Anisotropic Low-Field Magnetization of Heavy-Fermion Superconductor URu_2Si_2

Z. Kozioł, A.A. Menovsky, K. Bakker and J.J.M. Franse,
Universiteit van Amsterdam, Van der Waals-Zeeman Laboratorium, Valckenierstraat 65, 1018 XE Amsterdam, The Netherlands.

Abstract. **Using a sensitive Hall-probe technique, the magnetization anisotropy of the heavy-fermion superconductor URu_2Si_2, with T_c=1.2 K, was studied as a function of magnetic field and temperature on a cube-shaped sample. The estimated first-critical-field values, H_{c1}, extrapolated to T=0 are about 10 and 15 Oe for field parallel to the a- and c- crystallographic directions, respectively. The low-field critical-current density, J_c, exhibits a similar anisotropy as H_{c1} but J_c is suppressed in particular by magnetic field oriented along the c-direction. It is argued that results of magnetization measurements should depend on the sample size and shape.**

I. Introduction

The heavy-fermion materials $CeCu_2Si_2$, UBe_{13}, UPt_3 and URu_2Si_2 have attracted considerable attention. Power-law temperature-dependencies of the thermodynamic and electrodynamic properties at temperatures which are significantly lower than the superconducting transition temperature T_c are treated often as indications on the formation in these compounds of an unconventional type of superconductivity. In some of these compounds, the superconducting state coexists with low-magnetic-moment long-range antiferromagnetism. In URu_2Si_2, with a T_c value of about 1.2 K and with a Néel temperature of 17 K, some measurements of the specific heat were interpreted as the result of a two-step transition [1], as in UPt_3. Subsequent studies have not confirmed this observation [2]. These discrepancies may be caused by a strong susceptibility of the superconducting-state properties to impurities and metallurgical treatment [3]. Even in the best samples the superconducting transition remains unusually broad.

Recently, attention was paid to an apparent disagreement between the absence of anisotropy in the first critical field, H_{c1} ($\approx$30 G at T=0, according to ref. [4]) and the large temperature-dependent anisotropy of the second critical field H_{c2}: very close to T_c, H_{c2} is the same or nearly the same for all directions of field with respect to the crystallographic axes but at low temperatures H_{c2} becomes about 4-5 times larger for fields along the a-axis than for fields along the c-axis. In the conventional theory, there is an inverse relation between the critical fields, $H_{c1} \cdot H_{c2} \sim H_c^2$, where H_c is the thermodynamic critical field.

In this report, we concentrate on investigations of the low-field magnetization of URu_2Si_2. The cube-shaped sample (cubic axes of 3mm) is used in order to avoid possible geometry-dependent effects in the determination of anisotropies in quantities as H_{c1} and the critical current density. The specific heat of the sample shows a relatively sharp, one-step anomaly in the neighbourhood of the superconducting transition (fig. 1). For the magnetization measurements a convenient, sensitive and accurate Hall-probe technique is applied, which is described in details elsewhere [5]. Here we point out that in these measurements the magnetization is related to the difference between the applied magnetic field and the field registered by the Hall sensor, which is placed about 1 mm apart from the sample surface. At low fields, the sample does not screen completely the magnetic field. In the Meissner state, the virgin magnetization curve is measured. The calibration factor is determined such that the experimental data multiplied by this factor give the slope $d(4\pi M)/dH$ equal to -1, where the quantity M is the magnetization of the sample. At fields which are significantly larger than H_{c1} this procedure introduces a certain error in determining the absolute value of the magnetization, but this has a negligible influence on the determination of its anisotropy.

II. Results and discussion

The low-field magnetization of a superconductor has been analyzed according to the extended critical-state models [4,6,7]. It is determined primarily by the values of the first critical field and of the critical-current density and its field dependence, $J_c(B)$. There is a crossover from a linear M(H) dependence for fields $H<H_{c1}$ to a parabolic one above H_{c1}: $(4\pi M+H) \sim (H-H_{c1})^2/2H^*$, with a curvature determined by the value of H^*, the field for the first flux penetration into the sample centre. This field depends on J_c as well on the characteristic sample size. Some insight in the relative contribution of these quantities to the actual results is obtained from measurements of the virgin magnetization curves at different temperatures, as shown in fig. 2. A maximum in $|M(H)|$ is observed for the two curves at the highest temperatures in fig 2, which is caused by a field

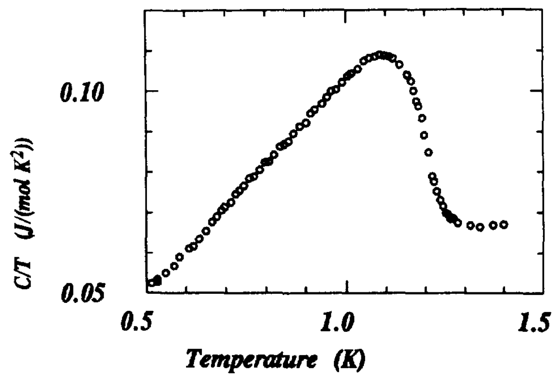

Fig. 1. Specific heat C/T of a URu_2Si_2 single-crystalline sample, near the superconducting transition temperature.

