Thermal conductivity of vanadium at low temperatures

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Experimental data are presented on the thermal conductivity of pure vanadium at low temperatures $T < 125$°K. The half width of the energy gap ($\Delta = 9.5$°K) is determined from a comparison of the thermal conductivities in the normal and superconducting states. A comparison of the experimental data leads to the conclusion that vanadium is a weak-coupling superconductor.

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The published data[1] on the thermal conductivity of vanadium pertain to very unpure samples, in which the thermal conductivity near the superconducting transition temperature ($T_c = 5.4$°K) is smaller by two or three orders of magnitude than the thermal conductivity of the sample investigated in the present study. Information on the purification technology and on the impurity composition, as well as more detailed experimental data on the electric properties of our large-grain polycrystalline sample, with 1.5 mm diameter and a resistivity ratio $\rho_{293}/\rho_{4.2} = 1570$, are given in[2]. The thermal conductivity was measured by the stationary-flow method with a carbon resistance thermometer and copper-constantan thermocouples.

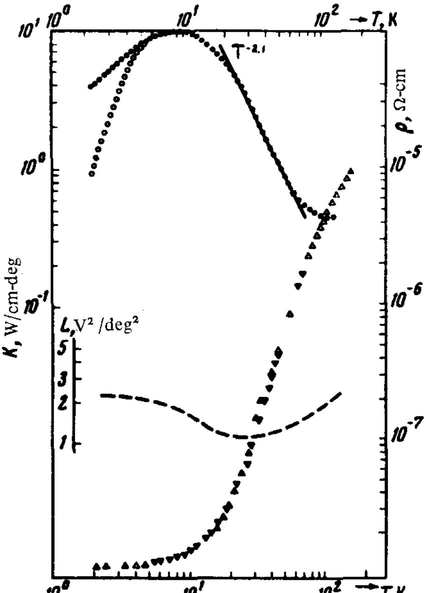

FIG. 1. Temperature dependences of the thermal conductivity K, of the resistivity ρ, and of the Wiedemann-Franz ratio $L = K\rho/T$ (dashed line). △—present data, —from[2], ●—K_n, ○—K_s.

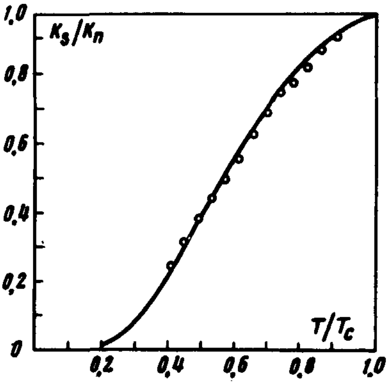

FIG. 2. Comparison of the theoretical curve for the thermal-conductivity ratio K_s/K_n (solid line) with experiment (points).

Figure 1 shows the measured thermal conductivity K and resistivity ρ, and also the Wiedemann-Franz ratio $L = K\rho/T$ calculated on the basis of these data in the region $T = 2$—125°K. At $T < 5.4$°K the indicated vanadium sample became superconducting (s), and a longitudinal magnetic field H was used to restore the normal state (n) (at $T < 5.4$°K). Since vanadium is a type-II superconductor, the field H used to restore ρ_n exceeded H_{c3} (the critical field for surface superconductivity), while the field H needed to restore K_n exceeded H_{c2}. With further increase of H, up to double the values of H_{c3} and H_{c2}, no change was observed in the values of ρ_n and K_n.

From the value of the Lorentz number L on Fig. 1, which does not exceed its Sommerfeld value $L_0 = 2.4 \times 10^8\ \mathrm{V}^2/\mathrm{deg}^2$, we can conclude that in the entire temperature region 2—125°K the thermal conductivity in the investigated vanadium sample is due to the electrons. From the form of $\rho(T)$ in the region $T < T_c$ it can be concluded that in this region the electrons are scattered by the impurities. For a comparison with the theory it is also necessary to estimate beforehand the coupling constant for V.

If the Debye temperature Θ is assumed to equal its low-temperature heat-capacity value $\Theta = 380$°K,[3] then the value obtained[4] for the coupling constant $g = [\ln(1.14\,\Theta/T_c)]^{-1}$ is 0.23, so that in first-order approximation vanadium can be classified as a superconductor with weak electron-phonon coupling. For scattering of the carriers by impurities, the Gel'likman formula[5] corresponding to this case determines the thermal conductivity in the superconducting state

$$K_S = \frac{2}{3}\,\frac{P_F^3 \tau_0}{\Pi^2}\,F(T)$$

where

$$F(T) = \frac{\Delta^2(T)}{T}\left[\exp\left(\frac{\Delta}{T}\right) + 1\right]^{-1} + 2T\sum_{S=1}^{\infty}\frac{(-1)^{S+1}}{S^2}\exp\left(-\frac{S\Delta}{T}\right) + 2\Delta\ln\left[1 + \exp\left(-\frac{\Delta}{T}\right)\right], \quad (1)$$

and Δ is the half-width of the energy gap. At $\Delta = 0$ formula (1) determines the thermal conductivity of the normal state:

$$K_n = \frac{P_F^3 \tau_0}{9m}\,T \quad (2)$$

P_F and m are the Fermi momentum and the effective mass of the electrons, and τ_0 is the relaxation time.

In the calculation of K_c, the $\Delta(T)$ dependence is taken into account with the aid of the table of[6], which corresponds to the case of weak coupling.

Figure 2 shows, in relative coordinates, the theoretical Geĭlikman curve for a selected value $\Delta = 9.5 \pm 0.05$ °K that ensures a satisfactory approximation of the experimental data. The conclusion that the thermal-conductivity data point to a weak electron-phonon coupling in vanadium is favored also by the obtained ratio of $\Delta = 9.5$ °K and $T_c = 5.4$ °K, namely $\Delta/T_c = 1.76$.[4]

Attention is called to another interesting experimental fact, not connected with the superconductivity of V. The temperature dependence of the thermal conductivity in the region of the electron scattering by phonons (25—60 °K) agrees with the standard-theory conclusion $K \sim T^{-2}$. To the left of the maximum of the thermal conductivity $K(T < 5.4$ °K) we have $k_n \sim T^{0.9}$ and $K_s \sim \exp(-8.1/T)$.

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