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Evidence for a Two Component Magnetic Response in UPt$_3$

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The magnetic response of the heavy fermion superconductor UPt$_3$ has been investigated on a microscopic scale by muon Knight shift studies. Two distinct and isotropic Knight shifts have been found for the field in the basal plane. While the volume fractions associated with the two Knight shifts are approximately equal at low and high temperatures, they show a dramatic and opposite temperature dependence around $T_N$. Our results are independent on the precise muon localization site. We conclude that UPt$_3$ is characterized by a two component magnetic response.

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The hexagonal heavy fermion superconductor UPt$_3$ is attracting much interest because it has been established as an unconventional superconductor as seen by the existence of three distinct superconducting phases in the magnetic field-temperature plane [1,2]. In zero field the two superconducting phase transitions occur at $\sim 0.475$ K and $\sim 0.520$ K. It is usually thought that this complex phase diagram arises from the lifting of the degeneracy of a multicomponent superconducting order parameter.

The most popular candidate for such a symmetry-breaking field is the short range antiferromagnetic order characterized by a Néel temperature of $T_N = 6$ K and an extremely small ordered magnetic moment [0.02 (1) $\mu_B$/U-atom in the limit $T \rightarrow 0$ K] oriented along the $a^*$ axis ($= b$ axis). The magnetic order has been observed only by neutron [3] and magnetic x-ray [4] diffractions.

Nuclear magnetic resonance [5] and zero-field muon spin relaxation [6] measurements as well as macroscopic studies have failed to prove the existence of static antiferromagnetic order on high quality samples [7]. Here we present transverse high-field muon spin rotation ($\mu$SR) data which present anomalies around $T_N$. Moreover, they show that UPt$_3$ is characterized by a two component magnetic response at least up to 115 K.

In the transverse $\mu$SR measurements [8], polarized muons are implanted into a sample where their spins $S_\mu$ ($S_\mu = 1/2$) precess in the local magnetic field $B_{loc}$ until they decay. The sample is polarized by a magnetic field $B_{ext}$ applied perpendicularly to $S_\mu$ ($t = 0$). $S_\mu$ ($t$) is monitored through the decay positron. By collecting several million positrons, one can readily obtain an accurate value for the field at the muon site(s).

We present results for three samples. Two samples have been grown in Grenoble. Each consists of crystals glued on a silver backing plate and put together to form a disk. They differ by the orientation of the crystal axes relative to the normal to the sample plane: either the $a^*$ or $c$ axis is parallel to that direction. Measurements have therefore been carried out either with $B_{ext}$ parallel to $a^*$ or $c$. The third sample has been prepared in Amsterdam. It is a cube of $5 \times 5 \times 5$ mm$^3$ which has been glued to a thin silver rod. The measurements on this sample have been done only with $B_{ext} || a$. The Grenoble samples have already been used for zero-field [6] and transverse low-field [9] $\mu$SR measurements. Their high quality is demonstrated by the splitting of the two zero-field superconducting transitions as seen by specific heat [9] and the low residual resistivities which are among the lowest ever reported [10]. The residual resistivities of the Amsterdam sample are a factor of ~3 higher. Nevertheless, the double superconducting transition is clearly resolved in the specific heat.

The experiments have been performed at the LTF and GPS spectrometers of the Paul Scherrer Institute $\mu$SR facility. $B_{ext}$ has been applied along the muon beam direction and a spin rotator has been used to flip $S_\mu$ ($t = 0$) away from the muon momentum. Most of the data have been recorded with $B_{ext} = 0.6$ T. Below 10 K, fields of magnitude 1.5, 2, and 2.3 T have also been used. A high statistic measurement has been done at 50 K with $B_{ext} = 0.45$ T. This spectrum, together with the 0.6 T ones, have been recorded with an electrostatic kicker device which ensures that only one muon at a time is present in the sample [11]. This device enhances the signal to noise ratio and extends the time window to $\sim 18 \mu$s.

We expect to observe a sum of oscillating signals, each corresponding to a given type of muon environment. An extra signal originating from muons stopped in the sample surroundings, basically a silver backing plate, is also expected.

In Fig. 1 we present two Fourier transforms of spectra. Two lines from the sample are clearly detected for
components have been analyzed with the polarization function $P_X(t)$ written as the sum of three components:

$$aP_X(t) = a_\exp \cos(\omega_{\exp} t) \exp(-\Delta^2 t^2/2) + a_S \cos(\omega_S t) \exp(-\lambda t) + a_{bg} \cos(\omega_{bg} t) \exp(-\lambda_{bg} t).$$  \hspace{1cm} (1)$$

The first two components describe the $\mu$SR signal from the sample and the third accounts for the muons stopped in the background. The subscripts F and S refer to the first and second components, respectively. $a_\exp$ is the initial asymmetry of component $\alpha$ oscillating at the pulsation frequency $\omega_\alpha = 2\pi \nu_\mu,\alpha = \gamma_\mu B_{loc,\alpha}$ where $\nu_\mu,\alpha$ is the precession frequency of component $\alpha$ and $\gamma_\mu$ the muon gyromagnetic ratio. $a_s$ is proportional to the fraction of muons experiencing field $B_{loc,\alpha}$. The envelope of the first component is best fitted by a Gaussian function, while the envelope of the second component is better described by an exponential damping. We stress that the measured temperature dependences of the two initial asymmetries and frequencies are not influenced by the choice of the envelope functions.

