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Magnetostriction of Heavy-Fermion UPt_3 in Magnetic Fields up to 24 Tesla

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The high-magnetic-field anomaly at 20 T in heavy-fermion UPt_3 has been studied by means of magnetostriction measurements on a single-crystalline sample at liquid helium temperatures. The data for a field direction in the basal plane reveal an orthorhombic distortion of the hexagonal crystal structure. An explanation for this distortion is offered in terms of a (antiferromagnetic) spin-fluctuation model.

1.INTRODUCTION

One of the salient properties of heavy-fermion UPt_3 is a magnetic anomaly near 20 T. This anomaly, first observed in magnetization measurements [1], occurs only at low temperatures, i.e. below the temperature at which the maximum in the susceptibility is found (~17K), and for field directions in the hexagonal plane. For these particular field directions and temperatures, the magnetization curves remind one of a metamagnetic-like transition (the differential susceptibility, $\Delta\sigma/\Delta H$, peaks at 20T). Subsequent magnetoresistivity experiments on single-crystalline samples [2] showed a large and positive $\Delta\rho$ for field directions in the basal plane, marking the anomaly as a pronounced maximum. Furthermore, these data confirmed the two-dimensional nature of this phenomenon. In sound velocity measurements the anomaly appeared as a strong softening of longitudinal acoustic modes [3]. Regarding the variety of experiments performed on UPt_3 [4,5], it is likely that the high-field anomaly has its origin in antiferromagnetic spin fluctuations. This is supported by the observation of long-range antiferromagnetic order in pseudobinary $U(Pt,Pd)_3$ compounds [6,7]. Evidence for antiferromagnetic spinfluctuations in UPt_3 is furthermore offered by inelastic neutronscattering experiments [8].

A theoretical description of the high-field transition is still lacking at present. In order to further investigate this anomaly, we performed magnetostriction measurements up to 24 T, herewith extending our earlier low-field data (B<8 T) [9].

2. EXPERIMENTAL

An annealed single-crystalline cube (5x5x5 mm^3, with the edges along the crystallographic directions) was mounted in a capacitance cell, made of OFHC-copper. A sensitive three-terminal method served to determine the length changes. Fields up to 24 T were generated at the Grenoble High Magnetic Field Facility by a combined Bitter-Polyhelix magnet. In order to reduce vibrations, mechanical contact between the cryostat and the magnet was avoided.

For a field direction along the hexagonal axis (B//c), the magnetostriction, $\lambda=\Delta L/L$, was measured parallel and perpendicular (along the a-axis) to the field. For B//a the magnetostriction was measured parallel (a-axis) and perpendicular (b-axis *and* c-axis) to the field. In order to look for a possible anisotropy in the basal plane, an equivalent set of data was obtained for B//b. Data were taken at 4.2, 3.0 and 1.8 K, the latter temperatures being determined by the vapour pressure of the He bath.

3.RESULTS

In fig.1 we present the experimental results for a field direction along the a-axis at 4.2 K. Apparently, the magnetostriction is strongly anisotropic. First we note a large anisotropy between the magnetostriction in the basal plane, λ_a or λ_b, and the one along the hexagonal axis, λ_c (the subscripts refer to the dilatation direction). But also in the basal plane λ is anisotropic, the magnetostriction perpendicular to the field (λ_b) being larger than the one along the field (λ_a). Data taken with the field applied along the b-axis yield a similar, but larger, anisotropy in the basal plane: $\lambda_a>\lambda_b$ [10]. However, the calculated volume magnetostrictions, $\lambda_v=\lambda_a+\lambda_b+\lambda_c$, are nearly equal for both field directions in the basal plane [10]. In fig.2 we show data for $\lambda_a' =(1/a)(\Delta a/\Delta B)$, for B//a, as a function of temperature. From this figure it follows that the transition becomes more pronounced when the temperature is lowered, whereas the position of the maximum at 20 T is found to be temperature independent. The inset in fig.2 shows calculated values for $\lambda_v'/3$ for B//a at different temperatures. For B//c, λ_a and λ_c were found to follow a B^2-law, with a positive (negative) coefficient for the a(c)-axis. This is illustrated in a plot of λ_a and λ_c versus B^2 (fig.3). The present results are in good agreement with the previous low-field data, taken on a different (and unannealed) sample [9]. Note that for this crystal a small anisotropy in the basal plane was reported as well [9].

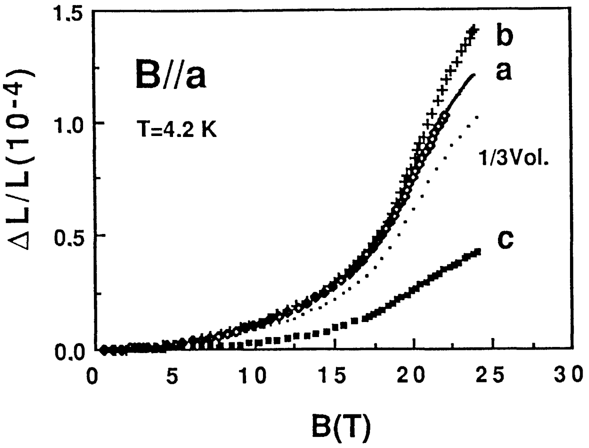

Fig.1 Magnetostriction of UPt_3 (B//a) for the a, b (taken ⊥a) and c-axis at 4.2 K. The dots represent $\lambda_v/3$. In order to calculate $\lambda_v/3$ above 22 T, data for the a-axis were extrapolated (solid line).

