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ON THE SUPERCONDUCTING PHASE DIAGRAM OF HEAVY-FERMION UPt_3

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The superconducting phase diagram of heavy-fermion UPt_3 has been investigated by means of sensitive dilatometry. The thermodynamic analysis indicates that all the phase lines are of second order. Ehrenfest relations reveal that the C phase is the stable phase under uniaxial pressure (p ∥ c).

In recent years it has been realized that the superconducting (SC) properties of heavy-fermion UPt_3 are unconventional. In particular the observation of two consecutive SC phase transitions at $T_c^+ = 0.493$ K and $T_c^- = 0.438$ K and the exotic SC phase diagram with a tetracritical point in the B-T plane are considered as solid evidence for non-singlet pairing ($L \neq 0$) [1,2]. The SC phase diagram of UPt_3 can be explained to a large extent by phenomenological Ginzburg-Landau (GL) models, which make use of a free energy expansion in terms of an unconventional SC *vector* order parameter. However, the various GL models, among which the appealing symmetry breaking field (SBF) scenario, are still subject of lively debates, as they are inadequate at several points [2]. In order to investigate the validity of the proposed GL models important aspects such as the thermodynamic stability of the phase diagram and the behaviour under external pressure should be taken into account. In this paper we examine these aspects for the SC phase diagram of UPt_3 ($B \perp c$ and $B \parallel c$) as resolved by accurate dilatometry, i.e. by thermal expansion ($\alpha(T)$) and magnetostriction ($\lambda(B)$) [3].

The phase diagrams are shown in Fig.1. The three SC phases are labeled A, B and C. For both field orientations the three SC phases and the normal state (N) meet at a tetracritical point (TP). 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 basal plane anisotropy was observed [3].

The specific-heat data ($c(T)$) yield steps at the NA, AB and NC phase boundaries and no latent heat [1]. This strongly suggests second order phase transitions, which is supported by the absence of hysteresis. Concerning the BC transition, the absence of hysteresis in $\lambda(B)$ [3] also suggests second order. The thermodynamic stability of a phase diagram with a TP, where at least three second order phase transition lines meet, was investigated by Yip *et al.*[4]. The stability criterion

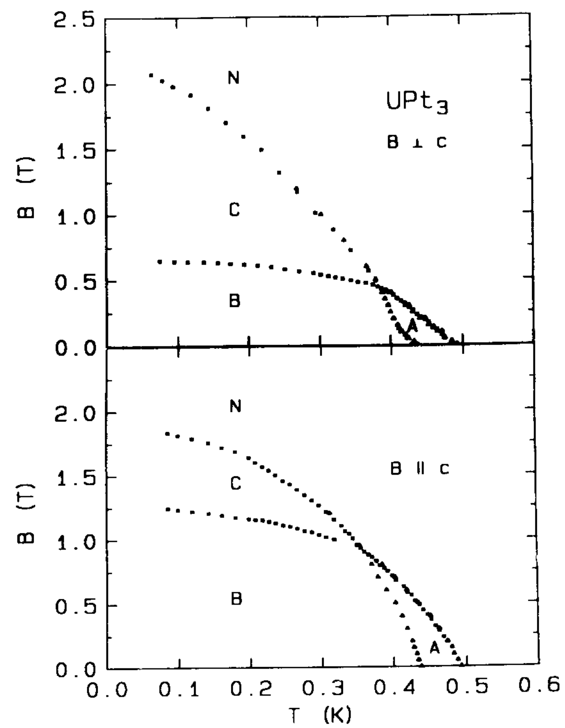

Figure 1. SC phase diagram of UPt_3 as determined by magnetostriction (■) and thermal expansion (▲).

