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Microwave-Absorption Determination of the Anisotropic Energy Gap in Superconducting Zinc*

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The anisotropic superconducting energy gap of pure zinc has been determined from microwave-absorption measurements for photon energies between 1.0 and $5.5kT_c$ where $T_c = 0.837$°K. The minimum and dominant energy gap corresponds to $(3.1 \pm 0.1)kT_c$ at $T=0$. A much larger energy gap is observed for directions near the c axis.

A LARGE anisotropy in the superconducting energy gap of zinc has been suggested by measurements of electronic specific heat,[1] thermal conductivity,[2] and depression of the transition temperature T_c by nonmagnetic impurities.[3,4] The technique of determining the absorption of polarized microwaves by single crystals developed by Biondi, Garfunkel, and Thompson[5] for superconducting aluminum makes possible a more direct observation of the anisotropic energy gap. In their paper on aluminum, they reported on some preliminary measurements of zinc which had too much scatter to be more than suggestive. It is the purpose of the present paper to give the detailed results of our measurements on single-crystal samples of zinc made on the same apparatus as the measurements of Biondi, Garfunkel, and Thompson.[5]

The microwave absorption was determined calorimetrically by observing the power absorbed by a disk-shaped single-crystal zinc sample (~1.2-in. diam and 0.060-in. thick) terminating, but thermally isolated from the end of a waveguide. For a fixed microwave frequency, a determination of the ratio of power absorbed for the sample in the superconducting state to that in the normal state yields the surface resistance ratio, $r \equiv R/R_n$. The use of a He^3 refrigerator provided temperatures down to ~0.35°K.

The single crystals of pure zinc were grown from Cominco stock of 69 grade.[6] Samples of the desired crystallographic orientation and shape were spark machined in a bath of oil heated to 100°C in order to eliminate cleavage problems. Samples were subsequently mechanically polished, chemically polished with equal parts of hydrogen perioxide, ethyl alcohol, and nitric acid solution, and then annealed near the melting point. The residual resistance ratio was found to be 2100 ± 100 as determined by eddy current decay.[7]

Figure 1 presents the dependence of the surface-resistance ratio on the photon energy as expressed in energy units of kT_c, k being the Boltzmann constant. The curves correspond to a reduced temperature $t = T/T_c = 0.5$. The transition temperature, $T_c = (0.837 \pm 0.003)$°K,[8] was determined by noting the temperature dependence of the surface-resistance ratio for photon energies much less than the energy gap. The crystal structure of zinc is hexagonal close packed. We have made measurements on two different crystal faces, one of them for two polarizations of the microwaves. These correspond to: (1) the [0001] or c axis along the direction of microwave propagation (i.e., perpendicular to the sample plane), (2) c axis perpendicular to both the microwave electric field $\mathbf{E}_\mu$ and the propagation direction, and (3) c axis parallel to $\mathbf{E}_\mu$.

When the superconducting penetration depth λ is much less than the superconducting coherence length ξ_0, one is in the regime of the anomalous skin effect for which the effective electrons for absorption of the microwaves are those which move in a plane nearly perpendicular to the microwave propagation direction, or parallel to the sample surface. Of the effective electrons in the plane, those which are nearly along $\mathbf{E}_\mu$ make the greatest contribution to the absorption. Examination of the three curves in Fig. 1 indicates that at $t=0.5$ there is an energy gap near the c axis which is much larger than the energy gap associated with most of the Fermi surface, namely, $2\Delta(0.5) = (3.0 \pm 0.1)kT_c$. This energy-gap model is consistent with the model Farrell, Park, and Coles[3] used to interpret the depression of T_c by impurity doping.