Recently, Kouroudis et al. reported oscillatory behaviour of the sound velocity in some shear modes, near 20 T and below 1.25 K [3]. In our magnetostriction experiments we did not observe any oscillations at the lowest temperature investigated (1.8 K).

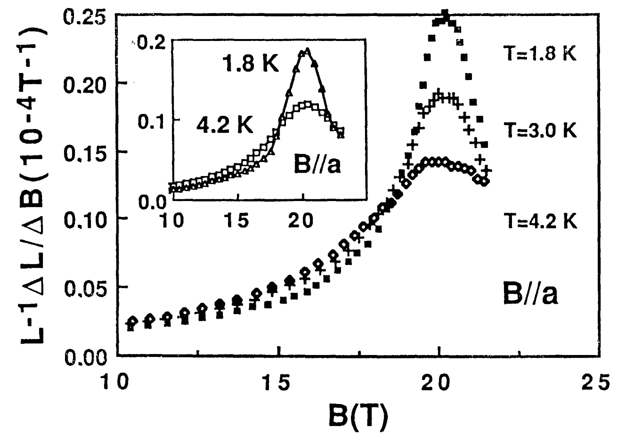

Fig.2 The derivative of the magnetostriction (B//a) for the a-axis, at temperatures indicated. The inset shows values for $\lambda_v'/3$ at 1.8 and 4.2 K.

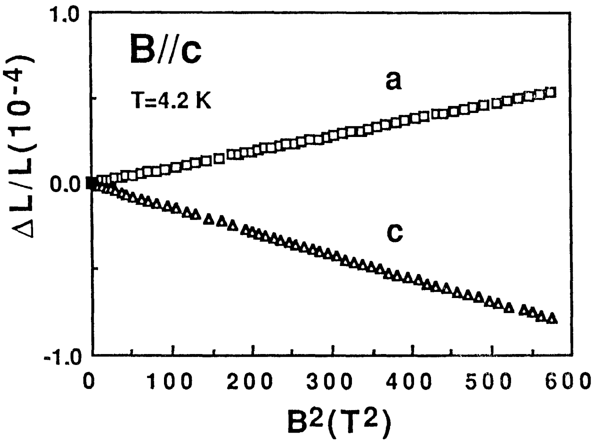

Fig.3 Magnetostriction of UPt_3 (B//c) for the a and c-axis, at 4.2 K.

4. DISCUSSION

The measured anisotropy in the values for the basal-plane magnetostriction evidences an orthorhombic distortion of the hexagonal lattice: for both field directions (B//a *and* B//b) it is observed that the basal-plane magnetostriction perpendicular to the field is larger than the magnetostriction along the field. For B//a λ_b-λ_a amounts to $1.9x10^{-5}$, whereas for B//b λ_a-λ_b attains a value of $4.7x10^{-5}$ [10], at 24 T and 4.2 K, which shows that the orthorhombic distortion is largest for B//b. The anisotropy in the basal plane appears at ~3 T, i.e. at the same field where deviations from the quadratic field dependence are observed [9].

The observed anisotropy is consistent with an interpretation of the anomaly in a simple spin-fluctuation model. Hereto we assume: (1) the presence of antiferromagnetic correlations (short-range order) between the uranium f-moments, (2) a considerable spacial orientation of the f-orbitals in the plane perpendicular to the magnetic moments, and (3) a quenching of the antiferromagnetic correlations above 20 T (reorientation towards a ferromagnetic alignment of the moments). At large fields the ferromagnetic alignment of the moments forces the f-orbitals into a plane perpendicular to the field, causing a larger magnetostriction perpendicular to the field, than along the field. Since the alignment of the f-orbitals in the plane perpendicular to the field is easier accomplished for B//a than for B//b (the distance between two uranium atoms is larger along the b-axis than along the a-axis) it can also be understood that the anisotropy is largest for the latter field direction.

The metamagnetic-like transition observed at H_a=8 T for the heavy-fermion system $CeRu_2Si_2$ has a strong resemblance to the anomaly observed for UPt_3 at 20 T. Recently, it has been shown [11] that for $CeRu_2Si_2$ the pressure dependence of the magnetization obeys a simple scaling law: $M(H,P)/\mu_B=f(H/H_a(P))$, i.e. M depends only on one pressure-dependent field parameter: $H_a(P)$. This scaling law was checked by comparing the volume magnetostriction with the differential susceptibility, according to: $(\partial V/\partial H)_{P,T}=H(\partial \ln H_a/\partial P)(\partial M/\partial H)_{P,T}$ (this equation follows after straightforward application of thermodynamic relations). Preliminary calculations reveal that this scaling law holds for UPt_3 as well [10], implying severe restrictions on theoretical models that are able to account for the observed high-field transition.

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