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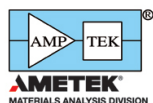
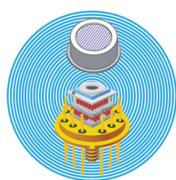
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# Anisotropy of the upper critical field in the magnetic heavy-fermion superconductor URu<sub>2</sub>Si<sub>2</sub>

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Measurements have been performed of the upper critical field  $H_{c2}$  anisotropy in the magnetic heavy-fermion superconductor URu<sub>2</sub>Si<sub>2</sub>. The  $dH_{c2}/dT$  value is constant within 5% when  $\mathbf{H}$  is rotated in the basal plane, whereas  $|dH_{c2}/dT|$  decreases by about 35% for  $\mathbf{H}$  rotated by 20°–30° out of the basal plane. Contrary to CeCu<sub>2</sub>Si<sub>2</sub> the  $H_{c2}$  anisotropy in URu<sub>2</sub>Si<sub>2</sub> is enhanced as temperature decreases below  $T_c$ . This disparity can be attributed to the different strengths of paramagnetic and spin-orbit effects responsible for the suppression of superconductivity by a magnetic field in CeCu<sub>2</sub>Si<sub>2</sub> and URu<sub>2</sub>Si<sub>2</sub>.

Recently the discovery of the magnetic heavy-fermion superconductor (HFS) URu<sub>2</sub>Si<sub>2</sub> has been reported.<sup>1–3</sup> This compound is characterized by a large linear specific-heat coefficient  $\gamma = 180$  mJ/mole K<sup>2</sup> and exhibits both antiferromagnetic and superconducting transitions at  $T_N = 17.5$  K and  $T_c = 1.2$  K, respectively. The URu<sub>2</sub>Si<sub>2</sub> compound, as well as the first-known HFS CeCu<sub>2</sub>Si<sub>2</sub>,<sup>4</sup> crystallize in the ThCr<sub>2</sub>Si<sub>2</sub> tetragonal structure. Hence we can compare the anisotropy of superconducting properties in magnetic and nonmagnetic heavy-fermion superconductors of the same crystal structure. Furthermore, it is interesting to apply the recent results of the symmetry classification for possible superconducting classes in HFS<sup>5</sup> in order to identify the superconducting state in URu<sub>2</sub>Si<sub>2</sub>.

In this paper we present the results of the upper critical field  $H_{c2}$  measurements in a URu<sub>2</sub>Si<sub>2</sub> single-crystal sample for different orientations of the magnetic field  $H$  with respect to the crystal axis.

The single-crystal samples were grown by a specially adapted Czochralski method. The as-grown crystal was annealed for 7 days at 1000 °C. A rectangular sample of typical dimensions  $1 \times 1 \times 5$  mm<sup>3</sup> was spark cut. Thin Cu probes for dc measurements were spark welded to the sample. The electric resistivity was obtained with a standard four-probe method, using a dc current of 1 mA. During computerized measurements the signal was averaged at each temperature interval  $T \pm \Delta T$  ( $\Delta T \approx 2$  mK) over 10 data points for a given current direction. The temperature was determined with a calibrated carbon-glass thermometer. The experimental apparatus,<sup>6</sup> consisting of one solenoid and two pairs of Helmholtz coils, makes it possible to rotate a chosen  $\mathbf{H}$  vector arbitrarily in 3D space. For fixed  $H = H_0$  the resistive transition was tracked and then least-square fitted between  $0.2\rho_0$  and  $0.8\rho_0$  by a linear dependence. The  $T_c(H_0)$  value was determined as the intersection point of this dependence with the  $0.5\rho_0$  straight line. Here  $\rho_0$  stands for the residual resistivity, which for our sample was  $\rho_0 = 26 \mu\Omega$  cm. The superconducting transition at  $H = 0$ ,  $T_{c0} = T_c = 1.16$  K, has the

width  $\Delta T = 0.12$  K between  $0.1\rho_0$  and  $0.9\rho_0$ .

Figure 1 shows the  $H_{c2}$ -vs- $T$  curves for two  $\mathbf{H}$  orientations,  $\mathbf{H}||c$  and  $\mathbf{H}||a$ . These data are in good agreement with  $H_{c2}(T)$  results obtained in Ref. 1 on other single-crystal URu<sub>2</sub>Si<sub>2</sub> samples. In low magnetic fields,  $H < 0.5$  kOe, the initial slope  $dH_{c2}/dT$  is almost the same for both  $\mathbf{H}||c$  and  $\mathbf{H}||a$  directions. As the external magnetic field is increased, the  $H_{c2}(T)$  curves exhibit a concave behavior in the vicinity of  $T = T_c(H = 0)$ .

