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THERMAL EXPANSION OF HEAVY-FERMION SUPERCONDUCTORS

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We have measured the coefficients of linear thermal expansion (α) of single-crystalline samples of the heavy-fermion superconductors UPt_3, URu_2Si_2 and UBe_{13}. For the non-cubic systems α shows a remarkable anisotropy. On entering the superconducting state a strong reduction of the volume expansion is observed for all three systems.

1. INTRODUCTION

The occurrence of superconductivity in the heavy-fermion compounds is undoubtedly an intriquing phenomenon and has received a wide interest, because of the unusual behaviour in the superconducting state. The measured large anomalies in the specific heat at the superconducting transition temperature (T_c) have shown unambiguously that the heavy fermions take part in the superconducting condensate. It is then of interest to investigate the corresponding volume and shape effects. Our normal state volume thermal expansion (α_v) measurements (1-3) yield large linear electronic terms at low temperatures, α_v= aT, just as the specific heat, c= γT, and give rise to large electronic Grüneisen parameters, $\Gamma \propto a/\gamma \simeq 50$ (4,5). From this we conclude that large volume changes can be expected at T_c. In this paper we present thermal-expansion measurements on the uranium based heavy-fermion compounds UPt_3, URu_2Si_2 and UBe_{13}. In order to study the anisotropy in the coefficients of linear thermal expansion, $\alpha = L^{-1}(dL/dT)$, the experiments have been performed on single-crystalline specimens.

2. EXPERIMENTAL

The samples were mounted in a dilatation cell (6) machined of OFHC copper. The thermal expansion was measured using a sensitive 3-terminal capacitance method with a detection limit of 0.1 Å. In the case of UPt_3, the cell was attached to the mixing chamber of a dilution refrigerator, whereas in the case of URu_2Si_2 and UBe_{13} it was attached to the cold plate of a ^3He cryostat. Data points were gathered stepwise ($\Delta T>$ 5 mK) in order to ensure thermal equilibrium of sample and cell. The data have been corrected for the cell effect, i.e. the signal of the cell with a copper sample.

3. RESULTS

The thermal expansion of hexagonal UPt_3 has been studied for two samples (7). In Fig.1 we present data taken on the specimen prepared by L.Taillefer (size 1x2x3 mm^3). The superconducting transition is most clearly observed in the expansion along the hexagonal axis ($\alpha_{//}$), where a negative jump occurs at a (midpoint) transition temperature of 490 mK.

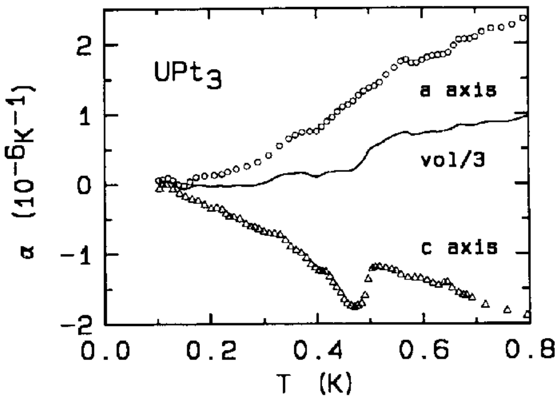

FIGURE 1
Coefficient of linear thermal expansion of UPt_3 for the a and c axis as indicated. The solid line represents $\alpha_v/3$.

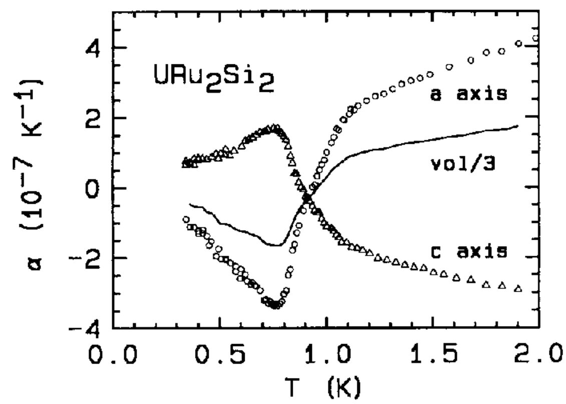

FIGURE 2
Coefficient of linear thermal expansion of URu_2Si_2 for the a and c axis as indicated. The solid line represents $\alpha_v/3$.

