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Anisotropic variation of T_c and T_N in URu_2Si_2 by uniaxial pressure

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The effect of uniaxial stress on the superconducting and magnetic transition temperature in the heavy-fermion system URu_2Si_2 has been investigated by means of resistivity measurements. The uniaxial pressure effects on T_c and T_N are inversely connected: T_c increases and T_N decreases for a stress along the tetragonal axis, while a stress in the plane results in the opposite effect.

The unusual coexistence of superconductivity ($T_c \approx 1$ K) and antiferromagnetic order ($T_N = 17.4$ K) [1] in the tetragonal heavy-fermion compound URu_2Si_2 has given rise to speculations about an unconventional pairing mechanism in the superconducting state, i.e. Cooper pairing mediated by antiferromagnetic interactions instead of by the usual electron-phonon interaction. Evidence for the coexistence of magnetism and superconductivity comes mainly from neutron-scattering experiments [2]. The ordered moment in URu_2Si_2 is extremely small ($|\mu| = (0.03 \pm 0.01)\mu_B$/f-atom) [2]. The question arises whether this small ordered moment can give rise to two superconducting transitions as recently reported for the small-moment superconductor UPt_3 [3]. The double superconducting transition in UPt_3 is possibly explained by a lifting of the order parameter by a symmetry-breaking field (the small ordered moment) [4]. However, as the moment in URu_2Si_2 is oriented along the tetragonal (c) axis, the crystal symmetry is not broken. A possible other way to induce several superconducting phases in a superconductor with non-trivial pairing, is by a lattice distortion brought about by uniaxial stress [5]. In this paper we report on the first investigations of the effect of a uniaxial stress ($P_i \leqslant 2$ kbar) on T_c and T_N of URu_2Si_2 by means of resistivity measurements.

As we were afraid to damage the single-crystalline sample by pressurizing, we used a specimen with moderate superconducting properties. The crystal was grown by a modified tri-arc Czochralski method using a very high pulling rate (100 mm/h). No additional annealing was applied. The crystal was shaped into a rectangular bar (dimension 0.76 (c-axis) $\times$ 0.80 (a-axis) $\times$ 2.62 (a-axis) mm^3) by means of sparc erosion. The residual resistance ratio, $\rho(300\ K)/\rho(1.5\ K)$, amounts to 18. The crystal was mounted in a uniaxial pressure cell made of a beryllium-copper alloy [6]. The pressure was applied either along the c-axis or along the (short) a-axis. Pressure was monitored by strain gauges that measure the calibrated deformation of the cell. The absolute uncertainty in the pressure determination amounts to 10%, while the relative accuracy amounts to 0.02 kbar. After each run, the cell and sample were warmed up to room temperature in order to change the pressure. The resistivity was measured with a standard ac-technique (with the current along the long a-axis).

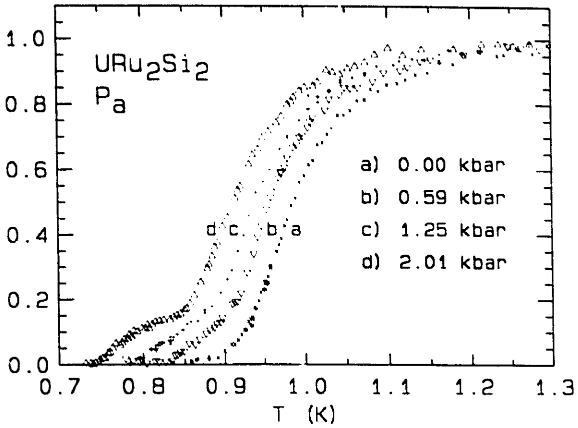

Fig. 1. Superconducting transition of single-crystalline URu_2Si_2 for uniaxial pressure (as indicated) along the a-axis.

The superconducting and antiferromagnetic transitions measured resistively, for a pressure along the a-axis (P_a), are shown in figs. 1 and 2, respectively. The data are normalized to 1 (at 1.5 K in fig. 1 and at T_N in fig. 2), because of small irreproducibilities in the absolute value of the resistivity. These irreproducibilities (5% of the absolute resistivity value) are caused by

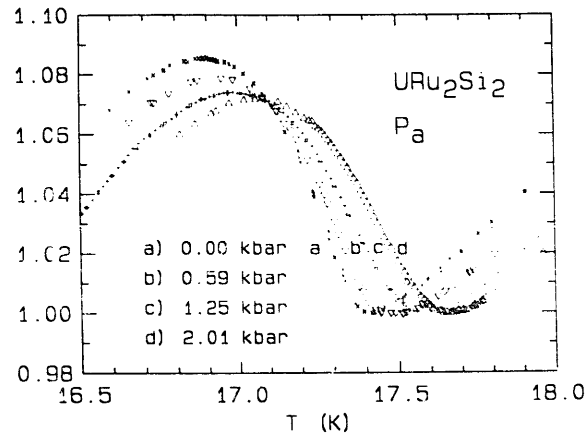

Fig. 2. Antiferromagnetic transition of single-crystalline URu_2Si_2 for uniaxial pressure (as indicated) along the a-axis.