The structure in the curves of Fig. 1 near 3.0, 3.4, and $3.9kT_c$ is thought to be instrumental in origin because it is found to be independent of temperature. A loss of polarization of the microwave field for certain frequencies is a likely explanation for the behavior at $3.9kT_c$, and occurs at the same *frequency* as a similar irregularity in aluminum observed by Budzinski.[9]

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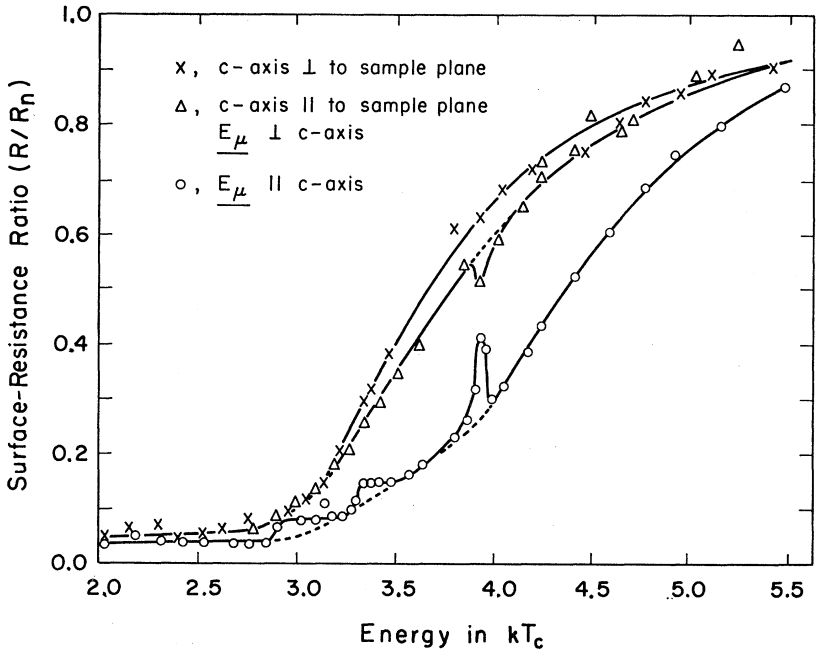

FIG. 1. Surface-resistance ratio for zinc at $t=T/T_c=0.5$ ($T_c=0.837$°K).

Assuming that the temperature dependence of the energy gap corresponds to that of the Bardeen-Cooper-Schrieffer microscopic theory of superconductivity,[10] it is concluded that most of the Fermi surface is associated with an energy gap near $2\Delta(0)=(3.1\pm0.1)kT_c$ while the energy gap near the c axis is at least $2\Delta(0)=(4.0\pm0.2)kT_c$.

There have been several other determinations of the superconducting energy gap in zinc. Unfortunately, the previous measurements were either direct determinations (observation of a frequency or potential onset) on polycrystalline samples, or indirect measurements (observation of the temperature variation of the thermal excitations) on single-crystal samples. In either case, above, it is difficult to get an accurate measure of the anisotropy.

Direct measurements were made by Zemon and Boorse[11] who observed the onset frequency for microwave absorption in polycrystalline samples. They found an average gap of $2\Delta(0)=(3.01\pm0.09)kT_c$. Donaldson,[12] in tunneling measurements of zinc films, found an average gap of $2\Delta(0)=(3.2\pm0.1)kT_c$. These average gaps are consistent with our observations, but do not give any indication of the anisotropy.

Zavaritskii[2] has measured the anisotropic electronic thermal conductivity. Using a prolate spheroidal model for the energy gap as a function of direction, he concluded that the maximum gap is $3.5kT_c$ along the c axis and the minimum gap is $2.4kT_c$ perpendicular to the c axis. Bohm and Horwitz[13] in measurements of the low-frequency longitudinal-acoustic attenuation concluded that the energy gap is $(3.8\pm0.2)kT_c$ for propagation along the $[\bar{1}210]$ directions and $(3.4\pm0.2)kT_c$ for propagation along the $[10\bar{1}0]$ direction. Lea and Dobbs[14] found similar values for the above propagation directions and $(3.41\pm0.1)kT_c$ for the $[0001]$ direction.

The value that we assign to the energy gap near the c axis is uncertain due to an effect of the surface on our results; the surface causing in general a large-angle scattering of the electrons which mix the energy gaps from two different directions. An analysis of this result is given in the following paper by Hays.[15]

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