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# Electronic thermal conductivity of a superconducting indium-chromium alloy film*

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Measurements have been made of the electronic thermal conductivity of a quench-condensed film of an indium-chromium alloy. The results are compared with calculations based on Shiba's theory of superconductors containing magnetic impurities by using $\epsilon_0$ (the normalized position in the energy gap of the excited state associated with a single impurity atom) as an adjustable parameter. The data are in good agreement with the theory for a value $\epsilon_0 = 0.7$.

In a recent paper[1] we reported measurements of the thermal conductivity of quench-condensed films of superconducting lead-manganese and indium-manganese alloys. The results were compared with calculations based on Shiba's theory of superconductors containing magnetic impurities.[2,3] This theory predicted that the exchange interaction between the magnetic impurity spin and the conduction electrons would result in the formation of a band of excited states in the energy gap about the position $\epsilon_0\Delta$, where $\Delta$ is the order parameter. We fitted our data to the theory by using $\epsilon_0$ as an adjustable parameter in the thermal conductivity equations given by Leon and Nagi.[4] We have now measured the thermal conductivity of a quench-condensed indium-chromium film, using substantially the same techniques as those reported previously,[1] and have compared the results with theory in the same way. The reader is referred to our previous paper[1] for experimental details; we describe here only those which are new.

The sample film was made by flash evaporating pellets (each with mass 10 mg or less) of an indium-chromium mixture onto a cold (4 K or less) substrate. The indium-chromium mixture was prepared by evaporating 99.999% pure electropolished chromium onto a sheet of 99.999% pure indium. A second sheet of the pure indium was laid over the chromium film, and the resulting sandwich was mechanically mixed by folding and pressing it out 22 times. Spectrographic analysis by flame emission of the resulting indium-chromium mixture showed it to contain 855 atomic parts per million chromium. Spectrographic analysis by dc arc emission detected no significant amounts of any other transition metal impurities. By pressing and folding together 3.843 g of this mixture and 16.164 g of pure indium, a more dilute mixture was obtained (164 atomic parts per million), which was cut into pellets for flash evaporation. They were dropped one at a time into a tungsten boat. For each pellet the boat was heated for 5 sec to about 2500 °C as indicated by optical pryometer readings.

The ratio $K_{es}/K_{en}$ of the electronic part of the thermal conductivity in the superconducting state to that in the normal state is shown as a function of temperature for this sample (sample *I*) in Fig. 1. The normal-state values below the transition temperatures $T_c$ were obtained by fitting the normal-state thermal conductivity $K_n$ to two forms: $K_n = AT + BT^2$ and $K_n = CT + DT^3$, as described previously,[1] since no magnet of sufficient pole-gap spacing was available to enable us to measure $K_n$ below $T_c$ directly. Values obtained were $A = 3.564$ mW/cm K$^2$, $B = 0.0486$ mW/cm K$^3$, $C = 3.658$ mW/cm K$^2$, and $D = 0.006\,19$ mW/cm K$^4$. The error bars shown in Fig. 1 include the uncertainty of the temperature dependence of $K_n$.

From the normal-state thermal conductivity, we calculated the electrical resistivity; we used this with the known dependence of transition temperature and order parameter on electrical resistivity for quench-condensed indium films[5] to obtain values of the transition temperature $T_{c0}$ and order parameter $\Delta_0$ which would be displayed by a pure quench-condensed indium film with the same degree of disorder. The pure indium would have had $T_{c0} = 4.092$ K and $\Delta_0 = 0.686$ meV. These values are used in our theoretical calculations. They are in excellent agreement with those actually obtained

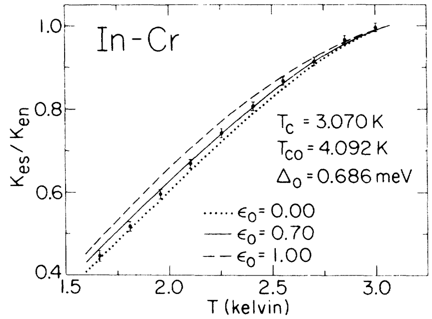

FIG. 1. Electronic thermal conductivity ratio vs temperature for In-Cr sample *I*.

for pure indium.[6]

Allowed theoretical values of $\epsilon_0$ lie between 0 and 1. Theoretical curves are shown in Fig. 1 for the values $\epsilon_0 = 0.00$ and 1.00, which give the lower and upper limits of the ratios $K_{es}/K_{en}$, and a curve is shown for the value $\epsilon_0 = 0.70$, which gives the best fit of theory to data for sample *I*.

The sample film thickness was 1769 ± 100 Å, as determined by optical interferometry.[1] The transition temperature $T_c$ was 3.07 K as determined both by electrical resistance measurements and by the temperature at which the measured ratio $K_{es}/K_{en}$ reached 1. The width of the resistive transition[1] was 20 mK.

We also measured the thermal conductivity of another indium-chromium film (sample *H* in Ref. 7), but those results are not reported here, since we believe the sample was inhomogeneously heated above the temperature of 9.5 K which we used to drive helium off the substrate. One indication of this undesired heating was provided by the normal-state thermal conductivity data for that sample, from which the value $A = 7.717$ mW/cm K$^2$ was obtained. Thermal conductivity data for 17 quench-condensed films of indium and low-concentration indium alloys made in this laboratory[1,7-10] show an average value of $A = 3.85$ mW/cm K$^2$, with a standard deviation of 1.78 mW/cm K$^2$. Since the normal-state thermal conductivity of sample *H* is more than two standard deviations larger than the average value, we speculate that the electron mean free path was made longer by inadvertantly heating the film well above 9.5 K during the quench condensation of the film onto the substrate.

If sample *H* was heated to a higher temperature during its condensation than sample *I*, this can be explained by the greater film thickness (4800 Å) of sample *H*, assuming the heating was caused by radiation from the vapor source and/or by heating from the metal vapors condensing on the film. This would cause the part of the film located away from the substrate to heat up more than the part near the substrate. For such a sample, the electron mean free path would vary across the thickness of the film. This variation would cause the order parameter to vary across the film, according to Bergmann's observations,[5] since the film's thickness was about five coherence lengths. There may even have been some precipitation of chromium in the hotter side of the film, again making the order parameter inhomogeneous. There is therefore no way at present to interpret the results from this sample, and indeed the data[7] for sample *H* lie lower than those allowed by the theory. (The boat temperature used in making each of the samples described previously[1] was at least 1000 °C lower than we had to use in making samples *H* and *I*.)

In summary, our data agree well with calculations based on Shiba's theory, and indicate the $\epsilon_0 = 0.7$ for an In-Cr sample which is thought to be homogeneous. The data for a much thicker sample, which was probably heated inhomogeneously, cannot properly be compared with the theory.

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