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

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Abstract

Using the Hall-probe technique, the magnetization anisotropy of URu_2Si_2 was studied as a function of magnetic field and temperature. The flux-pinning force, $F_p(T, H)$, is anisotropic and for $H \parallel a$-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.

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 $H \parallel a$ and $H \parallel c$, 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 behavior is consistent with the flux-pinning theories which predict that the flux-pinning force, $F_p = j_c H$, 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 $H \parallel a$ 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 $H_{c2}(T)$ cannot be described by the standard approximation, $H_{c2}(T) = H_{c2}(0)(1 - t^2)$, with $t = T/T_{c0}$. We made an attempt to fit the $H_{c2}(T)$ results, using the dirty-limit equations. For $H \parallel c$, 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 $H \parallel a$, only a less accurate estimate of the parameters is possible because the used equations cannot reproduce the upward curvature of H_{c2} observed there near T_c. For the orbital critical fields we obtain $H_{c2}^{*a} = 97.6$ kOe and $H_{c2}^{*c} = 56.4$ kOe, for $H \parallel a$ and $H \parallel c$, 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 $H_{c2}^{*c} = \Phi_0/(2\pi\xi_a^2)$ and $H_{c2}^{*a} = \Phi_0/(2\pi\xi_c\xi_a)$, we have $\xi_a = 130$ Å and $\xi_c = 74$ Å. From the height 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 $\kappa_{GL} = H_{c2}^{*c}/(\sqrt{2}\, H_c)$ and $H_{c1}H_{c2}^{*} = \ln(\kappa_{GL})\, H_c^2$. One gets $\kappa_{GL} = 266$ and a value for H_{c1} of about 2.2 Oe only, for $H \parallel c$. This is a much lower value than any reported estimate of H_{c1} for this material.

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

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

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

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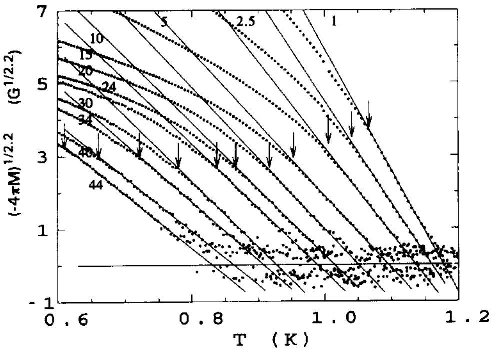

Fig. 1. $(-4\pi M)^{1/2}$ vs. T plot for $H \parallel a$-axis, for field values (in kOe) indicated in the figure. The straight lines indicate the power-like $M(T)$ dependence near $T_c(H)$.

$4\pi MH$ 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 $H \parallel a$ and $q = 3$ and $r = 2.8$ for $H \parallel c$. For low-field scaling, $F_p = h^p(1-t^2)^s$, with $p = 0.5$ and $s = 2.4$ for $H \parallel a$ and $p = 0.5$ and $s = 2.6$ for $H \parallel c$.

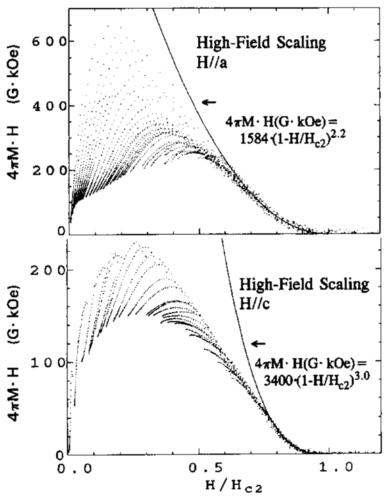

Fig. 2. High-field-side magnetization scaling of a URu_2Si_2 sample to the data determined at $T = 0.820$ K. The inner envelopes of the data points would give the scaling function at low temperatures while the outer envelopes at about $T = 1$ K.

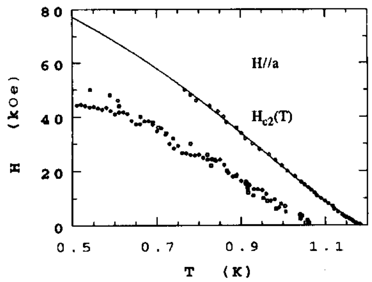

Fig. 3. The cross-over fields between the power-like dependence of the flux-pinning force on $(1-H/H_{c2})$, near H_{c2}, and a different type of dependence at lower fields. Full symbols correspond to the positions of arrows in Fig. 1 and empty symbols were obtained from the departure of the data from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

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. Fig. 3 presents data points indicating a cross-over between these pinning regions. Similar results we obtained also for $H \parallel c$. 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 superconducting 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 complex interactions between magnetism and superconductivity occur.

References

[1] S. Wüchner et al., Solid State Commun. 85 (1993) 355.
[2] Z. Koziol et al., IEEE Trans. Magn. 30 (1994) 1193.
[3] E.J. Kramer, J. Appl. Phys. 44 (1973) 1360.
[4] P. Thalmeier et al., Physica C 175 (1991) 61.
[5] R. Joynt and H. Bark, Phys. Rev. B 44 (1991) 12023.