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**Publication date**  
1995

**Published in**  
Physica B-Condensed Matter

[Link to publication](#)

**Citation for published version (APA):**

van Dijk, N. H., de Visser, A., Franse, J. J. M., & Taillefer, L. (1995). Meta-stable states in the low-field magnetostriction of UPt<sub>3</sub>. *Physica B-Condensed Matter*, 606-608.

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# Meta-stable states in the low-field magnetostriction of $\text{UPt}_3$

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## Abstract

Detailed magnetostriction measurements on single-crystalline  $\text{UPt}_3$  reveal an anomaly at a field of 0.1 T in the normal and the superconducting state, both for  $B \parallel c$  and  $B \perp c$ . The magnetostriction in a hysteresis loop reveals several transitions between history dependent meta-stable states below 1.5 K. In the superconducting state, the anomaly in the magnetostriction coincides with a kink in one of the phase lines for  $B \perp c$ , indicating a coupling between the meta-stable states and the superconductivity.

The heavy-fermion superconductor  $\text{UPt}_3$  ( $T_c = 0.5$  K) attracts a lot of attention because of its unconventional superconducting properties. Specific heat and sound velocity measurements [1,2] show the existence of a double superconducting transition. The second transition is located approximately 60 mK below the first transition within the superconducting state. Superconductivity co-exists with antiferromagnetic order. The formation of an antiferromagnetically ordered state below  $T_N = 6$  K is revealed by neutron diffraction measurements [3] and supported by muon spin rotation measurements [4]. The uranium moments are oriented along the  $b$ -axis of the hexagonal lattice. The size of the ordered moment is extremely small:  $0.02\mu_B/\text{U-atom}$ . Recently, much attention has been focused on lattice defects and microstructures in  $\text{UPt}_3$ . Combined transmission electron microscopy and X-ray measurements [5] indicate that the lattice structure is predominantly simple hexagonal with small double hexagonal regions with typical dimensions of 25–30 Å. This second phase occupies approximately 3% of the overall sample volume. Additional transmission electron microscopy and electron-diffraction studies [6] revealed the presence of an incommensurate structural modulation in  $\text{UPt}_3$  which forms above 800 K.

In this paper, we report on an investigation of the low-field magnetostriction of  $\text{UPt}_3$ , measured by a

sensitive three-terminal parallel-plate capacitance technique. Previous measurements of the linear magnetostriction,  $\lambda = (L(B) - L(0))/L(0)$ , showed a low-field anomaly ( $B < 0.1$  T) in the normal state as well as in the superconducting state of  $\text{UPt}_3$  [8,9]. In Fig. 1, a typical curve of the normal-state magnetostriction along the  $a$ -axis,  $\lambda_a$ , is shown for  $B \parallel b$  measured with a sweep rate of 25 mT/min. When the field is in-

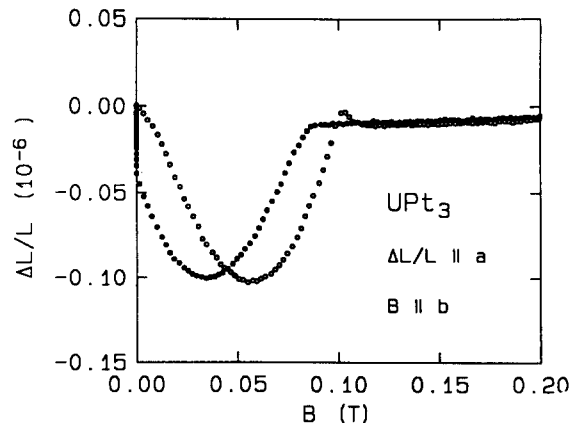


Fig. 1. Linear magnetostriction ( $\Delta L/L \parallel a$ ) for  $B \parallel b$  for a slowly increasing ( $\circ$ ) and decreasing ( $\bullet$ ) magnetic field (25 mT/min) at  $T = 0.594$  K.

creased, the magnetostriction goes through a minimum in low fields and becomes nearly constant above 0.1 T. After reaching a field of 0.2 T, we subsequently decreased the field down to  $B = 0$  T. In that case, the magnetostriction shows the same minimum below 0.1 T, however slightly shifted.

The anomaly is present in the normal state and the superconducting state and is only weakly temperature dependent up to 0.8 K. At higher temperatures, the anomaly shifts to lower fields and vanishes around 6 K, close to  $T_N$ . The anomaly is observed for all the measured orientations ( $\Delta L \parallel a, c$  with  $B \parallel a, b, c$ ) and weakly depends on the sweep rate of the magnetic field. In order to test the sample dependence of the anomaly, two different single-crystalline samples have been studied: the first single crystal was prepared in Cambridge [7,8] and the second in Amsterdam [2,9]. Both samples show the same anomaly in the low-field magnetostriction. The measurements reported in the present work have been performed on the first sample. In order to exclude that the anomaly is an artifact of our measuring system, the magnetostriction has also been studied with a different set-up in Grenoble leading to comparable results as those obtained in Amsterdam. A low-field anomaly with strong hysteresis has earlier been reported for measurements of the ultrasonic attenuation in the superconducting state [10].