$\Delta$ is approximately independent of the temperature and amounts to $\approx 0.55$ MHz at high field. It roughly scales with $B_{ext}$. $\lambda$ is independent of $B_{ext}$ and is equal to $\lambda \approx 0.14$ MHz at the lowest temperature. It decreases when the temperature is increased and becomes so small above 4 K that it can be fixed to zero. The values of the damping rates may reflect only partially the intrinsic properties of UPt$_3$ because of the field inhomogeneity due to the demagnetization field. However, $\Delta$ and $\lambda$ are remarkably small, indicating that the magnetic inhomogeneity detected for the two components is small.

In Fig. 3 we display the temperature dependence of the two initial asymmetries and the associated relative frequency shifts, $K_{\mu}$. These plots concern the spectra taken with $B_{ext} \perp c$ and for $T \leq 14.7$ K. $K_{\mu}$, which is the local magnetic susceptibility at the muon site, is usually called the Knight shift. It is deduced from the measured relative frequency shift, $K_{\exp}$, after correcting for the Lorentz and demagnetization fields. $K_{\exp}$ is defined by

$$K_{\exp} = B_{ext} \cdot (B_{loc} - B_{ext}^2)/B_{loc}^2.\hspace{1cm} (2)$$

We have determined $B_{loc}$ with a gaussmeter or through the pulsation frequency of the background: $B_{ext} = \omega_{bg}/\gamma_\mu$. Since the Knight shift of Ag is very small [12], this is a very good approximation.

The results of Fig. 3 show that the Grenoble and Amsterdam samples yield consistent results. Since the measurements have been done with either $B_{ext} \parallel a^*$ or $B_{ext} \parallel c$, we conclude that the $\mu$SR response is isotropic in the basal plane. The data display also two remarkable features.

First, the frequency splitting between the two lines is relatively large at low $T$, decreases rapidly as $T$ increases up to $\sim 6$ K, and exhibits a shallow minimum around 10 K. It increases again for higher temperatures (not shown). This explains the possibility of observing the beating between the two oscillating components at 50 K as shown in Fig. 2. Only the F shift has a strong temperature dependence below 6 K, while the S shift is practically.

FIG. 1. Two Fourier transforms of spectra recorded at 2.6 K with $B_{ext} = 2.3$ T. $B_{ext}$ is parallel to either the $a^*$ or $c$ axis. The background signal was intentionally enlarged in this measurement to evidence the difference between the applied field and the field at the muon site. This was achieved by fixing a 10-mm-diameter Ag mask on the sample, resulting in a reduced effective sample size. The line at $\sim 303.6$ MHz originates from the Ag mask.

$B_{ext} \parallel a^*$. A symmetric single line is observed for $B_{ext} \parallel c$. For the whole temperature range investigated two components are found for $B_{ext} \perp c$ and only a single component is detected for $B_{ext} \parallel c$. In Fig. 2 we present a time spectrum which clearly shows the existence of the two components far into the paramagnetic regime for $B_{ext} \perp c$.

We first discuss the spectra recorded for $B_{ext} \perp c$ which have been analyzed with the polarization function $P_X(t)$ written as the sum of three components:

FIG. 2. A spectrum recorded at 50 K in a field of 0.45 T applied perpendicular to the $c$ axis of UPt$_3$ and presented in a frame rotating at a precession frequency of 60 MHz. This experiment was performed in a setup designed to get the smallest possible background ($\omega_{bg} \approx 0.017$). The solid line is a fit to a sum of three oscillating components: two from the sample and one from the background. The reduced asymmetry observed on the plot around 10 $\mu$s, which is too small to be explained by a beating of the UPt$_3$ and background signals, reflects the beating of the two signals originating from UPt$_3$. 

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The spectra recorded with $B_{\text{ext}} \parallel c$ have been analyzed with a formula similar to Eq. (1) with $a_S = 0$. The precession frequency varies smoothly in temperature. The Gaussian damping rate scales again with $B_{\text{ext}}$ (~0.42 MHz at 1.5 T) and is essentially temperature independent up to ~30 K above which temperature it drops smoothly to very small values.

