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MEASUREMENT OF THE ANISOTROPY OF THERMAL CONDUCTIVITY OF ZINC AND CADMIUM IN THE SUPERCONDUCTING STATE

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The thermal conductivity of zinc and cadmium in the superconducting state has been measured along different crystallographic directions. The anisotropy in the temperature dependence of the electronic thermal conductivity is ascribed to an anisotropy in the width of the gap in the energy spectrum of the excitations in these metals.

RECENT investigations have shown the existence of an anisotropy in the energy spectrum of the excitations in the superconducting state for gallium[1] and tin.[2] In the present work these measurements are extended to zinc and cadmium. As before,[1] the form of the anisotropy of the spectrum was determined from the anisotropy of the electronic thermal conductivity in the superconducting state.

The conductivity of zinc and cadmium specimens, grown along the principal crystallographic directions by Kapitza's method,[3] was measured between 0.1 and 1° K. The method of measurement was similar to that used previously,[4] the change in the apparatus consisting only in a considerable improvement in the thermal contact between specimen and cooling salt. Figure 1 shows the results of the thermal conductivity measurements and Fig. 2 the relative change in conductivity of the specimens in the superconducting state. At $T = T_c$ the values of K (in w/cm-deg.) are as follows:

Zn-1	Zn-2	Zn-7	Zn-4	Zn-5	Cd-1	Cd-2	Cd-3
18	8.3	7.5	4.6	2.1	6.92	28.2	9.1

In order to determine the critical temperature T_c of the metals studied, the temperature dependence of the critical magnetic field H_c was measured, as previously.[1] The table gives the chief quantities characterizing the $H_c(T)$ dependence and the heat capacity of the metal in the normal state, based on these data. The critical temperature for zinc derived from these measurements agrees with Phillips' data,[5] but the critical temperature for cadmium comes out somewhat lower than that obtained earlier,[6] due evidently to the improvement in the magnetic temperature scale achieved by Cooke et al.[7]

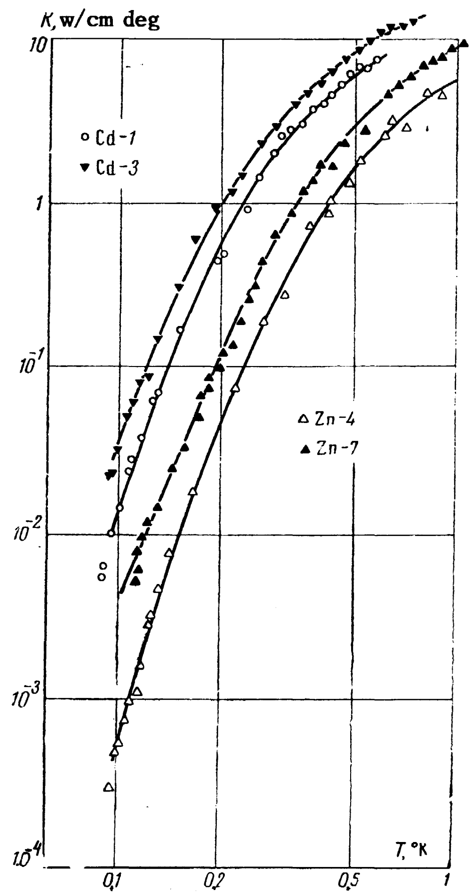

FIG. 1. The thermal conductivity of specimens of zinc and cadmium along the hexagonal axis (open points) and perpendicular to the hexagonal axis (full points).