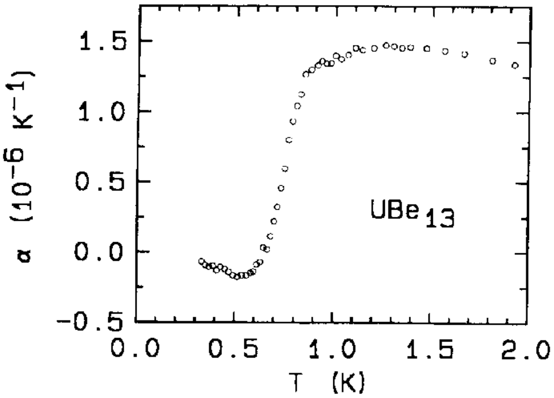

FIGURE 3
Coefficient of linear thermal expansion of UBe_{13}.

For the coefficient of thermal expansion in the basal plane ($\alpha_{\perp}$) no discontinuity is observed at T_c. The temperature variation of $\alpha_{\perp}$ changes from linear above T_c to quadratic there below. The overall anisotropy is preserved below T_c: the c-axis contracts and the basal plane expands with raising temperature. Recently, specific heat measurements have revealed the existence of two transitions at T_{c1}= 490 mK and T_{c2}= 430 mK in UPt_3 (8), that are thought to originate from a splitting of the superconducting transition by a symmetry breaking field. The transition at T_{c2} could not be detected from the data in Fig.1, but having increased the temperature resolution and the sensitivity of our dilatometer we have indeed resolved an anomaly at T_{c2} (9).

The coefficients of linear thermal expansion along ($\alpha_{//}$) and at right angles ($\alpha_{\perp}$) to the tetragonal axis of URu_2Si_2 have been measured in the temperature range 0.3-2 K (see Fig.2). The sample (size 5x5x5 mm^3) has been prepared by the Czochralski technique by A.A.Menovsky. Superconductivity sets in near 1.1 K, below which temperature broad anomalies are observed: $\alpha_{\perp}$ shows a rapid drop below T_c and attains a negative mimimum at 0.75 K, while $\alpha_{//}$ increases and has a positive maximum at 0.75 K. We would like to draw special attention to the reversal of anisotropy: well below T_c the tetragonal axis expands and the basal plane contracts, whereas in the normal state the contrary takes place.

The coefficient of linear thermal expansion of cubic UBe_{13} (prepared by J.L.Smith; sample size 2x4x6 mm^3) is shown in Fig.3, for 0.3<T<2 K. The normal-state expansion shows a weak maximum near 1.3 K, that is attributed to the Kondo-lattice effect. Superconductivity sets in at 0.85 K, where α starts to fall rapidly. A negative mimimum is attained at 0.52 K. Similar data have been obtained by Ott (10).

For UPt_3 and URu_2Si_2 the volume expansion has been calculated from $\alpha_v = \alpha_{//} + 2\alpha_{\perp}$ (see Figs 1 and 2). For all three compounds we observe a strong reduction of α_v on entering the superconducting state, which indicates that a positive volume is associated with the formation of the ground state. The Grüneisen parameters drop from large positive values above T_c, to small negative values well below T_c.

4. DISCUSSION

In a first analysis the anomaly in α_v at T_c can be used to calculate the pressure dependence of T_c via the Ehrenfest relation: $dT_c/dP= V_m T_c \Delta\alpha_v/\Delta c_p$ (V_m is the molar volume, and $\Delta\alpha_v$ and Δc_p are the jumps in the volume expansion and specific heat at T_c, respectively). From the data in Figs 1-3 and published specific heat data we derive values for dT_c/dP of -16.3, -101 and -19.4 mK/kbar for UPt_3, URu_2Si_2 and UBe_{13}, respectively. The values for the depression of T_c can be compared with the ones obtained from resistivity measurements as function of pressure: -24 (11), -95 (12) and -16 mK/kbar (13), respectively.

The anisotropy in α near T_c can be used to determine the uniaxial stress effects on T_c. For instance, in the case of UPt_3 the anomaly at T_c for $\alpha_{//}$ indicates a decrease of T_c for uniaxial stress along the c-axis, whereas stress in the basal plane will hardly effect T_c (7). In the case of URu_2Si_2 stress along c will increase T_c, whereas stress applied in the basal plane will lead to a reduction of T_c. In order to study further the volume and shape effects at the superconducting transitions in the heavy-fermion superconductors thermal expansion measurements in an external field are in progress.

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