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Physica C 388–389 (2003) 523–524

PHYSICA C

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## Low field DC SQUID nuclear magnetic resonance on single crystal $\text{UPt}_3$

R. Körber<sup>a,\*</sup>, A. Casey<sup>a</sup>, B.P. Cowan<sup>a</sup>, M.E. Digby<sup>a</sup>, J. Li<sup>a</sup>, J. Luo<sup>a</sup>,  
C.P. Lusher<sup>a</sup>, J. Saunders<sup>a</sup>, D. Drung<sup>b</sup>, T. Schurig<sup>b</sup>, J.B. Kycia<sup>c</sup>, J.I. Hong<sup>c</sup>,  
D.N. Seidman<sup>c</sup>, W.P. Halperin<sup>c</sup>

<sup>a</sup> Department of Physics, Royal Holloway University of London, Egham, Surrey TW20 0EX, UK

<sup>b</sup> Physikalisch-Technische Bundesanstalt, Abbestr. 2-12, D-10587 Berlin, Germany

<sup>c</sup> Northwestern University, Evanston, IL 60208, USA

### Abstract

A SQUID spectrometer is being used to study high-quality single crystals of  $\text{UPt}_3$  in low magnetic fields by performing pulsed NMR on  $^{195}\text{Pt}$ . The system uses a multiloop DC SQUID with additional positive feedback and operates in flux-locked loop mode from DC to 3 MHz. It has an overall coupled energy sensitivity of  $800h$  and a dead time of  $\sim 5$   $\mu\text{s}$ . NMR signals from  $\text{UPt}_3$  have been observed in both the superconducting mixed state and in the normal state. A bulk platinum marker is used to determine the magnetic field. Measurements of  $^{195}\text{Pt}$  Knight shifts in  $\text{UPt}_3$  are reported.

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**Keywords:**  $\text{UPt}_3$ ; DC SQUID; NMR

Traditionally NMR Knight shift measurements have been used to probe the electronic magnetic susceptibility in the superconducting state. They can potentially give insight into the nature of the spin pairing. In the heavy-fermion metal  $\text{UPt}_3$  the superconducting transition is split, with at least three phases present. The symmetry of the pairing is still under dispute—the heat capacity and penetration depth data favour an  $E_{1g}$  or  $E_{2u}$  ground state [1,2], whereas the NMR Knight shift measurements of Tou et al. [3] have been interpreted as ruling these states out. Further experimental data are required to resolve this conflict.

We have developed an NMR spectrometer which uses a DC SQUID as the front end amplifier, and which we are using to study high-quality single crystals of  $\text{UPt}_3$  at applied fields more than an order of magnitude lower

than is possible with conventional techniques. The broadband nature of the spectrometer allows measurements to be made over a wide range of frequencies—in principle important for distinguishing between the Knight shift and diamagnetic shifts in the superconducting state.

The NMR spectrometer has been described in detail elsewhere [4]. It uses a low- $T_c$  multiloop DC SQUID with additional positive feedback and operates in flux-locked loop mode from DC to 3 MHz. The overall coupled energy sensitivity of the spectrometer is  $800h$ , where  $h$  is Planck's constant. The NMR sample is located in a superconducting saddle coil which forms a flux transformer with the input coil of the SQUID. The dead time of the spectrometer is of order 5  $\mu\text{s}$ , following a transmitter pulse of up to 1.3 mT, enabling the study of solid state samples with broad lines.

The static NMR field is provided by a small superconducting magnet in a superconducting shield, operated in persistent mode. Improvements have been made

\* Corresponding author.

E-mail address: [r.koerber@rhul.ac.uk](mailto:r.koerber@rhul.ac.uk) (R. Körber).

to our experimental set-up from that described earlier [5], making possible the data presented here. In our initial experiments the transmitter pulse set up eddy currents in the copper magnet former, resulting in a transient response. This was reduced by inserting a grounded niobium shield, forming an open diamagnetic cylinder, between the magnet former and the RF coil set [6]. In addition a transient response was observed resulting from eddy currents in the UPT<sub>3</sub> which disappeared in the superconducting state. Improvements were made in the resolution of the signal capture, making possible precise measurements in the normal state.