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is formulated by relating the slopes of the phase lines to the steps in c(T) at the phase transitions near the TP. Conform Ref.[4] (note that we have interchanged the B and C label) we define p_1, p_2, p_3 and p_4 as the slopes dB/dT of the phase lines NA, NC, AB and BC in the vicinity of the TP, respectively, and r_1^2, r_3^2 and r_4^2 as the ratios of the stepsizes in c(T) $\Delta c_{NA}/\Delta c_{NC}$, $\Delta c_{AB}/\Delta c_{NC}$ and $\Delta c_{BC}/\Delta c_{NC}$ near the TP, respectively ($r_1^2+r_3^2=1+r_4^2$). Stable solutions can only appear for $r_4^2 > 0$. Note that the c(T) experiments [1] indicate $r_4^2 << 1$. With the experimental values for the slopes of the phase lines $p_1= -4.15$ (-4.76) T/K, $p_2= -6.35$ (-6.34) T/K, $p_3= -14.2$ (-8.7) T/K and $p_4= -1.19$ (-1.57) T/K (see Fig.1) we calculate, using the equations in Ref.[4], that the TP is stable for $r_1^2 < 0.37$ (0.40) or $r_1^2 > 0.54$ (0.46) for $B \perp c$ ($B \parallel c$). The experimental values for the ratios of the steps in c(T) [1] amount to $r_1^2 = 0.65 \pm 0.08$ (0.47 ± 0.05) and $r_3^2 = 0.35 \pm 0.08$ (0.53 ± 0.05) for $B \perp c$ ($B \parallel c$), hence we conclude that the phase diagram with a TP is thermodynamically stable. Furthermore, for a second order BC transition the stability criterion yields $r_1^2 = 0.58 \pm 0.04$ (0.52 ± 0.04) and $r_3^2 = 0.43 \pm 0.04$ (0.49 ± 0.04) for $B \perp c$ ($B \parallel c$). Taking into account the absence of hysteresis we conclude that the BC transition is of second order, in which case $r_4^2 = 0.01$ and $\Delta c'_{BC} \simeq 1$ mJ/molK for $B \perp c$ and $B \parallel c$. However, because of the experimental uncertainty a weakly first order BC transition cannot be ruled out.

The uniaxial pressure dependence p_i (where i refers to pressure along the a, b or c-axis) of the SC phases can be calculated using the Ehrenfest relation $dT/dp_i = V_m \Delta\alpha_i/\Delta(c/T)$. Using our $\alpha(T)$ [4] and the reported c(T) data [1] we calculate (in zero field): $dT_c^+/dp_a = 0.0$ mK/kbar, $dT_c^-/dp_a = -4.9$ mK/kbar, $dT_c^+/dp_c = -13.5$ mK/kbar and $dT_c^-/dp_c = 8.8$ mK/kbar. The uniaxial pressure effects are strongly anisotropic. For $p \parallel c$ the splitting $\Delta T_c = T_c^+ - T_c^-$ decreases 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. Assuming a linear pressure relation we find that for $p \parallel c$ the A phase vanishes at $T_{cr} = 0.460$ K and $p_{cr} = 2.5$ kbar. In Fig.2 we compare our results for $p \parallel c$ with the ones determined by c(T) under pressure [5]. The data in

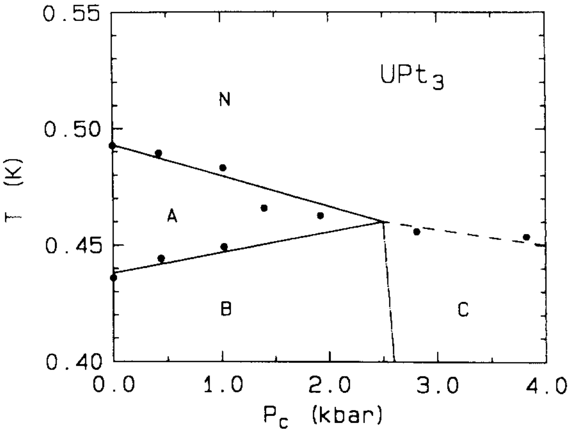

Figure 2. p_c-T phase diagram of UPt_3 as determined via Ehrenfest relations (solid and dashed-dotted line). Dashed line and closed circles: after Ref.[5].

Ref.[5] indicate that three phase lines meet in a critical point (T_{cr}, p_{cr}) in the p_c-T plane. However, the pressure dependence ($p \parallel c$) of the BC phase line in the vicinity of the TP is large (we calculate $dT/dp_c \simeq -170$ mK/kbar for $B \perp c$) as the step in c(T) is very small. Therefore, also the B phase is rapidly suppressed for $p \parallel c$ (at 2-3 kbar), which results in a fourth phase line in the p_c-T plane. Consequently, a TP is also found in the p_c-T plane and the C phase is the most stable phase under pressure. This is in clear contrast with the GL-model with the SBF scenario that predicts the B phase to be stable under pressure. However, a stable C phase is consistent with the accidental near degeneracy scenario [6].

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