DISCUSSION OF RESULTS

We shall first consider the results for zinc. It can be seen from Fig. 2 that the temperature dependence of the thermal conductivity is a function

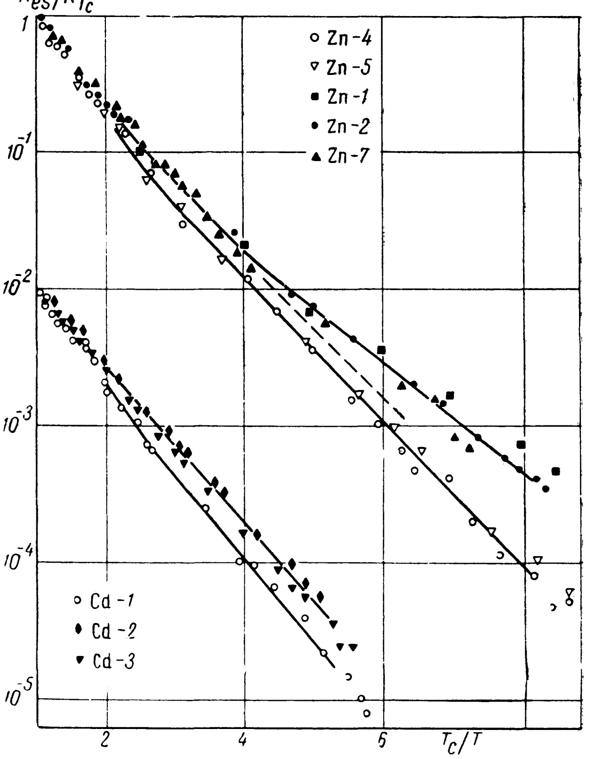

FIG. 2. The variation with temperature of the electronic thermal conductivity of zinc and cadmium in the superconducting state: open points – specimens along the hexagonal axis, full points – specimens perpendicular to the hexagonal axis.

of the crystallographic direction. The greatest difference is observed between the temperature dependence of the conductivity along the hexagonal axis and in a direction perpendicular to it. The results obtained previously[8] for zinc specimens of intermediate orientation lie between these two curves. The anisotropy in the temperature dependences of the thermal conductivity shows up most clearly in the variation of the ratio of conductivities along different crystallographic axes, as shown in Fig. 3. The mean values of K_{es}/K_{T_c} for all specimens of one orientation have been used for calculating these ratios, and we have taken the value $\rho_\perp/\rho_\parallel = 1.4$ for the residual resistance range, according to the measurements of V. B. Zernov (private communication), which corresponds to $K_{Tc\parallel}/K_{Tc\perp} = 1.40$. Since the lattice conductivity — the upper limit of which

Quantity	Zn	Cd
T_c	0.82_5	0.53
$(dH_c/dT)_{T\to T_c}$	100	95
$(H_c)_{T\to 0^\circ K}$	52(±0.5)	28.5(±0.5)
$(d^2H_c/dT^2)_{T\to 0}$	90	107
$10^3\gamma$, Joule/g-mole-deg	0.68(±0.03)	0.63(±0.06)

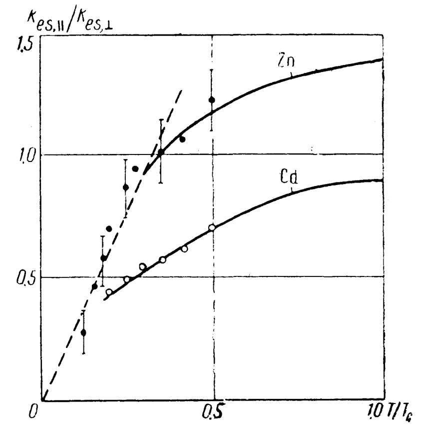

FIG. 3. The temperature dependence of the relative anisotropy of electronic thermal conductivity of zinc and cadmium ($K_\parallel$ and $K_\perp$ are the thermal conductivities of specimens along and perpendicular to the hexagonal axis). The dashed curve is the variation of the ratio $K_{\perp,\Delta_{min}}/K_{\parallel,\Delta_{min}}$ according to theory.

can be estimated from Casimir's formula (see, for example, reference 1) — is small compared with the electronic conductivity for the specimens studied, the results evidently reflect a temperature variation in the electronic thermal conductivity of zinc.

The anisotropy of the temperature variation of electronic thermal conductivity of a superconductor in the temperature region $T \ll T_c$ can be ascribed to an anisotropy in the width of the gap Δ which separates the excited state from the "superconductive" ground state of the electrons.[1,9] The more rapid change in conductivity along the hexagonal axis therefore indicates a more rapid reduction in excitation density with decreasing temperature, corresponding to a maximum of Δ in this direction.

