Superconducting Transition Temperature of High-Purity Tantalum Metal

J. G. C. Milne
Department of Physics, The University of Sheffield, Sheffield, England
(Received October 3, 1960)

The superconducting transition temperature of a high-purity sample of tantalum has been measured and a zero-field value of 4.457°K±0.003°K obtained. The ratio of room temperature resistivity ρ_{295} to the residual resistivity $\rho_{4.2}$ gave a measure of the purity of the sample, a value of 250 being obtained. These results compare very well with those of Budnick. The value of (dH_c/dT) near the zero-field transition temperature was −358 oersteds/°K. An approximate theoretical estimate similar to that done by Pippard for tin shows that small amounts of impurity as measured by the residual resistance ratio will give a decrease in transition temperature of about half that observed experimentally.

SOME recent experiments in this laboratory on a single crystal of high-purity tantalum have given a value of the superconducting transition temperature, T_c, considerably higher than the usually accepted value of 4.39°K.[1] The sample of tantalum used in our experiments was made by zone refining some high-purity tantalum obtained from Ciba Limited. Analysis of the starting material showed a purity of 99.9%. The zone-refined single crystal was in the form of a rod 5.7 cm long and of circular cross section with mean diameter 0.29 cm. This rod was then vacuum annealed at 1200°C at 10^{-6} mm Hg. A measure of the purity of the specimen is given by the ratio $\rho_{295}/\rho_{4.2}$, where ρ_{295} is the room temperature resistivity and $\rho_{4.2}$ is the resistivity at 4.2°K for the normal metal. The value of $\rho_{295}/\rho_{4.2}$ for this specimen was 250, $\rho_{4.2}$ being determined in a magnetic field of 110 oersted.

The superconducting transition temperatures were determined magnetically using the Meissner effect,[2] the temperatures being measured with a carbon resistor[3] calibrated using the formula of Clement and Quinnell.[4] A check on this was provided by the vapor pressure of the surrounding liquid helium bath.

For the zero-field transition a small magnetic field of 1.1 oersteds was used and this gave a temperature of 4.454°K for the mid-point of the transition. The width of the transition was about 0.007°K. Extrapolation to zero applied field gave a transition temperature of 4.457°K±0.003°K. The ratio of length to diameter of the specimen was such that effects from the demagnetizing field could be neglected.

The critical fields for various temperatures just below T_c were also determined. Curves of the magnetic induction B against applied field H were determined at constant temperature, the field being applied parallel to the long axis of the specimen. Values of B were measured for both switching on and switching off the applied field. No frozen-in flux effects were observed. It was also found that the B-H curve for the normal phase was a straight line which, when extrapolated, passed through the origin independent of the temperature. This shows that any small local inclusions of superconducting material at fields above H_c for the bulk material were too small to be detected. The value of (dH_c/dT) for temperatures near T_c obtained from the H_c values is −358 oersteds/°K. This gives a value of H_0, the critical field at 0°*K*, of 800 oersteds if a parabolic H_c-T curve is assumed. The critical field curve was not extensive enough to determine any departure from a parabola.

Some recent work by Budnick *et al.*[5] and Budnick[6] also shows an increase in T_c for high-purity tantalum. Budnick *et al.*[5] give a T_c value of 4.476°K for $\rho_{295}/\rho_{4.2} \approx 700$ and Budnick[6] gives a maximum T_c value of 4.483°K with $\rho_{295}/\rho_{4.2} \approx 10\,000$. If a graph is plotted of T_c against $\rho_{4.2}/\rho_{295}$ using these results and our result, a straight line can be drawn (see the work on impure tin by Lynton, Serin, and Zucker[7]), which extrapolates to give $T_c = 4.418$°K for a specimen with $\rho_{4.2}/\rho_{295} = 10^{-2}$, i.e., a decrease in T_c of 0.065°K. A theoretical estimate of the change in T_c can be made by performing a calculation similar to that done by Pippard for tin.[8] If we consider a tantalum alloy with $\rho_{4.2}/\rho_{295} = 10^{-2}$, the electron mean free path, l, is approximately 2×10^{-5} cm. This will affect the electron-phonon interaction responsible for superconductivity. Following Pippard,[8] we estimate the average wave number, k, of the phonons responsible for this interaction and obtain a value for kl of about 10^3. This gives a decrease of about 10^{-1}% in the interaction. Now $T_c \approx \Theta e^{-1/N(0)V}$ from the theory of Bardeen, Cooper, and Schrieffer,[9] where Θ is the Debye temperature (245°K) for Ta, $N(0)$ is the density of states at the Fermi surface, and V is the total electron interaction energy resulting from Coulomb repulsion