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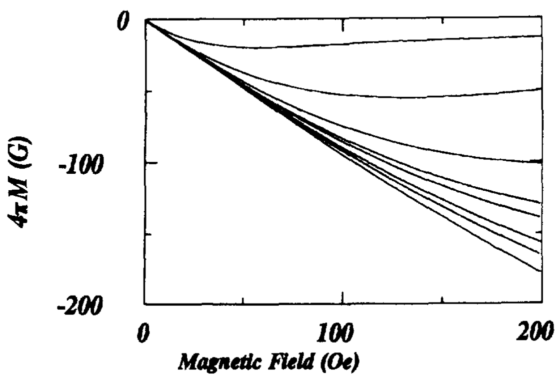

Fig. 2. The virgin magnetization curves for the cube-shaped single-crystalline sample, when the magnetic field is oriented along the a-crystallographic direction. The curves were measured at temperatures 1.100, 1.032, 0.962, 0.908, 0.878, 0.790, 0.715 and 0.468 K, from top to bottom, respectively.

suppression of the critical current-density. When the temperature is lowered, the maximum shifts to higher fields, due to an increase of the critical-current density. At low temperatures, the critical current-density is so high and the value of H^* so large that in the scale of fig. 2, hardly a deviation from a linear M(H) dependence can be noticed when the field becomes larger than the expected H_{c1} values. Figures 3 and 4 illustrate some measurements along different crystallographic directions in order to detect a possible anisotropy in the magnetic properties. Measurements of the zero-field-cooled magnetization (fig. 3) and of the remanent magnetization after cooling in field (fig. 4) give nearly identical results at low fields and low temperatures for a field along the c-axis (solid lines) and for a field in the basal plane of the tetragonal structure (broken lines). Near to T_c and/or at higher fields, differences are observed between the results for the two orientations. At low temperatures, the zero-field-cooled magnetization and the remanent magnetization, determined in higher field, are lower for a field along the a-axis, while at temperatures near to T_c the opposite result is observed.

The presented M(T) curves can be fairly well analyzed within the critical-state model [7]. The conclusion can be drawn that at low temperatures for the field along the c-axis the critical current is largest. At higher temperatures the low-field critical current seems to be smaller for H//c. This latter conclusion, however, may be wrong: a stronger suppression of the critical current by the magnetic field along the c-axis and not a lower value of it for H=0, would give the same result. In order to clarify this problem, the magnetization hysteresis was measured for two field orientations. Figure 5 contains an example of the virgin and decreasing branches of the magnetization hysteresis curves determined at T=1100 mK. While the width of the hysteresis for H//a is weakly affected by field, for H//c a stronger field-suppression of the magnetization is observed. Hence, we conclude that the lower magnetization for H//c near to T_c is due to a stronger field-suppression of J_c, rather than to a lower value of $J_c(B=0)$.

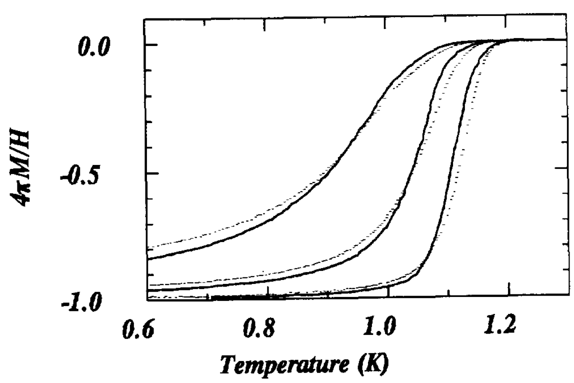

Fig. 3. The DC magnetic susceptibility (zero-field-cooled magnetization normalized by the magnetic field) for the cube-shaped sample. The continuous lines represent results for the field along the c-crystallographic direction, while the broken lines for the field along the a-axis. The measurements were done for fields of 20, 100, and 300 Oe, for the curves from right to left, respectively.

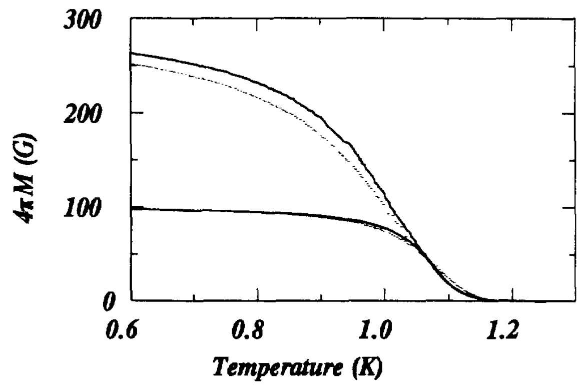

Fig. 4. The remanent magnetization, after the sample is cooled down in a magnetic field to low temperature, where the field is switched off, and remanence is measured after slowly heating the sample. The continuous lines represent results for the field oriented along the c-crystallographic direction, while the broken lines for the field along the a-axis. The two upper curves were registered after cooling in a field of 300 Oe, and the two lower curves in a field of 100 Oe.