In order to study the low-field anomaly in more detail, hysteresis experiments were performed at stable fields. Two typical magnetostriction curves of  $\lambda_a$  ( $B \parallel b$ ) at 0.6 K are shown in Fig. 2. In the upper curve of Fig. 2, the hysteresis of the magnetostriction is shown for a discrete measurement where the data points were taken at a stable temperature after changing the field. Under stable conditions the minimum for the magnetostriction is no longer shifted for fields up or down. When the direction of the magnetic field is reversed, the magnetostriction shows several steps which are accompanied by strong internal heating of the sample. The steps in the magnetostriction and the release of latent heat indicate that the transitions between the meta-stable states are of first order. In the lower curve of Fig. 2, the magnetostriction of the meta-stable states is studied. The magnetic field is decreased from 0.15 T until the first step occurs around  $-0.05$  T. After the first step, the field is increased until a second step occurs around 0.05 T. After the second step, the field was decreased again to  $-0.15$  T, where two additional steps were observed before the magnetostriction becomes nearly constant below  $-0.10$  T. The magnetostriction curves of the

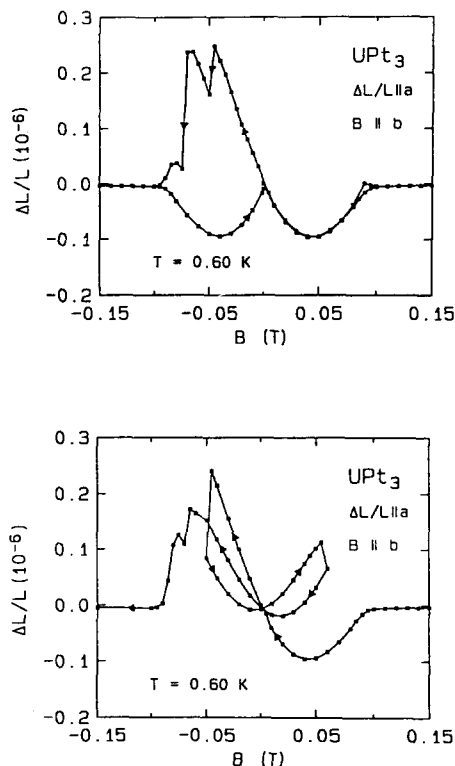


Fig. 2. Linear magnetostriction ( $\Delta L/L \parallel a$ ) for  $B \parallel b$  at  $T = 0.594$  K at stable points (solid dots). The connecting lines are guides to the eye.

meta-stable states show a parabolic field dependence crossing in a single point for zero field.

Repeated hysteresis runs reveal the presence of at least five meta-stable states for  $B \perp c$ . Hysteresis measurements of the continuous magnetostriction have also been performed for  $\Delta L \parallel a$  with  $B \parallel a$  and  $B \parallel c$ . When the magnetic field was reversed, several peaks were observed for both field orientations, predominantly caused by the internal heating of the sample. In order to check that the observed internal heating is an intrinsic property of the sample and is not related to the dilatation cell, the sample was mounted on a sapphire plate in a specific-heat cell. In this set-up the same internal heating of the sample was observed at the transitions between the meta-stable states, as found for the magnetostriction measurements, indicating that the internal heating is an intrinsic property of our sample. The internal heating is observed for temperatures up to 1.5 K.

The influence of the meta-magnetic states below a field of 0.1 T on the magnetostriction is similar for the

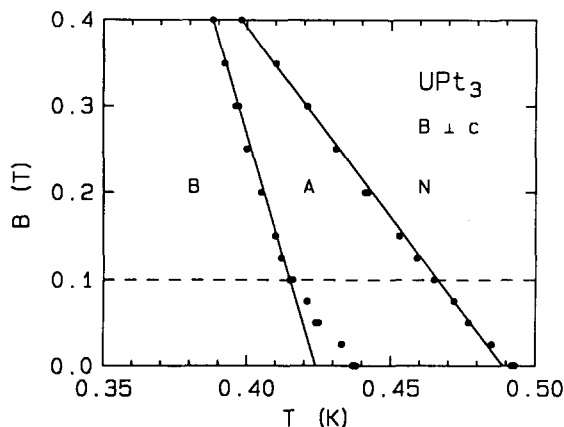


Fig. 3. The superconducting transition temperatures determined from the thermal expansion measurements in low fields for  $B \parallel a, b$ .

normal state and the superconducting state. A close-up of the superconducting phase diagram for  $B \perp c$  (Fig. 3), determined by previous thermal expansion measurements [11], shows a remarkable change of slope in the inner phase line at a field of 0.1 T. This change of slope coincides with the low-field anomaly in the magnetostriction and indicates a direct influence of the meta-stable state of the system on the superconducting state.

The anomaly is possibly related to a rotation of the magnetic domains for  $B < 0.1$  T. The transition at 0.1 T would then be related to the formation of a single domain, in which the antiferromagnetic moment is oriented perpendicular to the applied magnetic field. The main problem with this interpretation is that it does not predict an anomaly in the magnetostriction for  $B \parallel c$ , while an anomaly is observed for all field orientations. Another problem is that the system is insensitive to an inversion of the direction of the magnetic field when a single domain is formed.

The observed hysteresis in the magnetostriction seems more in line with the presence of ferromagnetic than antiferromagnetic interactions. A possible origin of these ferromagnetic interactions may be the presence of structural instabilities. In  $\text{UPt}_3$ , both stacking faults [5] and an incommensurate structural modulation [6] have been reported. The local symmetry of the U-atoms near the lattice distortions is no longer hexagonal. For a local cubic symmetry, as is induced by stacking faults, the magnetic interactions of the U-moments are expected to be less anisotropic and may have a ferromagnetic nature. For small magnetic

fields, these U-moments tend to orient along the magnetic field. A change in the direction of the magnetic field leads to a reorientation of the U-moments near the lattice distortions, which may be accompanied by transitions between meta-stable magnetic states.

In summary, several meta-stable states have been detected in the magnetostriction of  $\text{UPt}_3$  below 0.1 T. The anomaly at 0.1 T is present in the normal and the superconducting state and coincides with a change of slope in one of the phase lines indicating a coupling of the meta-stable states and the superconductivity.

This work was part of the research program of the 'Stichting FOM' (Dutch Foundation for Fundamental Research of Matter).

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