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Uniaxial pressure dependence of the superconducting phase diagram of UPt_3

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Abstract

Thermal expansion and magnetostriction techniques have been applied in order to determine the superconducting phase diagram of UPt_3 ($B \parallel c$ and $B \perp c$). The uniaxial pressure dependence of the various phases, as determined with the Ehrenfest relations, is strongly anisotropic. For pressure along the c-axis we obtain $\mathrm{d}\Delta T_c/\mathrm{d}p_c = -22.3$ mK/kbar, and for pressure along the a-axis, $\mathrm{d}\Delta T_c/\mathrm{d}p_a = 4.9$ mK/kbar ($\Delta T_c = T_c^+ - T_c^-$). The phase diagrams are discussed in view of the relevant Ginzburg–Landau models.

The heavy-fermion superconductor UPt_3 is one of the strongest candidates for unconventional superconductivity. Measurements of the specific heat [1], the sound velocity [2] and the thermal expansion [3] in a magnetic field revealed a complex superconducting phase diagram with at least three superconducting (SC) phases. Dilatometry experiments were performed on a single-crystalline UPt_3 sample (dimensions $a \times b \times c = 3 \times 1 \times 2$ mm^3). The coefficient of linear thermal expansion, $\alpha(T) = L^{-1}\mathrm{d}L/\mathrm{d}T$, and the linear magnetostriction, $\lambda(B) = (L(B) - L(0))/L(0)$, were measured using a sensitive parallel-plate capacitance dilatometer [3]. Measurements of the dilatation along the c-axis, and recently along the a-axis, have been performed for $B \parallel a$, $B \parallel b$ and $B \parallel c$.

Locating the anomalies at the SC phase boundaries, detected by the thermal expansion and the magnetostriction measurements, in the B–T plane the SC phase diagrams of Fig. 1 result. The phase diagrams show three SC phases (labelled A, B and C). For both field orientations the three SC phases and the normal state (N) meet at a tetracritical point (TP). In zero field two SC transitions are observed at $T_c^+ = 0.493(2)$ K and $T_c^- = 0.438(2)$ K. The TP is located at $T_{cr} = 0.389(3)$ K and $B_{cr} = 0.443(5)$ T for $B \perp c$ and at $T_{cr} = 0.351(3)$ K and $B_{cr} = 0.948(5)$ T for $B \parallel c$. No significant anisotropy was observed for fields in the basal plane ($B \parallel a$ and $B \parallel b$).

In order to determine the uniaxial pressure dependence of the superconducting phase lines we apply one of the Ehrenfest relations, $\mathrm{d}T_c/\mathrm{d}p_i = V_m \Delta\alpha_i/\Delta(c/T)$, where p_i ($i = a, b, c$) refers to the uniaxial pressure and V_m to the molar volume. Using our thermal-expansion data [3] and the specific-heat data [1] we calculate the following values for the initial uniaxial pressure dependence of T_c^+ and T_c^-: $\mathrm{d}T_c^+/\mathrm{d}p_a = 0.0$ mK/kbar, $\mathrm{d}T_c^-/\mathrm{d}p_a = -4.9$ mK/kbar, $\mathrm{d}T_c^+/\mathrm{d}p_c = -13.5$ mK/kbar and $\mathrm{d}T_c^-/\mathrm{d}p_c = 8.8$ mK/kbar. The uniaxial pressure dependence of T_c is highly anisotropic and in good agreement with specific-heat measurements under pressure [4], as shown in Fig. 2 for $p \parallel c$. The splitting $\Delta T_c = T_c^+ - T_c^-$

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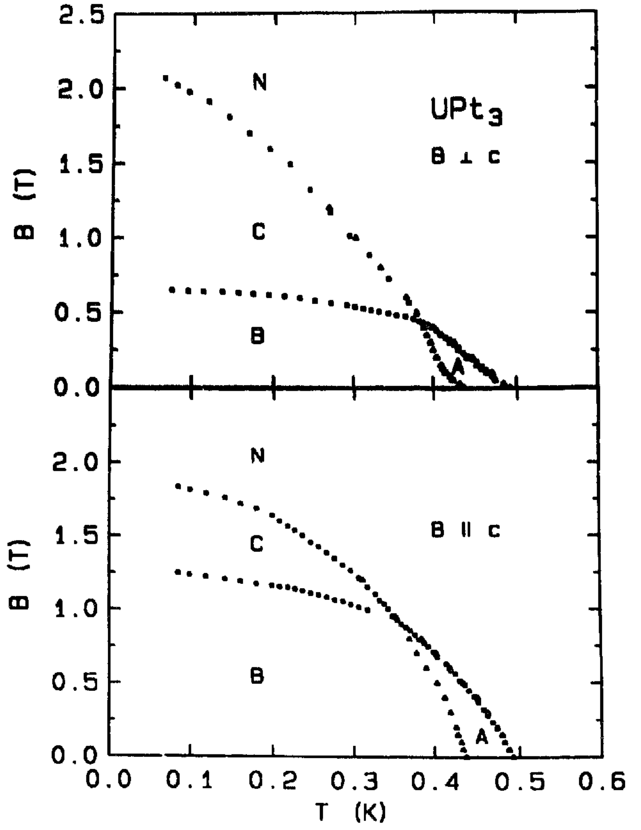

Fig. 1. The superconducting phase diagram of UPt_3 for $B \perp c$ and $B \parallel c$, constructed from the anomalies detected in the thermal expansion (▲) and the magnetostriction (■).