In Fig. 4 we present the $K_\mu$ data recorded for $B_{\text{ext}} = 0.6$ T with $1.7 \leq T \leq 115$ K as a function of the bulk susceptibility $\chi_B$. This is a so-called Clogston-Jaccarino plot, the temperature is an implicit parameter. The bulk susceptibilities for the different orientations have been measured on the Grenoble samples and are similar to those of Ref. [15]. Classically, we should find $K_\mu$ scaling with the susceptibility. This is approximately observed for $B_{\text{ext}} \parallel c$ but not for $B_{\text{ext}} \perp c$. In addition, as already pointed out when discussing $K_\mu(T)$, the Clogston-Jaccarino plots clearly show that while the F Knight shift provides a signature of $T_N$, such a signature is absent for the S Knight shift. The data of Fig. 4 suggest that $K_\mu$ passes smoothly through $T_N$ for $B_{\text{ext}} \parallel c$, although the almost constant value of $\chi_B(T)$ at low temperature does not allow for a definite statement.

We now discuss the muon diffusion properties and localization site in UPt$_3$. The shape of the zero-field depolarization and the constant value of the related damping rate show that the muons are static and occupy the same site in the muon time scale, at least below 30 K [6]. Our transverse field measurements suggest that, in fact, the muon is diffusing only above 115 K because the frequency splitting collapses above that temperature (not shown). Since we focus on the properties of UPt$_3$ itself, we consider only the data for which the muon

![Graph](image.png)

**FIG. 3.** Temperature dependence of the initial asymmetries and Knight shifts $K_\mu$ with $B_{\text{ext}}$ perpendicular to the $c$ axis. The data are for $0.05 \leq T \leq 15$ K, three field intensities and two samples denoted as Grenoble and Amsterdam. $K_\mu$ is corrected for Lorentz and demagnetization fields. The actual value of $K_\mu(T)$ is subject to an uncertainty due to the demagnetization correction. Nevertheless the shape of $K_\mu$ is independent on this correction. The F and S letters denote the two components.

**FIG. 4.** Clogston-Jaccarino plots obtained for $B_{\text{ext}} = 0.6$ T. For $B_{\text{ext}} \perp c$ we use the same symbol convention as in Fig. 3. The filled triangles correspond to $B_{\text{ext}} \parallel c$. The temperature is an implicit parameter: $1.7 \leq T \leq 115$ K. $K_\mu$ is extracted from the reported $\mu$SR measurements and the bulk susceptibility $\chi_B$ from measurements on our samples. The lines are guides to the eyes. Note the drastic change of slope at $T_N$ for the F set of data.
is static. Thus the anomalous temperature dependence of the two initial asymmetries around $T_N$ for $\mathbf{B}_{ext} \perp c$ cannot be due to muon diffusion. The eventual existence of two distinct muon sites cannot explain our data since their relative occupancy should not change for a static muon. Interestingly, the analysis for U of two distinct muon sites cannot explain our data since the Knight shift observed below $T_N$ is dynamic. The results obtained by the $\mu$SR and magnetic diffraction techniques are not contradictory. The diffraction results simply mean that the difference in the scattering properties of the two regions may be too subtle to be distinguished.

We now consider the possible origin for the additional Knight shift observed below $T_N$ for the F component. A change of the magnitude of the moments is excluded since high-field neutron diffraction measurements do not detect any sizable influence of a field up to 12 T [13,14]. Two mechanisms producing an additional shift can be imagined. The first mechanism involves the dipolar field produced at the muon site by the ordered uranium moments. A rotation of these moments induced by the applied field leads to an additional field at the muon site. A small rotation is not expected to observe below $T_N$ a new source of quasistatic magnetic polarization induced by the applied field which leads to an extra Knight shift.

Bulk magnetic susceptibility does not detect the phase transition since the relative sensitivity in these conditions is $\approx 10^{-3}$. As shown in Fig. 3, this is not enough.

The facts that the magnetic phase transition is detected only by transverse high-field and not by zero-field $\mu$SR measurements [6,17] are not inconsistent. It is not unexpected to observe below $T_N$ a new source of quasistatic magnetic polarization induced by the applied field which leads to an extra Knight shift.

Our most surprising result is the existence of the two components when $\mathbf{B}_{ext} \perp c$. Since the associated damping rates are small, we infer that the magnetic disorder is small. The near equality in most of the temperature range of the two initial asymmetries suggests that the two regions originate from a periodic modulation. The behavior of the initial asymmetries near $T_N$ implies that the proposed modulation is strongly coupled to the magnetic order parameter. The structural modulation observed by electron microscopy and diffraction some years ago [18] might be related to the regions discussed here. However, it has never been seen thereafter, including in our samples.

In summary, we have discovered by transverse high-field $\mu$SR measurements the existence of a two component magnetic response. While the volume fraction associated with these components is equal below $\sim 2$ K and above $\sim 10$ K, it is strongly temperature dependent around $T_N$. We also observe a signature of the magnetic transition for one of the two components. Our results are naturally explained if UPt$_3$ is intrinsically inhomogeneous at least in an applied field.

![Image](https://example.com/image.png)

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[7] The increase of the muon damping rate observed below $T_N$ with a first generation sample [R. H. Heffner et al., Phys. Rev. B 39, 11345 (1989)] has not been reproduced thereafter (see Refs. [6,17]).