Anisotropic flux pinning and upper critical fields of the heavy-fermion superconductor URu_2Si_2

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Using the Hall-probe technique, the magnetization anisotropy of URu_2Si_2 was studied as a function of magnetic field and tem-perature. The flux-pinning force, F_p(T,H), is anisotropic and for H//a-axis turns out to be strongly enhanced at large field. The temperature dependence of H_{c2} reveals the unusual nature of this compound: an unconventional order parameter is present or interactions between magnetism and superconductivity occur.

Keywords: heavy-fermion compounds, magnetic superconductors, magnetization, flux pinning

Recently, interest was revived in the heavy-fermion superconductor (T_c=1.2 K) and antiferromagnet (T_N=17 K), URu_2Si_2. At low temperatures, the upper critical field H_{c2} becomes 4-5 times larger for fields along the a-axis compared to fields along its tetragonal c-axis. However, only a small anisotropy in the first critical field, H_{c1}, is found ($H_{c1}\approx$30 Oe at T=0 and isotropic, according to ref. [1]; $H_{c1}\approx$10 and 15 Oe for H//a and H//c, respectively, according to our recent measurements on a cube-shaped sample [2]).

Using the Hall-probe technique, we have studied for the first time the magnetization anisotropy at fields up to H_{c2}. A large number of M_{ZFC}(T) curves has been registered in different magnetic fields. Then, after taking the data-points for the same temperature from all registered curves, the M(H) dependence is constructed for a given temperature.

M(T) curves have a smooth, power-like shape near T_c(H). This behaviour is consistent with the flux-pinning theories which predict that the flux-pin-ning force, $F_p=j_c\cdot H$, decreases to zero according to $(1-H/H_{c2})^q$ near H_{c2}. Since the magnetization at large fields is proportional to the critical current, it should behave in the same way near H_{c2}. This is shown in fig. 1, where M(T) curves for H//a are drawn, with arrows indicating the points of deviation from the simple power-law relation. Continuation of the straight lines in fig. 1 to M=0 allowed to determine T_c(H) precisely.

The temperature dependence of H_{c2}(T) can not be described by the standard approximation, $H_{c2}(T)= H_{c2}(0)\cdot(1-t^2)$, with $t=T/T_{c0}$. We made an attempt to fit the H_{c2}(T) results, using the dirty-limit equations. For H//c, it is possible to get an excellent agreement between calculated results and measurements under the assumption that the Pauli term plays an important role. With the effective g-factor value of 2, a value for the spin-orbit scattering parameter, λ_{SO}, of 0.2 is obtained. For H//a, only a less accurate estimate of the parameters is possible because the used equations can not reproduce the upward curvature of H_{c2} observed there near T_c. For the orbital critical fields we obtain $H^{*a}{}_{c2}$=97.6 kOe and $H^{*c}{}_{c2}$=56.4 kOe, for H//a and H//c, respectively. This anisotropy of $H_{c2}{}^{*a,c}$ is consistent with the anisotropy of H_{c1} which was reported previously [2]. For the coherence lengths obtained from the expressions $H^{*c}{}_{c2}= \Phi_0/(2\pi\xi_a{}^2)$ and $H^{*a}{}_{c2}=\Phi_0/(2\pi\xi_c\xi_a)$, we have ξ_a=130 Åand ξ_c=75 Å. From the hight of the specific heat jump at T_c, one can estimate the value of the thermodynamic critical field, H_c, to be about 150 Oe. Then, the Ginzburg-Landau parameter κ_{GL} and H_{c1} can be computed according to $\kappa_{GL}=H^{*c}{}_{c2}\ /(\sqrt{2}\cdot H_c)$ and $H_{c1}\cdot H^{*}{}_{c2}= \ln(\kappa_{GL})\cdot H_c{}^2$. One gets κ_{GL}=266 and a value for H_{c1} of about 2.2 Oe only, for H//c. This is a much lower value than any reported estimate of H_{c1} for this material.

