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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 $d\Delta T_c/ dp_c = -22.3$ mK/kbar, and for pressure along the $a$-axis, $d\Delta T_a/ dp_a = 4.9$ 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, $\alpha(T) = L^{-1} dL/dT$, and the linear magnetostriction, $\lambda_i(B) = (L_i(B) - L_i(0))/L_i(0)$, 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 $B \perp c$.

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 $T_c^+ = 0.503(2)$ K and $T_c^- = 0.389(2)$ K. The TP is located at $T_{cT} = 0.389(2)$ K and $B_{cT} = 0.435(5)$ T for $B \perp c$ and at $T_{cT} = 0.351(3)$ K and $B_{cT} = 0.948(5)$ 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, $d\Delta T_i/ dp_i = V_m \Delta \chi_i/ \Delta c (\Delta c T)$, 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 $T_c^-$: $d\Delta T_c^+ / dp_a = 0$ mK/kbar, $d\Delta T_c^+ / dp_b = 2.1$ mK/kbar and $d\Delta T_c^- / dp_c = 4.9$ mK/kbar. $d\Delta T_c^- / dp_a = 13.5$ mK/kbar, $d\Delta T_c^- / dp_b = 8.8$ 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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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.

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 $p_c$, and the C phase is most stable under pressure, as the B phase is suppressed between $p_{\text{cr}} < p_c < p_{\text{co}}$. 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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