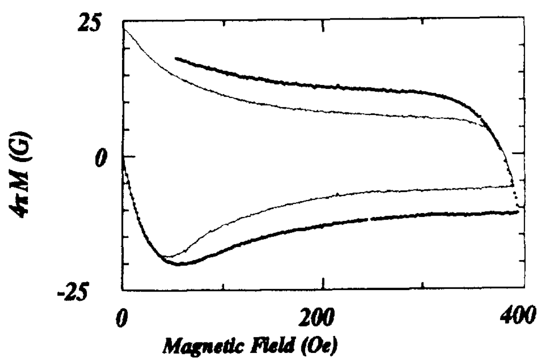

Fig. 5. The virgin and decreasing branches of the magnetization hysteresis curves for the cube-shaped sample, measured at a temperature of 1100 mK. The inner curve is obtained for field along the c-crystallographic direction and the outer one, for field along the a-axis.

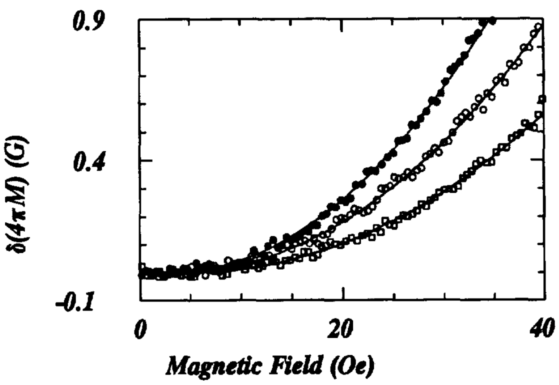

Fig. 6. A parabolic-like departure from the linear M(H) dependence for the virgin magnetization curves measured for the field along the a-axis at temperatures 803 mK (squares), 632 mK (empty circles) and 552 mK (filled circles). The solid lines are drawn according to the dependence $\delta(4\pi M) \sim (H-H_{c1})^2$, with $H_{c1}=3$, 3.5 and 5 Oe, respectively.

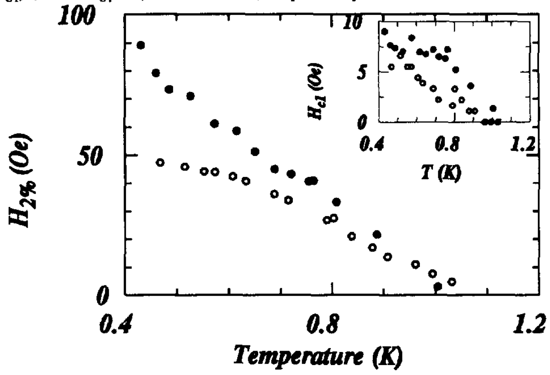

Fig. 7. The criterion of 2% deviation from the low-field linear M(H) dependence allows to determine the $H_{2\%}$ field for different orientations of the sample with respect to the crystallographic axis. The filled circles represent results for field along the c-axis and the empty circles for field along the a-axis. Inset shows the temperature dependence of the estimated first critical field values, where similar anisotropy is obtained as for the fields $H_{2\%}(T)$.

In order to clarify further the problem of an anisotropy of H_{c1}, careful measurements at low fields of the M(H) curves were performed. Figure 6 shows some examples of these data, with a fitting of a parabolic function to the departure from the linear magnetization. The results of this fitting procedure, which yields values for the first critical field, are shown in fig. 7. We should note, however, that this analysis is very difficult, despite the high accuracy of the measurements. This is due to the low values of H_{c1} and to the difficulty in fitting a proper linear dependence to the low-field data. However, since the sample shape is such that we avoid geometry-dependent problems in the interpretation of the results for the anisotropy, we are quite convinced that we estimate properly the anisotropy of the first critical field and the anisotropy in the departure from the low-field linear M(H) dependence above H_{c1}, related to the anisotropy of the low-field critical- current density. The values of H_{c1} in fig. 7 are comparable to those reported before [4,8], if we take into account the demagnetization effect. The apparent suppression of H_{c1} to zero at a temperature of about 1K, a temperature that is significantly lower than $T_c \approx 1.2$K, is a puzzling effect, as it was noticed before [4]. Our estimates of the value and the temperature dependence of the critical-current density give results which are very close to those reported in ref. [4]. Since the critical-current density depends on the magnetic field and this effect is anisotropic, the determination of H_{c1} and of J_c are very difficult for samples of arbitrary geometry. This may explain the absence of anisotropy for these quantities in earlier reports.

III. Conclusion

There is an indication from our results that H_{c1} is largest for fields along the c-axis. Although the achieved accuracy is not sufficient to decide finally about this suggestion, the anisotropy in H_{c1} is much smaller than expected for a superconductor characterized by a large anisotropy of the second critical field. We argue that the low-field critical-current density has also a different dependence on the magnetic induction for different field orientations. When the field is parallel to the c-axis, the current in the a-b plane is suppressed more strongly by the field than the critical current induced by a field perpendicular to the c-direction. At fields that are only a few times larger than H_{c1}, the analysis of the magnetization data suggests an opposite anisotropy of the zero-field critical-current densities.

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