The UPT<sub>3</sub> sample consists of six single crystals, each of approximate volume  $0.5 \times 0.7 \times 5 \text{ mm}^3$  cut parallel to the *c*-axis from a single ingot. They were etched and annealed at 870 °C after cutting. The superconducting transition at 0.555 K had a width of 12 mK, and the residual resistance ratio (RRR) was 866. These parameters testify to the quality of the sample. Thermal contact was made by bonding metallic foils along one side using silver epoxy. The RRR corresponds to a skin depth of  $\sim 60 \mu\text{m}$  at 100 kHz in the normal state. The crystals were oriented with the applied magnetic field parallel with the *c*-axis. A brush of 100 25  $\mu\text{m}$  diameter, 5 mm long platinum wires, bonded to a silver wire for thermal contact, was placed between two of the UPT<sub>3</sub> crystals along the field direction. The number of wires was chosen to give approximately the same signal size in the frequency domain as the UPT<sub>3</sub> sample at 100 kHz in the normal state.

Figs. 1 and 2 show data taken using a 280 kHz tipping pulse, with the UPT<sub>3</sub> in the normal and superconducting states respectively. For each line plotted the frequency,  $\nu$ , is normalized by the static magnetic field,  $B_0$ , required for resonance. The square of the amplitude of the fast Fourier transform of the free induction decays following background subtraction is plotted in all

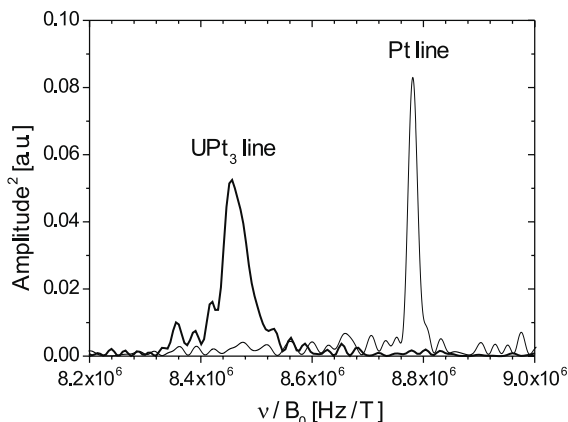


Fig. 1. <sup>195</sup>Pt NMR signals from UPT<sub>3</sub> in the normal state and bulk platinum, taken with 1000 averages. The temperature is  $\sim 600 \text{ mK}$  and the magnetic field is  $\sim 33 \text{ mT}$ .

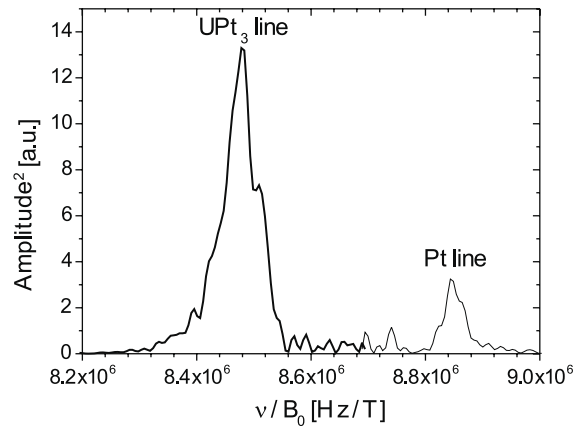


Fig. 2. <sup>195</sup>Pt NMR signals from UPT<sub>3</sub> in the superconducting mixed state and bulk platinum taken with 100 averages. The temperature is  $\sim 32 \text{ mK}$  and the magnetic field is  $\sim 32 \text{ mT}$ .

cases. Linewidths are extracted from Lorentzian fits to these data. The measured  $T_2^*$  for UPT<sub>3</sub> is  $\sim 200 \mu\text{s}$  in the normal state and  $\sim 150 \mu\text{s}$  in the superconducting mixed state. The signal size in the normal state is approximately that expected from the number of spins within half a skin depth of the surface ( $\sim 2 \times 10^{19}$ ). Noticeable broadening and a frequency shift of the bulk platinum line is observed when the UPT<sub>3</sub> is in the superconducting state, due to diamagnetic effects. Using the bulk platinum signal at 600 mK as a marker, the measured frequency shift from the bare <sup>195</sup>Pt value is  $-7.0\%$  in the normal state at 600 mK and  $-6.8\%$  in the superconducting mixed state at 32 mK. Similar to the measurements of Tou et al. [3], the change in the frequency shift observed on entering the superconducting state is small. However our observed normal state Knight shift is at variance with the  $-1.9\%$  observed in previous measurements in fields above 190 mT [3,7]. Our shift is consistent with our earlier data, taken on the same sample but without a marker, in which the inferred shift in the superconducting state was found to be approximately field independent from 10 to 60 mT. Our quoted shifts include possible shifts due to the diamagnetism of the UPT<sub>3</sub> in the superconducting state.

A more detailed study over a wide frequency range is presently in progress.

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