We can compare the results obtained with the theoretical analysis of the change in conductivity of an anisotropic superconductor, made by Khalatnikov.[9] If the directions for which the values of Δ are the minimum lie in a plane perpendicular to the principal direction, then for isotropic scattering of the excitations

$$K_{\perp,\Delta_{min}}/K_{\parallel,\Delta_{min}} = 4.1\ T/\Delta'', \tag{1}$$

where $K_\parallel, \Delta_{min}$ and $K_\perp, \Delta_{min}$ are the conductivities in the direction of Δ_{min} and perpendicular to it and Δ'' is the derivative of Δ in the direction of Δ_{min} with respect to angle,* or if we approximate Δ by an ellipsoid of revolution,

$$K_{\perp,\Delta_{min}}/K_{\parallel,\Delta_{min}} = 4.1\ \Delta_{min}T/(\Delta_{max}^2 - \Delta_{min}^2). \tag{1a}$$

*The calculation of the thermal conductivity for the case of anisotropy was carried out by A. F. Rusinov (private communication).

It can be seen from Fig. 3 that this dependence is close to that obtained experimentally in the temperature region $T/T_c < 0.3$, so that we can use the results of the calculation to determine Δ_{min} and the anisotropy* of Δ. The direct proportionality of $K_{\perp, \Delta_{min}}$ to $\exp(-\Delta_{min}/T)$ for temperatures where $(\Delta_{max} - \Delta_{min})/T > 1$ was used to determine Δ_{min}, and Eq. (1a) was used to determine $\Delta_{max} - \Delta_{min}$. Comparison of the results of this calculation with the data of Figs. 2 and 3 shows that for zinc $\Delta_{min} \approx 1.2\ T_c$, i.e. $\sim 1.0°K$ and $\Delta_{max} - \Delta_{min} \sim 0.55\ T_c$.

Let us now consider the results for the thermal conductivity of cadmium. Here the temperature dependence in the superconducting state is also a function of the crystallographic direction. The form of the anisotropy of K_{es} is similar to that found for zinc (Figs. 2 and 3). The nature of the anisotropy of Δ in these two metals is evidently similar. A quantitative comparison with theory can not be made in this case. An estimate of the value of Δ_{min} leads to the value $\Delta_{min} \sim 1.35\ T_c$, i.e. $\sim 0.67°K$ for cadmium.

Measurements made up to the present thus indicate the existence of an anisotropy in the energy spectrum of the excitations in a whole range of superconductors: gallium, tin, zinc and cadmium — all the metals which have so far been studied. The form of the anisotropy in the energy gap can, apparently, differ. For example, while in the case of gallium the value of Δ can be represented to a first approximation by an ellipsoid compressed along the axis of rotation, in the case of zinc and cadmium this ellipsoid is stretched out along the axis of rotation. The considerable magnitude of the anisotropy in Δ and its differing character show that one must be very wary of the comparison of the properties of different metals according to the mean value of the gap width[8,10] and of the results of comparing the properties of real superconductors with the results of a theory based on an isotropic model. There is as yet insufficient data to relate unambiguously the anisotropy of Δ with the anisotropy of the properties of a metal in the normal state, but the agreement between the form of the anisotropy of Δ for gallium and the details of the Fermi surface, which can be derived from the galvanomagnetic properties by using the theory of Lifshitz et al.,[12] can hardly be considered fortuitous. There is obviously a similar correlation for zinc and cadmium.

In conclusion, I take the opportunity of expressing my sincere thanks to P. L. Kapitza and A. I. Shal'nikov for their constant interest in this work.

*In the earlier[1] analysis of the anisotropy of Δ for gallium it was impossible to compare the experimental results with the theory since, owing to the large anisotropy of thermal conductivity in the normal state over the whole temperature range studied, the added condition $K_{\perp, \Delta_{min}}/K_{\parallel, \Delta_{min}} < 1$ which follows from (1) and the conditions for the calculation, $(\Delta_{max} - \Delta_{min})/T > 1$ was not fulfilled.

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