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Upper critical magnetic field of the superconducting heavy fermion system $(U_{1-x}Th_x)Be_{13}$

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Measurements of the ac electrical resistance as a function of temperature and applied magnetic field $R(T,H)$ were made for various compositions $x \lesssim 0.03$ in the mixed binary system $(U_{1-x}Th_x)Be_{13}$. All samples within this range of x exhibit heavy Fermion superconductivity with a superconducting transition temperature T_c that is rapidly suppressed by the substitution of Th for U. The shape of the upper critical field curve $H_{c2}(T)$ determined from the $R(T,H)$ data is similar for all compositions with a very large initial slope $(-dH_{c2}/dT)_{T_c}$.

INTRODUCTION

There has been considerable interest recently in a small class of "heavy Fermion" compounds in which the effective mass of the conduction electrons is enormous, ~ 100 times the free electron mass. Superconductivity has been observed in this class of compounds for $CeCu_2Si_2$,[1] UBe_{13},[2] UPt_3,[3] and U_2PtC_2,[4] characterized by superconducting transition temperatures $T_c \lesssim 1$ K and very large electronic heat capacities. Studies of alloy systems revealed that T_c is rapidly suppressed by the substitution of any other element for U in UBe_{13}.[5] Measurements of the heat capacity $C(T)$ of samples in the $(U_{1-x}Th_x)Be_{13}$ system[6] showed the large discontinuities at T_c characteristic of heavy Fermion systems. Of special interest in these data was the observation of two distinct transitions in $C(T)$ for $x \sim 0.03$, possibly indicating another condensation of the superconducting electrons at a temperature lower than the observed T_c.[6] We present here the temperature dependence of the upper critical magnetic field $H_{c2}(T)$ determined from measurements of the ac electrical resistance R for several compositions in the $(U_{1-x}Th_x)Be_{13}$ mixed binary system.

EXPERIMENTAL DETAILS

The polycrystalline samples used in this study were prepared at Los Alamos National Laboratory (LANL) by arc melting stoichiometric quantities of the elements on a water-cooled copper hearth. Bar-shaped specimens were spark cut from the arc-melted ingots and leads of copper wire were attached using silver epoxy. Measurements of the ac electrical resistance at 16 Hz were performed in a He^3-He^4 dilution refrigerator at the University of California, San Diego (UCSD) for $T \gtrsim 0.07$ K in magnetic fields H up to 6 T applied with a superconducting solenoid. A Speer 100-Ω resistor calibrated in zero field against the susceptibility of cerium magnesium nitrate (CMN) was used to determine the temperature. The magnetoresistance of this thermometer could be estimated to yield a maximum error of 12 mK for measurements in this range of T and H from data for other resistors.[7] Measurements were made as a function of temperature in fixed magnetic fields. The T_c was defined as the temperature at which R decreased to 50% of the value extrapolated from the normal state, while the transition width was determined from a similar extrapolation of the 10 and 90% points. Resistance measurements at the Francis Bitter National Magnet Laboratory, (FBNML), Massachusetts Institute of Technology, were performed at 40 Hz in the mixing chamber of a dilution refrigerator at fixed temperature by sweeping the magnetic field produced by a Bitter solenoid up to 17.5 T.[8] Two carbon thermometers within the mixing chamber were used to determine the temperature and a correction for magnetoresistance was made in a manner described elsewhere.[8] For a given temperature, H_{c2} was defined from the 50% point of the transition while the width in applied field was defined from the 10 and 90% points.

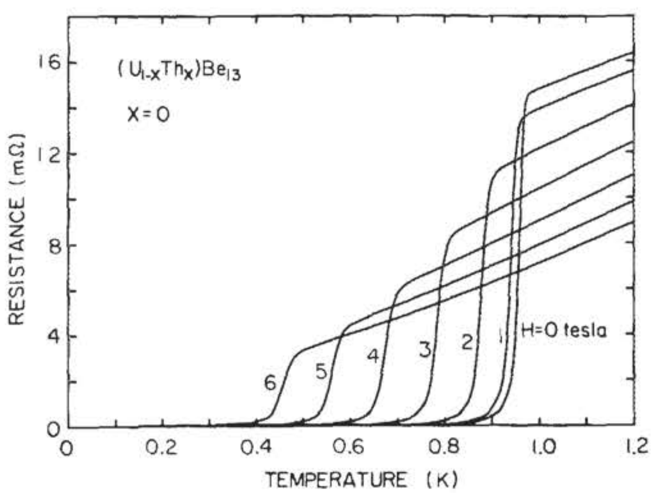

FIG. 1. ac electrical resistance vs temperature in various applied magnetic fields in T for a polycrystalline sample of UBe_{13}.

