRh_2Si_2$ at 400 mK and 16 mK. Dotted lines are fits to the power exponential form $G(t) = \exp[-(\Lambda t)^\gamma]$.

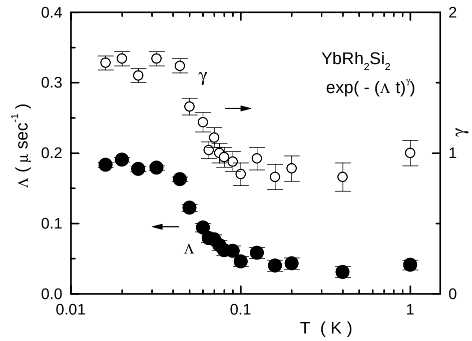

Fig. 2. T dependence of the zero-field μ^+SR relaxation rate Λ (solid circles) and exponent γ (open circles) in $YbRh_2Si_2$ from fits of zero-field μSR relaxation data to the power exponential form $G(t) = \exp[-(\Lambda t)^\gamma]$.

The shape of $G(t)$ at 400 mK is essentially exponential, indicative of dynamic (spin-lattice) relaxation, but at 16 mK has changed to approximately Gaussian with an increased relaxation rate. A Gaussian form is characteristic of the initial behavior of static Kubo-Toyabe (K-T) relaxation [5] due to μ^+ local fields from the onset of AFM order. The depolarization rate at 16 mK is too slow for the K-T recovery $G(t\to\infty) = 1/3$ to be observed within the time window of the experiment. It should be noted that the amplitude of $G(t)$ at 16 mK is the full asymmetry, which shows that the magnetic order occurs over the entire sample. Thus the magnetic order is an intrinsic bulk effect and does not originate from a spurious impurity phase.

To describe the change of $G(t)$, one must fit the μSR asymmetry data to an appropriate function. We have chosen the ‘power exponential’ form $G(t) = \exp[-(\Lambda t)^\gamma]$ to parameterize the experimental data, where Λ is a generalized relaxation rate and the exponent γ interpolates between exponential ($\gamma = 1$) and Gaussian ($\gamma = 2$) limits. We employ this fitting formula for convenience, but its parameters give a crude indication of the behavior of the relaxation, i.e., whether the relaxation is dynamic (exponential), static (Gaussian), or an intermediate behavior.

The parameters Λ and γ are plotted versus temperature in Fig. 2. Both parameters are independent of temperature from 0.1 K to 1 K, and increase below 70 mK. The exponential relaxation ($\gamma \approx 1$) found above 100 mK is quite in contrast to the K-T behavior expected when the relaxation rate is solely due to dipolar fields from nearly static nuclear moments. An exponential relaxation function suggests dynamic relaxation in this temperature range, as discussed elsewhere [4], although the value $\Lambda \approx 0.041\ \mu s^{-1}$ is of the order of the K-T (Gaussian) relaxation rate expected from the nuclear dipolar field in $YbRh_2Si_2$. Both Λ and γ begin to increase substantially below 70 mK, and level off below 40 mK. The increase of the exponent γ suggests a crossover from dynamic to nearly static K-T relaxation in the AFM state at low temperatures. The low-temperature value $\gamma \approx 1.6$ is less than 2, however, which indicates that the relaxation function is nearly but not quite Gaussian. This suggests that dynamic relaxation coexists with dominant static relaxation (quasistatic regime).

The width ΔH of the μ^+ field distribution in the AFM state can be estimated from the increase $\Delta\Lambda$ in the μ^+ relaxation rate: $\Delta\Lambda = \gamma_\mu \Delta H$, where γ_μ is the μ^+ gyromagnetic ratio. With $\Delta\Lambda \approx 0.15\ \mu s^{-1}$ we obtain $\Delta H \approx 2$ Oe. This yields a rough estimate for the magnitude of the ordered moment of $\mu_{\rm ord} \approx 10^{-3}$–$10^{-2}\ \mu_B$ using the hyperfine field at a plausible μ^+ stopping site [4]. The presence of dynamical relaxation at low temperatures was also shown from longitudinal-field decoupling experiments. The detailed nature of the dynamics will be discussed elsewhere [4,6].

In conclusion, muon spin relaxation studies show that static magnetism, indicative of magnetic order, sets in below 70 mK in $YbRh_2Si_2$. The static magnetism occurs over the entire sample, with an ordered moment in the range 10^{-3}–$10^{-2}\ \mu_B$.

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References

[1] O. Trovarelli *et al.*, Phys. Rev. Lett. **85** (2000) 626.

[2] P. Gegenwart *et al.*, Phys. Rev. Lett., to be published.

[3] K. Ishida *et al.*, Phys. Rev. Lett., to be published.

[4] K. Ishida *et al.*, unpublished.

[5] R. S. Hayano *et al.*, Phys. Rev. B **20** (1979) 850.

[6] K.Ishida *et al.*, Physica B, to be published.