Figure 2 displays the angular dependence of the  $dH_{c2}/dT$  derivative determined for  $\mathbf{H}$  rotated in the basal plane. Here the  $dH_{c2}/dT$  value was calculated as the ratio  $H(= 3 \text{ kOe}) / [T_{c0} - T_c(H = 3 \text{ kOe})]$ . No  $H_{c2}$  anisotropy has been found in this case, at least within the experimental error bars of approximately 5%.

The  $dH_{c2}/dT$  vs  $\theta$  dependencies are shown in Fig. 3 for  $\mathbf{H}$  rotated by an angle  $\theta$  away from the  $a$  axis into the  $ac$

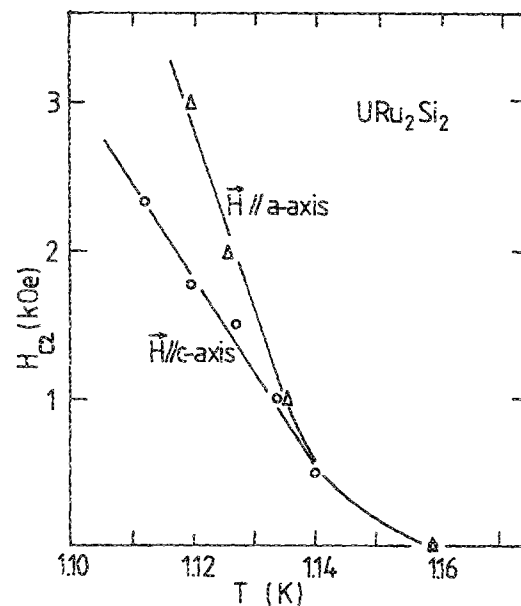


FIG. 1. Temperature dependencies of the upper critical field  $H_{c2}$  in URu<sub>2</sub>Si<sub>2</sub> for  $\mathbf{H}||a$  ( $\Delta$ ) and  $\mathbf{H}||c$  ( $\circ$ ).

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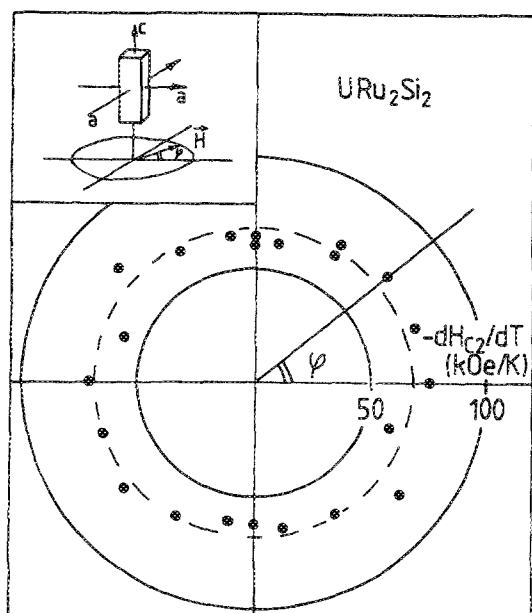


FIG. 2. Angular dependence of the derivative  $-dH_{c2}/dT = H(=3 \text{ kOe})/T_c(H=0) - T_c(H=3 \text{ kOe})$  for  $\mathbf{H}$  being rotated in the basal ( $ab$ ) plane.

plane. A 35% decrease is found in the slope  $|dH_{c2}/dT|$  for  $\mathbf{H}$  rotated by  $20^\circ$ – $30^\circ$  out of the basal plane. The  $dH_{c2}/dT$  anisotropy decrease becomes even larger ( $\approx 50\%$ ) when we determine the  $dH_{c2}/dT$  value as the ratio  $[H(=3 \text{ kOe}) - H(=1 \text{ kOe})]/[T_c(H=1 \text{ kOe}) - T_c(H=3 \text{ kOe})]$  corresponding to the slope of linear parts of  $H_{c2}$ -vs- $T$  curves in Fig. 1.

