Superconductivity in Single-Crystal YIn$_3$

S.D. Johnson, J.R. Young, and R.J. Zieve
Physics Department, University of California Davis, Davis, CA 95616

J.C. Cooley
Los Alamos National Laboratory, Los Alamos, NM 87545
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We measure the superconducting transition of YIn$_3$ by resistivity, susceptibility, and specific heat. Despite using high-quality single-crystal samples, the transitions detected by the three techniques are shifted from each other in temperature, suggesting a region of filamentary superconductivity. We discuss the possible implications for filamentary superconductivity in unconventional superconductors.

I. INTRODUCTION

One hundred years after the discovery of superconductivity, the goal of predicting whether a material will superconduct from its atomic composition and crystal structure remains elusive. Even more difficult is estimating the transition temperature $T_c$. Over the decades, researchers have often examined families of related materials, trying to quantify the effects of replacing a single atomic constituent with a related atom. One such family, investigated 40 years ago, had the cubic AuCu$_3$ structure. Much work followed the belief that $T_c$ directly correlated to the valence electron concentration [1, 2]. During this time a large number of compounds with AuCu$_3$ structure were synthesized and tested for superconductivity at ambient pressure, e.g. MIn$_3$ (M = Y, La, Lu) at reported $T_c$ of 0.78 K, 0.71 K, and 0.24 K, respectively [3].

Subsequently the discovery of superconductors that contain magnetic ions in their crystal structures overturned the traditional view that magnetism and superconductivity cannot coexist. The field of potential superconductors vastly broadened with the inclusion of magnetic ions, and several new families have appeared since the early heavy-fermion and high-temperature superconductors. In heavy-fermion materials, conduction electrons acquire an effectively “heavy” mass, often hundreds of times greater than the bare electron mass [4], from interaction with the magnetic ions. Furthermore, it appears that the superconductivity is unconventional in that magnetic interactions actually cause the electron pairing required for superconductivity, a role played by phonons in conventional superconductors.

One of the heavy-fermion superconductors is CeIn$_3$, with $T_c$ peaking at 0.2 K under 26.5 kbar of hydrostatic pressure [5]. Related heavy-fermions CeMIn$_3$ (M = Co, Ir, Rh) and PuXGa$_5$ (X = Co, Rh) are also superconducting with ambient-pressure $T_c$ reaching 18.5 K in PuCoGa$_5$. CeIn$_3$ has the AuCu$_3$ structure, which has inspired new studies of the AuCu$_3$ family of materials. Normal state properties have been measured in YIn$_3$ via de Haas-van Alphen experiments [6], thermal conductivity [7], and heat capacity [8], leaving it well characterized and a promising candidate for further exploration of the interplay between crystal structure and magnetic superconductivity.

Here we present measurements on much higher-quality samples of YIn$_3$ than those previously explored below 1 K [3]. We confirm the earlier ac susceptibility measurements of the superconducting transition and also provide resistivity and specific heat data. We find an unusual shift in the transition temperature using the different techniques, which may be connected to behaviors in related heavy-fermion compounds.

II. SAMPLE PREPARATION

YIn$_3$ crystallizes in a cubic AuCu$_3$ structure with lattice constant 4.593 Å [9]. The single crystal samples were grown from an excess Indium flux at a ratio of approximately 50:1 in an alumina crucible with an integral alumina frit. The crucible was sealed in a quartz tube under argon, held at 1150°C for 72 hours and slow cooled to 450°C. The 450°C crucible was removed from the furnace, inverted, and placed in a centrifuge to spin off the excess flux. After cooling to room temperature crucible was broken out of the quartz tube and the samples removed from the crucible. The starting materials were 99.9999% purity indium and 99.9% purity yttrium.

The measurements were performed on a $^3$He/$^4$He dilution refrigerator, except that the ac susceptibility measurement on sample A was done on a $^3$He sorption cryostat. The sample was mounted in close proximity to the cryostat thermometer. For resistivity and susceptibility we took data on both warming and cooling through the transition, with no sign of hysteresis. For the susceptibility and heat capacity measurements we did not polish or clean excess indium from the sample. For the resistivity measurement we cut down and polished all sides, both to improve the sample geometry and to ensure a good connection between the leads and the YIn$_3$. 

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FIG. 1: Susceptibility of sample B, with a sharp jump at 950 mK. The inset shows susceptibility of sample A, measured to 3.65 K. The values are scaled to 0 at the highest temperatures (sample fully normal) and -1 at the lowest temperatures. The large jump above 3 K indicates the superconducting transition of the remnant indium in and around the sample. The contribution of YIn3, barely visible near 1 K, makes up only 3% of the entire transition.

III. RESULTS AND DISCUSSION

We performed ac susceptibility measurements at a frequency of 12 Hz and an ac field of about 0.4 gauss. As shown in the main graph of Figure 1, the onset of the drop in susceptibility is at 960 mK, and the sample is fully superconducting by 825 mK. We scale the data to 0 in the normal state and -1 in the superconducting state. The inset shows susceptibility extended to higher temperature. A much larger transition appears at 3.4 K from the excess indium in and around the sample. The YIn3 transition makes up only ~3% of the total susceptibility change. A simple estimate of the expected signal, based on the sizes of the sample and the measurement coils and assuming the sample becomes entirely superconducting by 825 mK, gives about 1.5 times the observed signal. This reasonably good agreement suggests that in fact the indium is shielding almost the entire sample volume. The small magnitude of the YIn3 transition then stems from the shielding by the indium, and does not indicate that only a small portion of the YIn3 is superconducting. We believe the shielding arises from remnant indium on the surface of the sample; subsequent cutting into the interior confirmed that only a few small isolated veins of indium reside there.