[1] J. Eisenstein, Revs. Modern Phys. **26**, 277 (1954).
[2] D. Shoenberg, *Superconductivity* (Cambridge University Press New York, 1952), p. 55.
[3] The carbon resistor was of 110-ohm nominal resistance, $\frac{1}{8}$-watt type 5*B*, made by the Erie Resistor Company Limited. At 77°K its resistance was 152 ohms; at 20.4°K, 281 ohms; at 14°K, 377 ohms; at 4.2°K, 1955 ohms. The resistance at 4.2°K was independent of the measuring current provided this was less than 30 μa.
[4] J. R. Clement and E. H. Quinnell, Rev. Sci. Instr. **23**, 213 1952.
[5] J. I. Budnick, W. B. Ittner, and D. P. Seraphim, Suppl. Physica **24**, S151 (1958).
[6] J. I. Budnick, Phys. Rev. **119**, 1578 (1960).
[7] E. A. Lynton, B. Serin, and M. Zucker, J. Phys. Chem. Solids **3**, 165 (1957).
[8] A. B. Pippard, J. Phys. Chem. Solids **3**, 175 (1957).
[9] J. Bardeen, L. N. Cooper, and J. R. Schrieffer, Phys. Rev. **108**, 1175 (1957).

and electron-phonon induced attraction. If we use the expression given by Pines[10] to calculate the interaction energy, we obtain a value of 0.51 for that part of $N(0)V$ due to the electron-phonon interaction. Hence $N(0)V$ decreases by about 5×10^{-4}. Taking $T_c\approx4.5$°K, $N(0)V\approx0.25$ and the decrease in T_c is about 0.039°K. This is a little more than half the experimental value, so that the agreement is satisfactory considering the difficulty in estimating l and the simple nature of the calculation.

ACKNOWLEDGMENT

I wish to thank Dr. B. B. Argent of the Department of Metallurgy for preparing the tantalum specimen used in this work.

[10] D. Pines, Phys. Rev. **109**, 280 (1958).

PHYSICAL REVIEW VOLUME 122, NUMBER 2 APRIL 15, 1961

Specific Heat of Yttrium Iron Garnet from 1.5° to 4.2°K*

SAMUEL S. SHINOZAKI†
Department of Physics, University of California, Berkeley, California

(Received December 19, 1960)

The specific heats of two samples of yttrium iron garnet have been measured between 1.5 and 4.2°K. The data have been analyzed into lattice- and spin-wave contributions characterized, respectively, by the Debye temperatures $\Theta_1=538$°K, $\Theta_2=567$°K, and by $D_1=0.81\times10^{-28}$ erg-cm², $D_2=0.85\times10^{-28}$ erg-cm², where D is defined by the dispersion relation for spin waves, $\hbar\omega=Dk^2$.

I. INTRODUCTION

THE low-temperature specific heat of yttrium iron garnet (YIG) is of interest in connection with the expected spin-wave contribution to the thermal properties. Recently, several specific-heat measurements have been reported, but the results are not in agreement with one another. In order to check the former results, measurements on two samples of YIG were carried out in the temperature range 1.5° to 4.2°K.

II. EXPERIMENTAL

In order to avoid errors associated with the desorption of exchange gas during the heating periods, a mechanical heat switch was used to cool the samples to 1.1°K. The switch consisted of two copper jaws connected to the helium bath by flexible copper wires. The jaws could be closed on a small copper sample holder which made thermal contact to the sample. The motion of the jaws was controlled by applying tension to a piano wire which went directly to the top of the apparatus and out into the atmosphere through a bellows. Half an hour was required to cool the sample from 77° to 4.2°K. When the switch was opened, a temperature increase in the sample was observed which corresponded to a heat input of between 10 ergs and 100 ergs. The sample was mounted rigidly in the cryostat with cotton thread.

The thermometer was an American Ohmite resistor ($\frac{1}{2}$ watt, 47 ohms), which was found to be more sensitive than the Allen-Bradley resistor. It was calibrated against the vapor pressure of the helium bath at 22 points between 1.5° and 4.2°K. During the calibration, power was supplied to the bottom of the bath at a rate of 0.04 watt and a correction for the hydrostatic

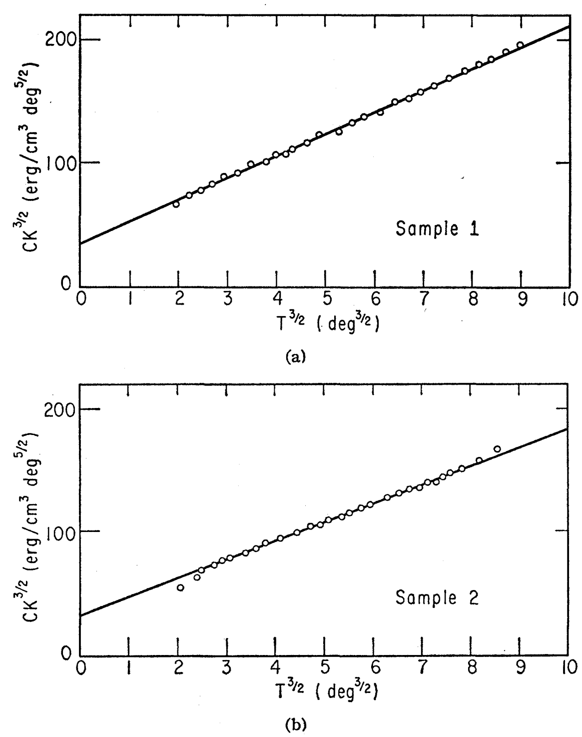

FIG. 1. The specific heat of the two YIG samples. The points for sample 1 give the results obtained in one experiment. The points for sample 2 give the results obtained in two separate experiments.

* Supported in part by the National Science Foundation.

† Present address: Ford Scientific Laboratory, Dearborn, Michigan.