Anomalous pinning near H_{c2} in the heavy fermion superconductor UPd_2Al_3 studied by magnetic measurements

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Magnetic measurements were performed on single crystalline UPd_2Al_3 samples. Slightly below H_{c2} an anomaly has been observed, which indicates a sudden change from weak to strong pinning of the flux vortices. We discuss possible explanations, e.g. the formation of a spatially modulated superconducting („Fulde-Ferrell") state, and compare our results with similar ones in $CeRu_2$.

The heavy-fermion (HF) compound UPd_2Al_3 in which antiferromagnetic order among relatively large local U-moments ($\mu = 0.85\ \mu_B$, $T_N \approx 14$ K) coexists homogeneously with HF superconductivity below $T_c = 2$ K, has recently attracted much interest [1]. For example, length measurements as a function of both temperature and external magnetic field revealed distinct anomalies below $T \approx 0.8\ T_c$ and at fields somewhat below the upper critical field $H_{c2}(T)$ [2]. The main conclusion derived from these length measurements was the existence of a strong anomalous pinning mechanism which was tentatively ascribed to the formation of a non-uniform (Fulde-Ferrell [3]) superconducting state. In order to gain a deeper insight into this problem, we discuss results of magnetic measurements, in particular of the ac-susceptibility (χ_{ac}), on UPd_2Al_3.

The measurements described below were made on two different single crystalline samples of UPd_2Al_3. Both samples were cut from larger single crystals: The first one (# 1) had an irregular shape (approx. 1 x 1 x 2 mm), while the second one (# 2) was somewhat bigger and had a cylindrical shape ($\varnothing$ = 3 mm, l = 4 mm). The ac-susceptibility measurements (ν = 117 Hz, $B_{ac} \approx 1\ \mu$T) were done in a dilution cryostat with a superconducting magnet, allowing the superposition of a magnetic dc-field. The field was applied along the c-axis of the first sample and about 15° off the c-axis of the second sample. Usually the dc-field is set to a fixed value and the temperature is swept giving a $\chi_{ac}(T)$-curve. Most of our measurements were done the other way round: While sweeping the dc-field the temperature was kept constant leading to $\chi_{ac}(H)$. These field sweeps were quasistatic (i.e. stepwise) or continuous (0.2 ... 2 T/min). The obtained results were normalized to the expected full diamagnetic value. These experiments were complemented by measurements of the dc-magnetization using a SQUID magnetometer.

Fig. 1 shows $\chi_{ac}(H)$-measurements at T = 150 mK. Upon increasing the magnetic field the value of $-\chi_{ac}$ decreases first in the usual way [4], while near H_{c2} the value increases again reaching nearly the full diamagnetic value. In this region one can observe strong hysteretic behavior and time dependent effects: This is shown in fig. 2 on a quasistatic sweep with increasing and decreasing field at T = 135 mK. The arrow pointing downwards indicates an observed relaxation when the field was held constant over several hours. The open circles are values obtained from $\chi_{ac}(T)$-measurements done in the usual way, i.e. after heating the

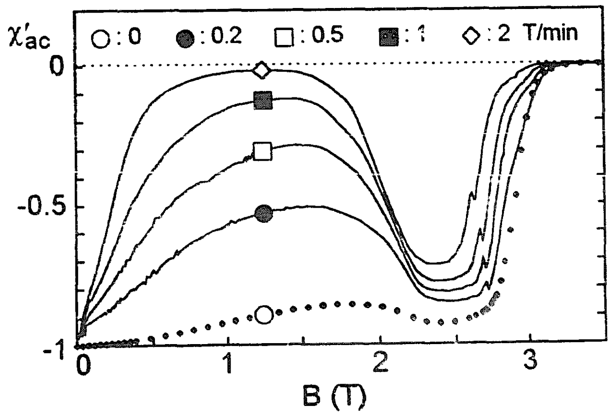

Fig. 1: *ac-susceptibility of UPd_2Al_3 (# 2) at T = 150 mK in increasing field at different sweep ratios.*