Figure 2 shows the specific heat of sample B, with a feature at 825 mK. We use a relaxation method with a 50:50 AuCr heater, a Cernox film thermometer, and a graphite thermal link. The sample mass is 57.55 mg, and our heat pulses produce a temperature change of about 20 mK. In the normal state, $C/T$ is by no means constant, but it is the same order of magnitude as in conventional superconductors. This is consistent with de Haas-van Alphen measurements reporting a small effective electron mass $\delta$. The relative size of the transition is $\frac{\Delta C}{C(T_c)} = 0.35$. The small size of the heat capacity feature is another indication that the electrons which form pairs in the superconducting phase have low effective mass. The jump size is probably less than the BCS value of 1.43 in part because we made no adjustment for any addendum heat capacity.

Figure 3 presents resistivity data for two YIn3 samples. These were the same two samples shown in Figure 1, but cut down and polished to increase the aspect ratio and remove excess indium. We used a four-wire technique with platinum wires 0.051 mm in diameter spot-welded to the four corners. The other ends of the wires were soldered to a small copper plate which in turn connected to a resistance bridge via fixed wiring on the cryostat. At room temperature the measured resistivities of the two samples differ by about 10%, with $\rho \approx 8 \mu \Omega \cdot\text{cm}$. The resistivity ratios from room temperature to 4 K are 21 and 36 for samples A and B, respectively. A sharp drop in resistivity with decreasing temperature indicates the superconducting transition. For sample A the drop begins about 1.2 K and is completed above 1 K; for sample B it occurs between 1.08 K and 0.98 K.

An earlier report of superconductivity in YIn3 was based solely on ac susceptibility measurements. The transition midpoint was 780 mK, with half-width of 210 mK. The half-width was calculated by taking the tangent line to $\chi$ at the transition midpoint, and then finding...
the temperatures where it attained the full normal and superconducting susceptibilities. Using this same definition, the susceptibility transition shown in Figure 1 has half-width 36 mK. Our sample has a higher transition temperature, a much smaller width, and a fairly high residual resistivity ratio of 36. All of these suggest better sample quality than in the previous work.

Strangely, measurements by resistivity, susceptibility, and heat capacity give significantly different transition temperatures. For sample B, the transition onsets are at 1.08 K, 0.95 K, and 0.90 K, respectively, with the three techniques. The transition widths, from onset to completion, are less than 100 mK in resistivity, and less than 150 mK with the other techniques. This means that the resistive transition does not overlap the other two, and there is a gap of nearly 100 mK between the completion of the resistive transition and the onset of the heat capacity transition. Although discrepancies in $T_c$ can result from sample quality issues, a clear separation between the transitions such as we observe is unusual in conventional superconductors. However, it appears in a variety of heavy-fermion and other unconventional superconductors, including CeIrIn$_5$, URu$_2$Si$_2$, and Fe(Se,Te). The discrepancy indicates a regime of filamentary superconductivity, where despite a complete transition in resistance the superconducting volume is too small to register with bulk probes.

In CeIrIn$_5$ the resistive $T_c$ occurs at 1.2 K, while the susceptibility and heat capacity signals occur only at 0.4 K [10]. Improved samples have not brought the two closer together; if anything, they have raised the resistive $T_c$. URu$_2$Si$_2$ also shows a large discrepancy in the superconducting phase boundary as mapped out by resistivity or specific heat [11]. At ambient pressure the values of $T_c$ are 1.4 K and 0.8 K, respectively. Both decrease with applied pressure, but the specific heat transition disappears by 0.5 GPa, while the resistive transition persists to 1.8 GPa. Similarly, at certain Se concentrations $x$, Fe$_{1+y}$(Te$_{1-x}$Se$_x$) exhibits a resistive transition without any specific heat signal. The onset of partial diamagnetism may [12] or may not [13] accompany the resistive transition. These materials all have different crystal structures, but they have in common a large and highly anisotropic response to strain. One possible source of the filamentary superconductivity is this extreme sensitivity to uniaxial pressure combined with internal strain within the sample [14].

One of these unconventional superconductors, CeIrIn$_5$, has a crystal structure closely related to that of YIn$_3$. As noted previously, its parent compound CeIn$_3$ has the AuCu$_3$ lattice structure. In both these Ce compounds, the magnetic cerium atom imparts a heavy effective mass to the charge carriers. Both become superconducting, and the sizes of their specific heat discontinuities show that the heavy particles themselves form the pairs necessary for superconductivity. By contrast, with no magnetic ions, YIn$_3$ has quasiparticle masses not far above that of free electrons. Its superconductivity is likely conventional, with electron pairing mediated by phonons. Our finding filamentary regime in a conventional superconductor supports the internal strain explanation. Further comparative studies of YIn$_3$, its cerium-based relatives, and (Y,Ce)In$_3$ alloys may pinpoint how strongly the filamentary superconductor is linked simply to the crystal structure, rather than to any magnetic behaviors.

IV. CONCLUSION

We have measured ac susceptibility, specific heat, and resistivity on two single-crystal samples of YIn$_3$ and confirmed superconductivity by all three techniques. We find a $T_c$ somewhat higher from that previously reported and varying based on measurement technique. The temperature range between the resistive and bulk transition temperatures supports filamentary superconductivity, which may share the same origin as non-bulk superconductivity in several unconventional superconductors.

V. ACKNOWLEDGEMENTS

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