The quantity $4\pi M\cdot H$ is proportional to the flux-pinning force. The conventional scaling [3],

$$F_p = A(T) \cdot h^p \cdot (1-h)^q\,, \quad h = H/H_{c2}\,, \quad A(T) \sim H_{c2}^{p+q}\,, \qquad (1)$$

fails to describe the experimental data of URu_2Si_2. Kramer [3] predicts p=0.5 and q=2 in eq. (1) but we observe that the shape of the $F_p(H/H_{c2})$ curves changes with temperature. Nevertheless, in order to characterize the obtained results, attempts were made to find scaling relations between the flux pinning, h and t. An example is given in fig. 2, where a scaling to the high-field side of the data at T=820 mK is shown: all the results for $4\pi M\cdot H$ were multiplied by a scaling coefficient, dependent on temperature, in order to obtain a coincidence of the data near H_{c2}. A similar method was applied for the scaling at the low-field side. The following sets of the exponents were found. For high-field scaling, $F_p=(1-h)^q(1-t^2)^r$, with q=2.2 and r=3.4 for H//a and q=3 and r=2.8 for H//c. For low-field scaling, $F_p=h^p(1-t^2)^s$, with p=0.5 and s=2.4 for H//a and p=0.5 and s=2.6 for H//c.

There is a clear indication from the M(T) dependences (fig. 1) and from the scaling of the flux-pinning force (fig. 2) that a narrow region near $T_c(H)$ exists where a different temperature or field dependence should be used for the studied quantity than in a region more distant from the critical point. Figure 3 presents data points indicating a cross-over between these pinning re-gions. Similar results we obtained also for H//c. One can find an analogy between the diagram of fig. 3 and a diagram constructed from elastic constants and susceptibility measurements [4]. There is also a similarity of these diagrams with the phase diagram of an unconventional superconduc ting state in URu_2Si_2 predicted theoretically by Joynt and Bark [5]. These authors studied different consequences of a coupling between a two-dimensional order parameter of the superconducting state and the magnetism in this compound.

The characteristic parameters of URu_2Si_2, κ_{GL} and H_{c1}, calculated from the thermodynamic critical field and our estimates of H_{c2}^*, indicate an extreme type-II character of this superconductor. The $H_{c2}(T)$ dependences and the flux-pinning curves reveal the unusual nature of its superconducting properties: either an unconventional order parameter is present or a complex interactions between magnetism and superconductivity occur.