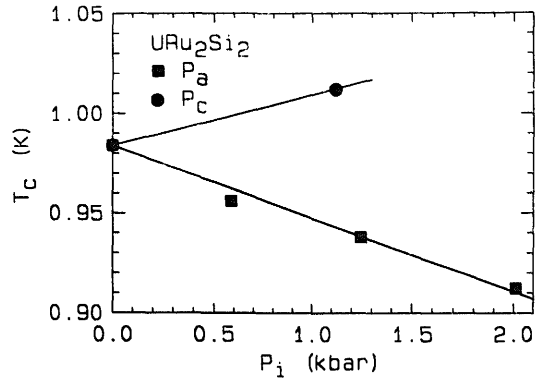

Fig. 3. T_c of single-crystalline URu_2Si_2 as function of uniaxial pressure along the a- (■) and c-axis (●).

small changes of the voltage contacts at thermal cycling and by cracks at applying pressure. A stress of 2 kbar along the a-axis left the sample intact. The crystal appeared to be much weaker for a stress along the c-axis: for P_c larger than ~1 kbar it broke (also a second crystal broke at about the same pressure). A shoulder appeared at the low-temperature side of the superconducting transition with increasing pressure along the a-axis. After releasing the pressure, the value of T_c, as obtained before pressurizing, reproduced, but a trace of the shoulder remained. The appearance of a second transition (indicated by the shoulder) is likely connected to a sample inhomogeneity [7], and not to the appearance of a second superconducting phase. The transitions do not broaden noticeably under pressure, indicating a rather homogeneous pressure.

The variations of T_c and T_N with P_a and P_c are shown in figs. 3 and 4. T_c has been determined by the midpoint of the transition, while T_N has been determined by the local minimum in $R(T)$. Note that T_c increases and T_N decreases for P_c, while for P_a the opposite effects is observed. In a first approximation the pressure variation is taken as linear: $dT_c/dP_a = -35$ mK/kbar, $dT_c/dP_c = 25$ mK/kbar, $dT_N/dP_a = 126$ mK/kbar and $dT_N/dP_c = -41$ mK/kbar. The present data can be compared with the hydrostatic

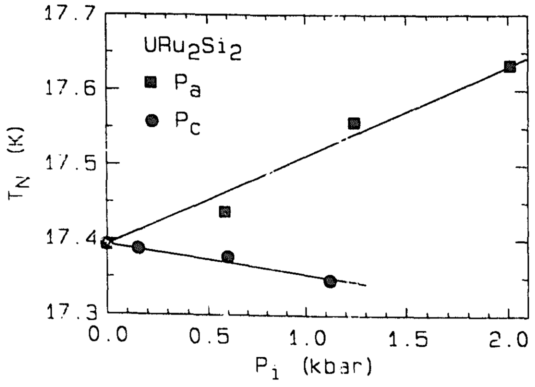

Fig. 4. T_N of single-crystalline URu_2Si_2 as function of uniaxial pressure along the a- (■) and c-axis (●).

pressure dependence of T_c and T_N by taking $dT_{c,N}/dP = dT_{c,N}/dP_c + 2dT_{c,N}/dP_a$, yielding $dT_c/dP = -45$ mK/kbar and $dT_N/dP = 211$ mK/kbar. Specific-heat measurements under hydrostatic pressure yield $dT_c/dP = -56$ mK/kbar and $dT_N/dP = 127$ mK/kbar [8], whereas resistivity measurements under hydrostatic pressure yield $dT_c/dP = -95$ mK/kbar [9] and $dT_N/dP = 130$ mK/kbar [9,10]. Similar values have been deduced from the discontinuities in the thermal expansion and the specific heat at T_c and T_N using the Ehrenfest relation [6,11,12]. The reported values for dT_c/dP and dT_N/dP are somewhat at variance with each other, which is probably related with the reported sample inhomogeneity [7]. It has been suggested that the inverse correlation of T_c and T_N, as follows from the hydrostatic pressure experiments, is consistent with superconductivity and antiferromagnetism (of the spin-density wave type) competing for parts of the Fermi surface [9]. As the inverse correlation of T_c and T_N also holds for uniaxial pressure, further support for this idea is provided.

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