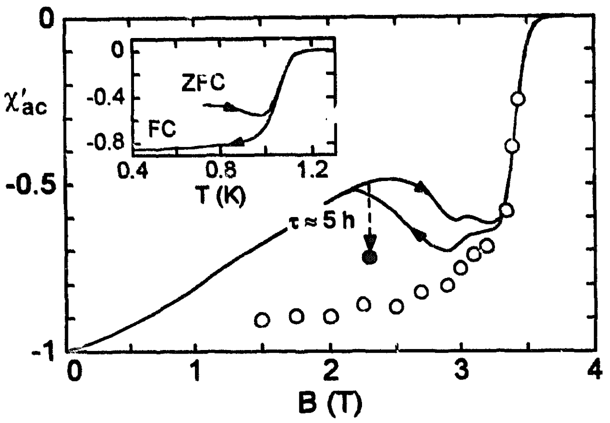

Fig. 2: *Observed hysteretic and time dependent behavior of UPd_2Al_3 (# 1) (see text).*

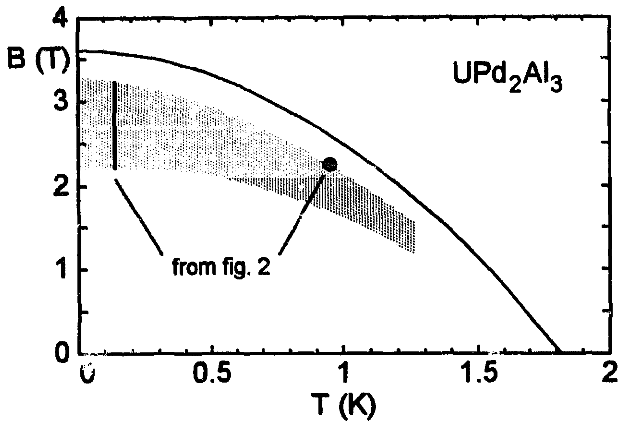

Fig. 3: *$B_{c2}(T)$ curve and observed area of hysteretic behavior of UPd_2Al_3 (# 1).*

sample above T_c a magnetic field was applied and the sample cooled down very slowly (FC-curve, inset fig. 2: $B = 2.25$ T). A striking difference is observed if the same field is applied after the sample was cooled and then warmed up quite fast (ZFC-curve). The minimum seen in the ZFC-curve is in good agreement with the minimum near H_{c2} in the field sweeps and with an anomaly found near H_{c2} in dc-magnetization measurements made on a different sample.

The obtained results are summarized in fig. 3. Here the solid line connects the obtained $B_{c2}(T)$-values, which fit neatly a $1-(T/T_c)^2$ -law giving T_c = 1.81 K and $B_{c2}(0)$ = 3.59 T. The shaded area is the region of negative slope, i.e. of anomalous and hysteretic behavior of the $\chi_{ac}(H)$-measurements done up to 1.25 K. Using Bean's critical state model expanded by the model of reversible flux motion a relationship between critical current (i.e. flux pinning) and the χ_{ac}-signal can be derived: a large signal in χ_{ac} indicates strong flux pinning. This means that at sufficient low field, after the usual softening of the flux lattice, upon isothermally increasing the field in UPd_2Al_3 the vortices are strongly pinned again near H_{c2}. In conventional superconductors such an anomaly arises from a matching of the vortices with lattice defects or with inclusions of a second phase with a lower critical temperature („peak effect"). Here the first possibility can be excluded since the anomaly should be field independent as a function of temperature. The other one seems unlikely too, since the observed zero field superconducting transition is quite narrow and there was no evidence for a second phase in X-ray measurements. – The hysteretic behavior of the anomalies and an observed anomaly in the magnetostriction [2] may indicate a genuine first-order thermodynamic transition, although up to now no corresponding anomaly has been detected in the specific heat. Since the upper critical field is slightly above the Clogston limit (3.33 T) and the superconductor is in the clean limit too, there may be a change from the usual uniform to a nonuniform superconducting state as predicted by Fulde and Ferrell [3]. It is interesting to note that similar magnetic anomalies have also been observed in UPt_3, with big changes for $\omega H_{ac} \approx \dot{H}_{dc}$ [5], as well as in the strong intermediate-valence superconductor $CeRu_2$ [6]. However, in the latter system, the upper critical field is found to be well below the paramagnetic limit so that this explanation is still questionable.

Therefore, the origin of the very strong pinning near H_{c2} and, associated with it, the pronounced time-dependent effects which hint at a non-equilibrium state, remain to be explained.

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