The main features of the  $H_{c2}$  anisotropy in  $\text{URu}_2\text{Si}_2$ , especially the  $H_{c2}$ -vs- $\phi$  dependence for  $\mathbf{H}$  lying in the basal plane, are the same as in  $\text{CeCu}_2\text{Si}_2$ .<sup>7</sup> However, at the same time, there are some important differences in the  $H_{c2}(T)$  behavior between  $\text{URu}_2\text{Si}_2$  (see Figs. 1–3) and  $\text{CeCu}_2\text{Si}_2$ .<sup>7</sup> First of all, the  $\mathbf{H}$  anisotropy in  $\text{CeCu}_2\text{Si}_2$  is larger for tem-

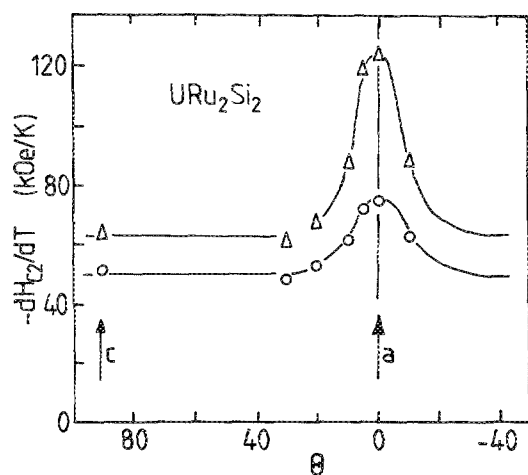


FIG. 3. Angular dependence of the derivative  $-dH_{c2}/dT$  for  $\mathbf{H}$  rotated from the  $a$  to  $c$  axis. For the lower curve  $-dH_{c2}/dT = H(=3 \text{ kOe})/T_c(H=0) - T_c(H=3 \text{ kOe})$ , whereas for the upper curve we use the slope of the linear parts of the  $H_{c2}$ -vs- $T$  curves between 1 and 3 kOe (see Fig. 1).

peratures close to  $T_{c0}$ , whereas in  $\text{URu}_2\text{Si}_2$  the  $H_{c2}$  anisotropy increases from zero as  $T$  becomes less than  $T_{c0}$ . This is illustrated in Fig. 1. On the other hand, the  $dH_{c2}/dT$  vs  $\theta$  dependence for  $\mathbf{H}$  being rotated from the  $a$  to  $c$  axis is much sharper for  $\text{CeCu}_2\text{Si}_2$  than for  $\text{URu}_2\text{Si}_2$  (Fig. 3). The difference in the  $H_{c2}$  anisotropy of  $\text{CeCu}_2\text{Si}_2$  and  $\text{URu}_2\text{Si}_2$  can be interpreted in terms of the paramagnetic effect being more significant (see below) for the suppression of superconductivity by a magnetic field in the case of  $\text{URu}_2\text{Si}_2$ . While the spin-orbit scattering is expected to be larger in  $\text{URu}_2\text{Si}_2$  than in  $\text{CeCu}_2\text{Si}_2$ , its exact influence on  $H_{c2}$  as a function of orientation is unknown. Further critical field studies at lower temperatures are warranted.

The 2D ferromagnetic ordering<sup>8</sup> of the strongly Kondo screened effective moments in the basal planes of  $\text{URu}_2\text{Si}_2$  reduces the  $H_{c2}(0)$  value for  $\mathbf{H}||c$ , whereas for  $\mathbf{H}$  lying in the basal plane, the electron orbits intersect many different planes with oppositely oriented spins (the interplane coupling is antiferromagnetic) and this leads to a higher  $H_{c2}(0)$ . Qualitatively this is in agreement with the observation that the  $H_{c2}$  anisotropy increases as  $T$  is further decreased.

The absence of the fourfold  $H_{c2}(\phi)$  rosette in the basal plane (Fig. 2) excludes the possibility of  $p$ -wave (odd parity) pairing in  $\text{URu}_2\text{Si}_2$ , as was shown by symmetry considerations by Volovik and Gor'kov.<sup>5</sup> However, a slight chance for such pairing still remains if, due to the fact that the electron effective mass along the  $c$  axis is much larger than in the basal plane, the fourfold rosette in the basal plane is strongly smeared out, as was calculated by Burlachkov.<sup>5</sup> In this situation we probably could not observe an  $H_{c2}(\phi)$  rosette within the limits of our error experimental bars (see Fig. 2). Experimentally there are no indications of an anisotropy of the electron effective mass. Still, the situation is complicated by the gapped Fermi surface due to the magnetic ordering at 17.5 K.<sup>1,3</sup>

In conclusion, we have measured the  $H_{c2}$  anisotropy in the magnetic HFS  $\text{URu}_2\text{Si}_2$ . The  $H_{c2}$  behavior at fixed temperature in  $\text{URu}_2\text{Si}_2$  is similar to that in  $\text{CeCu}_2\text{Si}_2$ , but the temperature dependence of the ratio  $H_{c2}(\mathbf{H}||a)/H_{c2}(\mathbf{H}||c)$  and the  $\theta$  ( $a \rightarrow c$  axis) dependence of  $-dH_{c2}/dT$  are quite different for these two compounds. This indicates the importance of magnetic ordering for the suppression of superconductivity in  $\text{URu}_2\text{Si}_2$  by a magnetic field.

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