Spin dynamics in a structurally ordered non-Fermi liquid compound: YbRh$_2$Si$_2$

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Abstract

Muon spin relaxation ($\mu$SR) experiments have been carried out at low temperatures in the non-Fermi-liquid heavy-fermion compound YbRh$_2$Si$_2$. The longitudinal-field $\mu$SR relaxation function is exponential, indicative that the dynamic spin fluctuations are homogeneous. The relaxation rate $1/T_1$ varies with applied field as $H^{-y}$, $y = 1.0 \pm 0.1$, which implies a scaling law of the form $\chi''(\omega) \propto \omega^{-y} f(\omega/T)$, $\lim_{x \to 0} f(x) = x$ for the dynamic spin susceptibility.

Key words: Non-Fermi liquids, quantum criticality, heavy-fermion compounds, YbRh$_2$Si$_2$.

Non-Fermi liquid (NFL) behavior and quantum critical (QC) phenomena in strongly correlated electron systems are among the most intensively studied subjects in condensed matter physics [1]. NFL behavior is observed in a number of f-electron systems as pronounced deviations from conventional Landau

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Fermi-liquid properties. These include anomalous temperature dependences of the electrical resistivity $\Delta \rho = \rho(T) - \rho(T=0) \propto T^\alpha$, $1 \lesssim \alpha < 2$ and the f-electron specific heat coefficient $(C_{el}/T \propto -\ln T)$ [2,3]. This contrasts with the Fermi-liquid behavior seen in ordinary metals ($\Delta \rho \propto T^2$, $C_{el}/T = \text{const.}$). One mechanism for NFL behavior invokes a quantum critical point (QCP), which is attained by varying a control parameter such as doping, pressure, or magnetic field [2].

Microscopic techniques such as $\mu$SR are powerful tools with which to investigate QC magnetic fluctuations. NMR and $\mu$SR experiments on the NFL alloys UCu$_{5-x}$Pd$_x$, $x = 1.0$ and $1.5$, have revealed strongly inhomogeneous spin fluctuations and glassy dynamics; the $\mu$SR results suggest a quantum spin-glass state near the QCP [4] with extremely slow fluctuations, i.e., thermally-excited fluctuations with strong spectral weight at very low frequencies. Thus disorder may strongly influence the spin fluctuation behavior, so that it is important to determine whether or not low-frequency fluctuations associated with a QCP are present in ordered stoichiometric compounds.

The NFL compound YbRh$_2$Si$_2$ appears to be a suitable system for the study of such “clean” NFL physics. YbRh$_2$Si$_2$ appears to be located in the vicinity of a QCP from a number of bulk measurements [5]; resistivity and specific heat measurements at low temperatures show $\Delta \rho \propto T$ and $C_{el}/T \propto -\ln T$ over a temperature range of more than a decade. The NFL behavior is suppressed by the application of an external magnetic field, and Fermi-liquid behavior is recovered. Low-field ac susceptibility measurements show an anomaly suggestive of a magnetic phase transition around 70 mK that is suppressed by small magnetic field of $\sim 500$ Oe. These results suggest that YbRh$_2$Si$_2$ is quite close to a QCP, but undergoes a phase transition at very low temperatures and magnetic fields.

In order to investigate the 70-mK anomaly and the character of spin fluctuations at zero and weak magnetic fields, we have carried out muon spin relaxation experiments on YbRh$_2$Si$_2$ at the LTF facility of the Paul Scherrer Institute, Switzerland. A full report of this work, which will be published elsewhere [6], discusses in more detail questions of static magnetism in the low-temperature state in YbRh$_2$Si$_2$, the muon stopping site, and static susceptibility inhomogeneity.

Figure 1 shows the relaxation function $G(t)$ for the muon decay asymmetry in YbRh$_2$Si$_2$ at $T = 20$ mK for longitudinal fields $H = 0, 11, 28,$ and 100 Oe. At zero field the data can be fit to a static Kubo-Toyabe (K-T) relaxation function [7] corresponding to a random distribution of static $\mu^+$ local fields with rms width $\approx 2$ Oe. As discussed elsewhere [6,8], we attribute these static fields to weak ordered Yb moments ($10^{-3} - 10^{-2}$ $\mu_B$) in the antiferromagnetic state (Néel temperature $T_N = 70$ mK), since the K-T rate is much larger.
than expected from nuclear dipolar fields and sets in only below $T_N$. The relaxation data for nonzero applied field can be fit to an exponential relaxation function $G(t) = A \exp(-t/T_1)$. An applied field of 11 Oe is more than five times larger than the estimated field at the muon site due to static Yb-moment magnetism [6], and therefore is large enough to decouple this static field. Thus the relaxation observed for $H \gtrsim 10$ Oe is dynamic. Therefore the field dependence of $1/T_1$ is not due to decoupling, but instead suggests a significant frequency dependence to the local-field fluctuation spectrum at the low muon frequencies.

It is important to note that the observed exponential form is evidence that the relaxation rate $1/T_1$ is substantially uniform throughout the sample, since the signature of inhomogeneity in $1/T_1$ is a sub-exponential or “stretched” exponential relaxation function [4]. The muon relaxation is therefore probing spin fluctuations in a structurally ordered non-Fermi liquid.

Figure 2 shows the dependence of $1/T_1$ on longitudinal field at $T = 20$ mK. The zero-field rate given by the arrow is the static K-T value obtained from the fit shown in Fig. 1. The relaxation rate shows a weak field dependence for magnetic fields less than 10 Oe but varies more strongly, as $H^{-y}$, $y = 1.0 \pm 0.1$, for higher fields.

In the motional narrowing limit $1/T_1$ is related to the spin autocorrelation...
Fig. 2. Longitudinal field dependence of LF-μSR relaxation rate $1/T_1$ in YbRh$_2$Si$_2$, $T = 20$ mK. Arrow: zero-field static K-T rate from fit of Fig. 1. The muon decay lifetime limits accuracy for $1/T_1 \lesssim 0.01 \mu s^{-1}$.

The observed frequency dependence of $1/T_1$ is therefore consistent with a scaling law of the form

$$\chi''(\omega, T) \propto \omega^{-y} f(\omega/T), \quad (3)$$

provided that $f(x) \to x$ as $x \to 0$. This scaling would then leave $1/T_1(\omega, T)$ independent of temperature, in rough agreement with the observed weak $(-\ln T)$ dependence at $H = 19$ Oe (not shown) [6]. For $\chi''(\omega)$ of the form of Eq. (3) this gives $q(t) \propto t^{-1+y}$ at long times [9]. Thus $q(t)$ varies slowly with $t$, i.e., the low-temperature spin fluctuations are very long lived.

The exponential behavior of the relaxation function in the present μSR experiments indicates that YbRh$_2$Si$_2$ is an ordered stoichiometric compound. Thus
disorder-driven theories \[10,11\] seem to be ruled out, although these have been considered as promising scenarios for NFL behavior in disordered heavy-fermion materials. Our results strongly suggest that YbRh$_2$Si$_2$ is a compound in which NFL behavior is induced by homogeneous critical spin fluctuations.

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