References

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Figure Captions

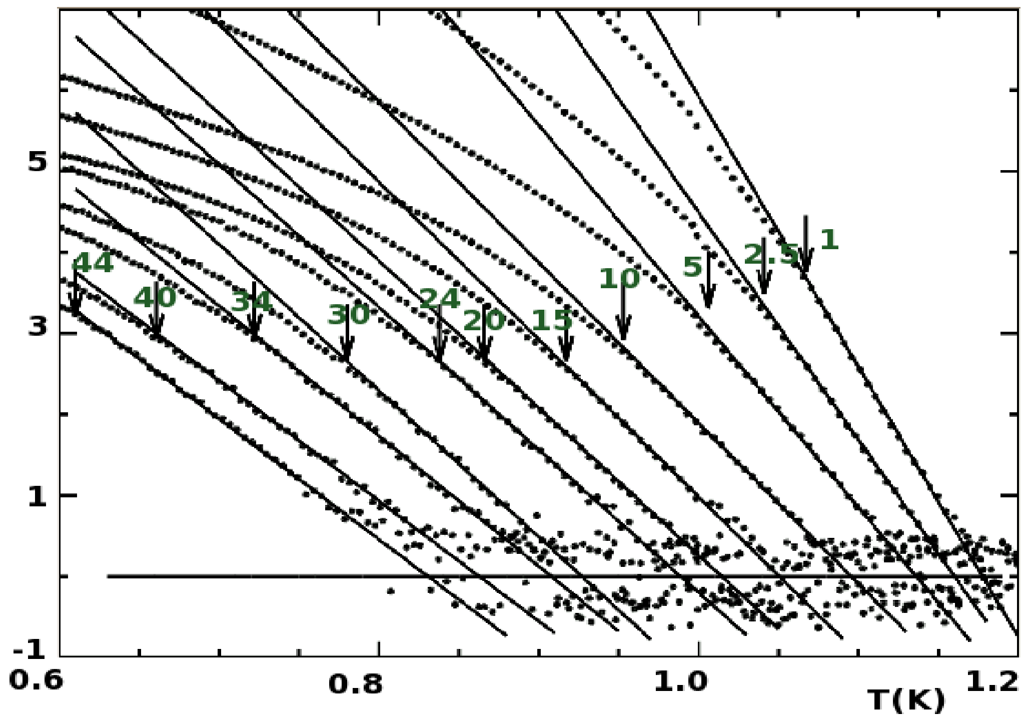

Figure 1: (-4πM) $^{1/2.2}$ vs. T plot for H//a-axis, for field values (in kOe) indicated in the figure. The straight lines indicate the power-like M(T) dependence near T_c(H).

