Reduction of critical temperatures in pure and thoriated UBe$_{13}$ by columnar defects

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We investigate the influence of columnar defects on the superconducting transition temperatures of UBe$_{13}$ and U$_{0.97}$Th$_{0.03}$Be$_{13}$. The defects cause all the transitions to widen and to drop slightly in temperature. Quantitatively, the lower transition in U$_{0.97}$Th$_{0.03}$Be$_{13}$ more strongly resembles the single UBe$_{13}$ transition.

Heavy fermion (HF) superconductors are good candidates for non-$s$-wave electron pairing. They display low-temperature power laws in thermodynamic quantities, unusual behavior of the critical field, and, in the cases of UPt$_3$ and (U,Th)Be$_{13}$, phase transitions within the superconducting state. Impurity scattering, which is sensitive to order parameter symmetry, has been vigorously investigated in high-temperature superconductors (HTS), but there has been little corresponding work in HF systems. Here we report on (U,Th)Be$_{13}$ with columnar defects.

Although the most striking effects of columnar defects should appear in their interactions with vortices, here we focus on their influence on $T_c$. We compare the behavior of the single transition in pure UBe$_{13}$ with that of both the upper and the lower transitions in U$_{0.97}$Th$_{0.03}$Be$_{13}$. Debate continues on the nature of the lower thoriated transition, and on which (if either) of the thoriated transitions can be viewed as an extension of the single pure transition $[1]$ $[4]$. Our present measurements support identifying the lower thoriated transition with that of pure UBe$_{13}$.

Our samples are long-term annealed polycrystals, sanded to about 25 $\mu$m thickness and 50 $\mu$g. The defects were created by irradiation with 1.4 GeV $^{238}$U$^{67+}$ ions. Defect densities range from $4.8 \times 10^{13}$ to $2.4 \times 10^{15}$ per m$^2$, corresponding to matching fields of 0.1 to 5 Tesla. Since TRIM results based on Monte-Carlo simulations give a sharp ion distribution with an average penetration depth of 56 $\mu$m, our thinned samples should suffer little ion implantation.

In order to detect the lower transition of thoriated UBe$_{13}$, we use heat capacity measurements. We use an adiabatic method, with a RuO$_2$ thin film thermometer and a [50:50] AuCr thin film heater. A fine copper wire provides the heat link to a dilution refrigerator. By measuring heat capacity, we conveniently avoid attaching leads to our tiny samples. The unusually large specific heat of the heavy fermions makes the measurements challenging but not heroic.

Fig. 1 shows $C/T$ for both unirradiated and irradiated U$_{0.97}$Th$_{0.03}$Be$_{13}$ samples. For clarity, we show only data from the most heavily irradiated sample. Since we do not know the precise sample sizes, we use a multiplicative constant to set the normal state value of $C/T$ to 1 J/mole K$^2$ for each curve. We do not adjust the measured heat capacity for any contribution from the thermometer, heater, or mount; but comparing the curves shown to previous heat capacity measurements on
bulk samples suggests that background effects are less than 30% of our signal. In any case, the background should not affect our determination of the $T_c$ suppression or transition width.

The heat capacity curves of Figure 1 have the same overall shape, including the heights of both transitions. Irradiation has a similar effect on pure UBe$_{13}$, reducing $T_c$ and slightly broadening the transition, while retaining the shape of the $C/T$ curve.

Table 1 summarizes the changes in the transitions. The $T_c$ values correspond to the midpoints in $C/T$, and are reproducible to within 2 mK for different cooldowns. The transition widths are taken as the temperature difference between the 10% and 90% points in $C/T$. We note that the percentage change in $T_c$ in pure UBe$_{13}$ is nearly identical to that of the lower transition in U$_{0.97}$Th$_{0.03}$Be$_{13}$, and somewhat larger than that of the upper transition. The two former transitions also undergo a 7 mK change in width, while the width of the latter increases by only 3 mK. These values suggest that the lower transition in thoriated UBe$_{13}$ is a continuation of the phase boundary in the pure material. Work on the pressure-dependence of the transitions also supported this conclusion [2,3], although recent thermal expansion measurements did not [4]. The generally similar behavior of all three transitions is also evidence that the lower transition in U$_{0.97}$Th$_{0.03}$Be$_{13}$ is a superconducting transition.

Without resistivity data we cannot compare our results to theoretical work on impurity scattering, but we can examine other experiments. The $T_c$ reduction from columnar defects in HTS is up to 5.3% for $10^{15}$ defects/m$^2$ in YBa$_2$Cu$_3$O$_{7-\delta}$ [5] and 2.4% for $5 \times 10^{14}$ defects/m$^2$ in Bi$_2$Sr$_2$CaCu$_2$O$_8$ [6]. Since transition temperatures are so different for HTS and HF, we also con-

FIG. 1: Heat capacity $C/T$ for U$_{0.97}$Th$_{0.03}$Be$_{13}$ with (□) and without (●) heavy-ion irradiation. The arrows indicate the two transition temperatures for the irradiated sample.
TABLE I: Effects of irradiation on transitions in (U,Th)Be$_{13}$.

|                | $T_c$(unirr) | $T_c$(irr) | width (unirr) | width (irr) |
|----------------|--------------|------------|---------------|-------------|
| UBe$_{13}$     | 770          | 750        | 35            | 42          |
| $U_{0.97}Th_{0.03}$Be$_{13}$ (upper transition) | 625          | 613        | 38            | 41          |
| $U_{0.97}Th_{0.03}$Be$_{13}$ (lower transition) | 412          | 400        | 37            | 44          |

All temperatures are given in millikelvin.

sider a recent study in UPt$_3$ [7]. Here point defects were created by electron irradiation, with most of the electrons passing through the sample to insure a homogeneous defect density. If 1% of the electrons produced defects, then for the sample sizes given in [7] an electron flux $3 \times 10^{22}$/m$^2$ would yield a final defect spacing slightly under 20 nm. The measured $T_c$ reduction for this flux was 20 mK (3.6%), slightly more than the reductions in our highest-density samples, which have 20 nm defect spacing. Thus our $T_c$ data is consistent with experiments on other unconventional superconductors.

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