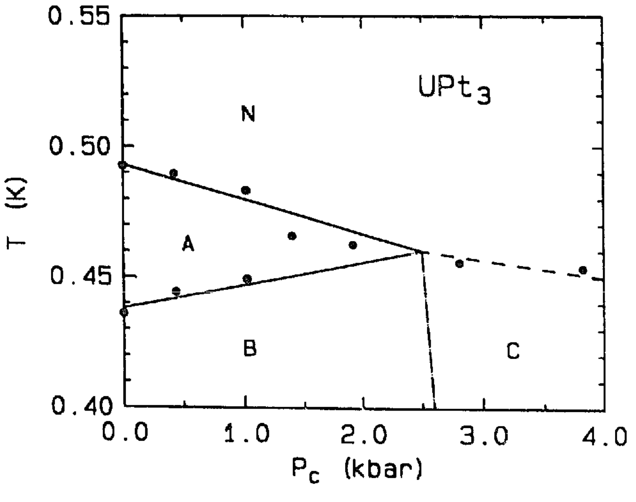

Fig. 2. Comparison of the uniaxial pressure dependence of T_c for $p \parallel c$ according to the Ehrenfest relations and the measured values (●) [4] (renormalised at T_c). The dashed line and the dash-dotted line correspond to an extrapolation of the NC and BC phase lines, respectively.

decreases for $p \parallel c$ at a rate $d\Delta T_c/dp_c = -22.3$ mK/kbar, while for $p \perp c$ ΔT_c increases: $d\Delta T_c/dp_a = 4.9$ mK/kbar. Using a linear extrapolation of the initial pressure dependence of T_c we find that for $p \parallel c$ the A phase vanishes at $T_{cr} = 0.460$ K and $p_{cr} = 2.5$ kbar. The uniaxial pressure dependence of the NC phase line is $dT_c/dp_a = -4.8(5)$ mK/kbar and $dT_c/dp_c = -3.0(5)$ mK/kbar for $B \parallel c$ ($B = 1.2$ T), while $dT_c/dp_a = -6.5(5)$ mK/kbar and $dT_c/dp_c = -0.5(5)$ mK/kbar for $B \perp c$ ($B = 0.6$ T). The uniaxial pressure dependence of the BC phase line at $T = 0.3$ K is $dT_c/dp_c = -0.21(5)$ K/kbar for $B \parallel c$ and $dT_c/dp_c = -0.17(5)$ K/kbar for $B \perp c$, while $dT_c/dp_a = 0.00(5)$ K/kbar for both field orientations. It is interesting to note that the B phase is rapidly suppressed for $p \parallel c$, while a weak pressure dependence for $p \parallel a$ is found. Extrapolation of the pressure dependence for $p \parallel c$ indicates a suppression of the B phase between $p_{cr} = 2.5$ kbar at T_{cr} and $p_{c0} \simeq 4$ kbar at $T = 0$ K. This gives a stable C phase for large pressure. These results are consistent with recent sound velocity measurements for $B \parallel c$ and $p \parallel c$ [5].

In the frequently used Ginzburg-Landau scenario with a symmetry breaking field (SBF) ε, the hybrid gap function (E_{1g}) is given by $\psi(\boldsymbol{k}) = \eta_x k_x k_z + \eta_y k_y k_z$, where the complex vector $\boldsymbol{\eta} = (\eta_x, \eta_y)$ determines the order parameter (E model) [6]. The A, B and C phases then correspond to the (1, 0), the (1, αi) and the (0, 1) phase, respectively ($B \perp c$). Above the critical pressure p_{cr} the SBF vanishes, leading to a critical point where the (1, 0) phase is suppressed and the (1, αi) phase transforms into the (1, i) phase under pressure. The specific heat anomaly at this transition is relatively small and given by $\Delta(c/T) \propto (d\varepsilon/dT)^2$. In the absence of a SBF the (1, i) phase is most sable in contrast to the prediction of the extrapolated phase diagram under pressure, which favours the (0, 1) phase. Recent calculations [7] indicated a possible transition from the (1, i) to the (1, 0) phase in a field for $p_c > p_{cr}$. The sound velocity measurements [5] partly traced two critical fields for 2.5 kbar ($= p_{cr}$) $< p_c <$ 3.7 kbar, but only detected the upper critical field for $p_c >$ 3.7 kbar.

An alternative scenario uses two nearly degenerate 1D order parameters (AB model) [8]. Here the A and C phases correspond to states with a different 1D order parameter and the B phase shows a mixing of these 1D order parameters. In this scenario a TP is formed at p_{cr} and the C phase is most stable under pressure, as the B phase is suppressed between $p_{cr} < p_c < p_{c0}$. This is in good agreement with the experimental phase diagram. The SC phase diagram, as determined with the Ehrenfest relations, is more in line with the AB model, although the E model can not be excluded. High precision measurements above the critical pressure are needed to resolve this question.

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