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Uniaxial pressure dependence of the superconducting phase diagram of UPt₃

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Abstract

Thermal expansion and magnetostriction techniques have been applied in order to determine the superconducting phase diagram of UPt₃ (B || c and B ⊥ 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 \( \frac{dA_T}{dp_c} = -22.3 \text{ mK/kbar} \), and for pressure along the a-axis, \( \frac{dA_T}{dp_a} = 4.9 \text{ mK/kbar} \). The phase diagrams are discussed in view of the relevant Ginzburg-Landau models.

The heavy-fermion superconductor UPt₃ 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 UPt₃ sample (dimensions \( a \times b \times c = 3 \times 1 \times 2 \text{ mm}^3 \)). The coefficient of linear thermal expansion, \( \alpha(T) = \left. \frac{1}{L} \right| \frac{dL}{dT} \), and the linear magnetostriction, \( \lambda(B) = \left. (L(B) - L(0))/L(0) \right| \), 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 \( B || a, B || b \) and \( B || c \).

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 \( T_c^* = 0.493(2) \text{ K} \) and \( T_c^* = 0.438(2) \text{ K} \). The TP is located at \( T_c^* = 0.389(3) \text{ K} \) and \( B_c^* = 0.443(5) \text{ T} \) for \( B || c \) and at \( T_c^* = 0.351(3) \text{ K} \) and \( B_c^* = 0.948(5) \text{ T} \) for \( B || b \). No significant anisotropy was observed for fields in the basal plane (\( B || a \) and \( B || b \)).

In order to determine the uniaxial pressure dependence of the superconducting phase lines we apply one of the Ehrenfest relations, \( \frac{dA_T}{dp_i} = V_n \Delta \gamma_i \Delta T \), where \( p_i (i = a, b, c) \) refers to the uniaxial pressure and \( V_n \) 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 \( T_c^* \):

- \( \frac{dA_T}{dp_a} = -4.9 \text{ mK/kbar} \)
- \( \frac{dA_T}{dp_b} = -13.5 \text{ mK/kbar} \)
- \( \frac{dA_T}{dp_c} = -8.8 \text{ mK/kbar} \)

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 \( p || c \). 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. 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.

In the frequently used Ginzburg–Landau scenario with a symmetry breaking field (SBF) $\ell$, the hybrid gap function ($E_{1\ell}$) is given by $\psi(k) = \eta_x k_x k_x + \eta_y k_y k_y$, where the complex vector $\eta = (\eta_x, \eta_y)$ determines the order parameter (E model) [6]. The A, B and C phases then correspond to the (1, 0), the (1, $\pm i$) and the (0, 1) phase, respectively ($B \perp c$). Above the critical pressure $p_c$, the SBF vanishes, leading to a critical point where the (1, 0) phase is suppressed and the (1, $\pm i$) phase transforms into the (1, $\pm i$) 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 stable 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 $p_{cr} < p_c < p_{co}$. 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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