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Anisotropic variation of $T_c$ and $T_N$ in URu$_2$Si$_2$ 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$_2$Si$_2$ 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 ($T_c = 1$ K) and antiferromagnetic order ($T_N = 17.4$ K) [1] in the tetragonal heavy-fermion compound URu$_2$Si$_2$ 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$_2$Si$_2$ 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$_2$Si$_2$ 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].

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 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) × 0.80 (a-axis) × 2.62 (a-axis) mm$^3$) by means of spark erosion. The residual resistance ratio, $\rho(300 \text{ K})/\rho(1.5 \text{ K})$, 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).

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. 1. Superconducting transition of single-crystalline URu$_2$Si$_2$ for uniaxial pressure (as indicated) along the a-axis.](image1)

![Fig. 2. Antiferromagnetic transition of single-crystalline URu$_2$Si$_2$ for uniaxial pressure (as indicated) along the a-axis.](image2)
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 phase 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 transitions 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 \( \varepsilon \) 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 first approximation the pressure variation is taken as linear: \( dT_c/dP_a = -35 \text{ mK/kbar} \), \( dT_c/dP_c = 25 \text{ mK/kbar} \), \( dT_N/dP_a = 126 \text{ mK/kbar} \) and \( dT_N/dP_c = -41 \text{ mK/kbar} \). The present data can be compared with the hydrostatic pressure dependence of \( T_c \) and \( T_N \) by taking \( dT_{c,N}/dP = dT_{c,N}/dP_a + 2dT_{c,N}/dP_a \), yielding \( dT_c/dP = -45 \text{ mK/kbar} \) and \( dT_N/dP = 127 \text{ mK/kbar} \) [8], whereas resistivity measurements under hydrostatic pressure yield \( dT_c/dP = -56 \text{ mK/kbar} \) and \( dT_N/dP = 127 \text{ mK/kbar} \) [8]. Specific-heat measurements under hydrostatic pressure yield \( dT_c/dP = -95 \text{ mK/kbar} \) [9] and \( dT_N/dP = 130 \text{ mK/kbar} \) [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 \( dT_{c,N}/dP \) 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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References

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