Studies of superconductivity in U(Pt$_{1-x}$Pd$_x$)$_3$ for $x < 0.006$

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We report measurements of the specific heat and resistivity ($T < 1$ K) for high quality polycrystals of U(Pt$_{1-x}$Pd$_x$)$_3$ with $x < 0.006$. The $T_c$-$x$ phase diagram can be constructed, and superconductivity is destroyed for $x \approx 0.006$; this is approximately the same concentration above which the onset of large-moment antiferromagnetism is observed to occur. The splitting of the double superconducting transition increases smoothly with increasing Pd content, and is large enough that for Pd concentrations $0.004 < x < 0.006$ only the superconducting A-phase will be present.

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Pd-substitution is a powerful method to study unconventional superconductivity and magnetism in UPt$_3$. Studies of U(Pt$_{1-x}$Pd$_x$)$_3$ for $x \leq 0.002$ showed that Pd-substitution is unique in that it increases the splitting $\Delta T_c$ between the A and B superconducting phases by 40 mK for $x=0.002$ [1]. Addition of Pd also increases the zero-temperature moment associated with “small-moment” antiferromagnetism (SMAF) above the $x = 0$ value of 0.02 $\mu_B$, and the correlation between the increased moment and $\Delta T_c$ has been confirmed [2]. For $x > 0.01$, “large-moment” antiferromagnetism (LMAF) is observed[3] through $\mu$SR[4] and other conventional methods; in contrast, SMAF is convincingly observed only via neutron and magnetic x-ray scattering [5]. In this work we address two questions: does the splitting increase with continued increase of Pd above $x = 0.002$, and at what concentration does the superconducting $T_c$ approach 0 K?

Polycrystalline samples with $x = 0, 0.0025, 0.003, 0.0035, 0.004, \text{ and } 0.005$ were studied. For $x=0$, the ratio of the RT resistivity to the extrapolated $T=0$ K normal-state resistivity $\rho_o$ is over 1000. $\rho_o$ varies linearly with $x$, showing that the series is uniform. In Fig. 1 we show the resistive $T_{cA}$ versus $x$ (solid symbols); $T_{cA}$ approaches 0 K at $x = 0.006$. This is also the estimated concentration at which the LMAF state begins, based on neutron[3] and $\mu$SR[4] studies for $x \geq 0.005$. This strongly suggests that the LMAF and superconducting phases compete with one another, presumably because the superconducting pairing mechanism is based on AFM spin-fluctuations. We are investigating several samples with $0.006 < x < 0.010$ to study the phase diagram in more detail.

In Fig. 2 we show the specific heat results. The splitting clearly increases smoothly with Pd-concentration (see also Fig. 1, open symbols). $\Delta T_c$ is increased to 150 mK for $x=0.003$, compared to 55 mK for $x = 0$. Comparing the variation of $T_{cA}$ and $\Delta T_c$ with $x$, we
estimate that for $x > 0.004$ there will be only one superconducting phase (A). We also see that for $x \geq 0.0025$ \( \Delta C/T(T_{ci}) < \Delta C/T(T_{ci}) \), where $\Delta C/T(T_{ci})$ is the specific heat discontinuity at $T_{ci}$ measured relative to the normal state. This appears to violate the stability condition derived from a Ginzburg-Landau analysis near $T_c$ within the “E-rep” models of superconductivity [6]. However, $\Delta T_c$ is large, and there is a substantial temperature variation of $C/T$ for $T_{cB} < T < T_{cA}$. Since the calculations are carried out only to fourth-order in the order parameter, they constrain $C/T$ to be constant, and the comparison is invalid. However, correcting for this temperature dependence of $C/T$ by using the $\Delta C/T(T_{cB})$ as measured from the A-phase value, we estimate that the ratio of the discontinuities is nearly constant and has a magnitude consistent with the weak-coupling E-rep models [6]. A more exact analysis of the data will require calculations which are carried out to higher order.

Our results demonstrate that the temperature-dependent properties of the A-phase can now be studied over a wider temperature range. For example, we find that the $x = 0.003$ sample exhibits a $C/T$ which depends linearly on temperature for $T_{cB} < T < T_{cA}$ (see Fig. 3). Analysis of the data in Fig. 2 shows that the slope is independent of $x$, and the extrapolated $T = 0$ K intercept increases very weakly with $x$. From this we infer that the thermodynamic properties of the A-phase in UPt$_3$ are essentially unchanged by addition of Pd. Measurements of other temperature-dependent A-phase properties, such as transverse sound attenuation[7], may give greater insight into the nature of the unconventional superconductivity in this system.

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Figure Captions

Fig. 1. Data for transition temperature $T_{cA}$ (solid symbols) and splitting $\Delta T_c$ (open symbols) versus Pd-content. Circles are from this work, squares are from Ref. [1]. The lines are polynomial fits to the data.

Fig. 2. Specific heat data. Curves have the same normal-state value at $T_c$, but are offset for clarity.

Fig. 3. Specific heat data for $x = 0.003$. Solid circles are the data, and the line represents an idealized fit to the double superconducting transition using the criteria from Ref. [1].
FIGURE 1

U(Pt$_{1-x}$ Pd$_x$)$_3$
Figure 3

$C/T \text{ (J mole}^{-1} \text{ K}^{-2})$

$U(Pt_{0.997} Pd_{0.003})_3$

Temperature (K)