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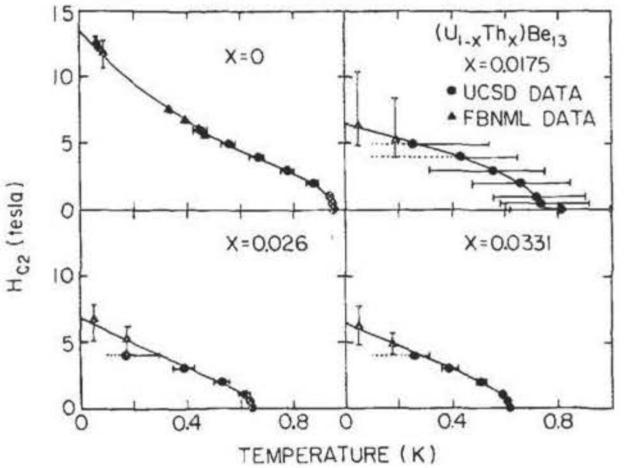

FIG. 2. Upper critical magnetic field H_{c2} vs temperature for four compositions of $(U_{1-x}Th_x)Be_{13}$. Solid lines are guides to the eye and for $x = 0.0175$ show the results of more detailed low field measurements. The horizontal and vertical lines reflect the width of the transitions in either temperature or applied magnetic field as defined in the text.

RESULTS

Figure 1 shows a plot of $R(T)$ in various applied magnetic fields for $(U_{1-x}Th_x)Be_{13}$ with $x = 0$. The normal-state resistance decreases as the temperature is lowered in all applied magnetic fields. In addition, strong negative magnetoresistance is evident. Rather sharp transitions into the superconducting state are found with transition widths that increase from 30 to 60 mK as H increases from 0 to 6 T. Similar data are observed for $x = 0.0260$ and 0.0331. For $x = 0.0175$, very broad superconducting transitions are observed, possibly indicating a sample of lesser quality.

Shown in Fig. 2 are the $H_{c2}(T)$ data for the four samples investigated in this study with transition widths, indicated by horizontal and vertical lines, defined as described above. The solid lines are guides to the eye, and in the case of $x = 0.0175$ indicate the results of more detailed low field measurements. In agreement with previous work,[5] T_c decreases rather rapidly as Th is substituted for U. However, the overall shape of $H_{c2}(T)$ remains nearly the same. In each case, a rapid increase of H_{c2} is observed for low H with strong curvature at intermediate fields. In higher fields, $H_{c2}(T)$ varies nearly linearly with T with a slope ~ 9 T/K. For $x = 0$, one point at $T \sim 90$ mK and $H \sim 12$ T lies significantly above a linear extrapolation of the lower field data. A more extensive set of measurements on this sample are currently in progress. It is noteworthy that the shape of the $H_{c2}(T)$ curves is the same for $x = 0.0331$ as it is for lower x. As noted above, two transitions have been observed in heat capacity measurements of samples with $x \sim 0.03$.[6] These data show that the lower temperature transition at $T \sim 0.47$ K for this composition has no effect on $H_{c2}(T)$ determined from resistance measurements.

In addition to the data presented in Fig. 2, more detailed low field measurements were made at UCSD to investigate the initial slope of the H_{c2} curve, $(-dH_{c2}/dT)_{T_c}$. For measurements over such a small range of temperature (~ 20 mK) in magnetic fields up to 1 T, the magnetoresistance of the carbon thermometer becomes a very important factor. The low field magnetoresistance of our thermometer was estimated by comparing $H_{c2}(T)$ data measured at UCSD on a single crystal of UBe_{13} in the He^3-He^4 dilution refregerator with that determined in a He^3 cryostat where the temperature was inferred from the vapor pressure of He^3.[9] Following the work of others,[7] we assumed a linear variation of $T[R(H) - R(H=0)]/R(H=0)$ with H for low values of H to determine the magnetoresistance for various temperatures. The initial slope of $H_{c2}(T)$ resulting from this analysis is given in Table I, where for $x = 0.0175$ the steepest part of the $H_{c2}(T)$ curve has been measured. It is difficult to estimate the uncertainty in these values since our extrapolation of the magnetoresistance could be incorrect. Nevertheless, it is clear that very large values of the initial slope are found for all compositions. Also listed in Table I is $T_c(H=0)$.

TABLE I. The superconducting transition temperature T_c in zero applied magnetic field and the initial slope of the $H_{c2}(T)$ curve $(-dH_{c2}/dT)_{T_c}$ for four compositions x in the mixed binary system $(U_{1-x}Th_x)Be_{13}$.

x	T_c (K)	$(-dH_{c2}/dT)_{T_c}$ (T/K)
0	0.952	35
0.0175	0.740[a]	27[a]
0.0260	0.645	46
0.0331	0.620	32

[a] For steepest part of H_{c2} curve.

CONCLUSIONS

We have determined the upper critical magnetic field $H_{c2}(T)$ from measurements of the ac electrical resistance for four compositions in the $(U_{1-x}Th_x)Be_{13}$ mixed binary system. Despite the strong suppression of the superconducting transition temperature T_c when Th is substituted for U, the shape of $H_{c2}(T)$ remains nearly the same. This indicates that the nature of superconductivity of the system of heavy Fermions remains unchanged despite a decrease by $\sim 30\%$ of $T_c(H=0)$. The data are characterized by very large values of the initial slope $(-dH_{c2}/dT)_{T_c}$ and strong negative magnetoresistance in the normal state.

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