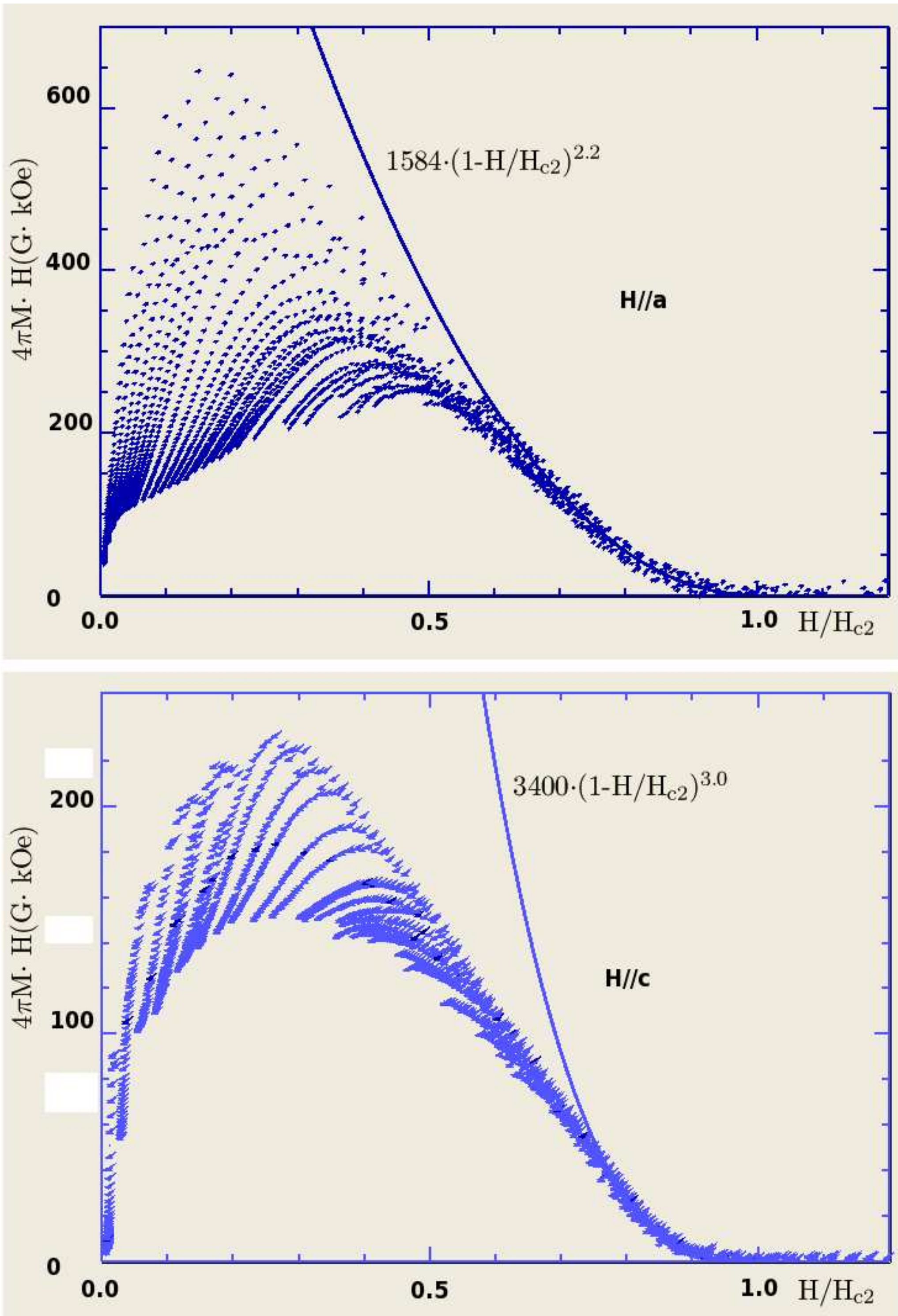

Figure 2: High-field-side magnetization scaling of a URu_2Si_2 sample to the data determined at T=0.820 K. The inner envelopes of the data points would give the scaling function at low temperatures while the outer envelopes at about T=1K.

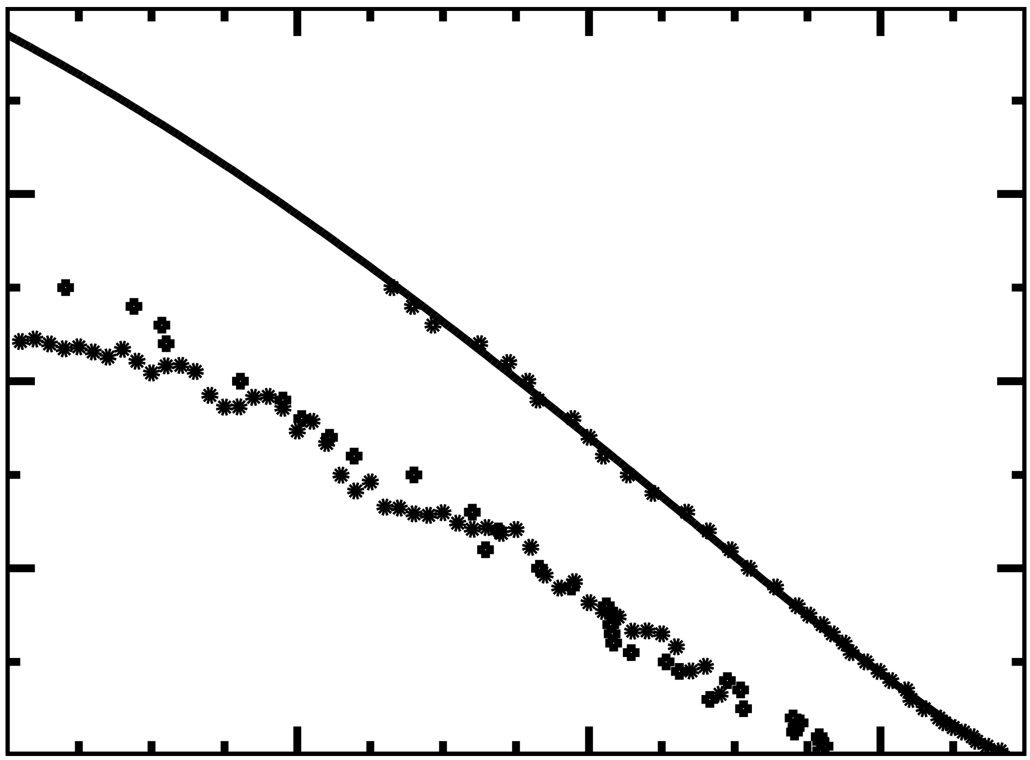

Figure 3: The cross-over fields between the power-like dependence of the flux-pinning force on (1-H/H_{c2}), near H_{c2}, and a different type of dependence at lower fields. Full symbols correspond to the positions of arrows in fig. 1 and empty symbols were obtained from the departure of the data from the solid line in fig. 2.