

# Temperature minimum of the resistivity of beryllium

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A minimum has been observed in the temperature dependence of the resistivity  $\rho(T)$  of beryllium. The value and position of the minimum agree with estimates obtained from the theory of Kozlov and Flerov (Abstracts of Nineteenth Conference on Low Temperature Physics, Minsk, 1976 [in Russian], page 200). It is suggested that the possible contribution due to the Kondo anomaly [J. Kondo, Solid State Physics **23**, 184 (1969)] should be much less than the observed effect.

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It follows from the quantum theory of transport processes<sup>[1]</sup> that in metals at low temperatures, when the characteristic wavelength of the thermal phonons becomes larger than the electron path length due to the scattering by non-magnetic impurities, the phonon contribution to the resistivity  $\rho(T)$  is negative and is described by the formula

$$\frac{\Delta\rho}{\rho_0} \equiv \frac{\rho(T) - \rho(0)}{\rho(0)} \approx -13.5\lambda \frac{\Theta_D}{E_F} \frac{\hbar^2}{(\tau E_F)^2} \ln \frac{T_1}{T} \quad (1)$$

in the range of temperature  $T$  such that

$$T_2 \ll T \ll T_1, \quad (2)$$

Here  $\lambda$  is the constant of the electron-phonon interaction,  $\Theta_D$  is the Debye temperature,  $E_F$  is the Fermi energy,  $\tau$  is the electron relaxation time due to scattering by nonmagnetic impurities or defects,  $\hbar$  is Planck's constant,  $T_1$

$=\Theta_D/\tau E_F \sim c\Theta_D$  is the first quantum temperature,  $c$  is the concentration of the impurities or defects, and  $T_2 = T_1\Theta_D/E_F$  is the second quantum temperature. At  $T \lesssim T_2$  the quantity  $\Delta\rho(T)$  tends to 0 quadratically. This should produce on the plot of  $\rho(T)$  a minimum located between the temperatures  $T_1$  and  $T_2$  and having a depth determined by the constant preceding the logarithm in (1).

For ordinary metals, in which the rule  $\Theta_D \sim 300\text{--}400^\circ\text{K}$  and  $E_F \sim 4 \times 10^4^\circ\text{K}$ , the observation of this effect is a rather complicated problem. An exception from this rule is beryllium, for which  $\Theta_D = 1416^\circ\text{K}$ <sup>[3]</sup> and  $E_F = 0.7\text{ eV}$ . Beryllium has a very narrow range of  $T_1/T_2 = E_F/\Theta_D = 5.5$ , and relation (2) cannot be rigorously satisfied, so that the behavior of  $\rho(T)$  should be described by a more complicated expression. For a comparison with experiment, we can use the approximate estimate

$$\Delta\rho_{\text{min}}/\rho_0 \cong -10c^2\Theta_D/E_F.$$

It is clear that the largest value of this effect should be expected in a beryllium sample with many impurities or defects, but their number must still not be large enough to change the values of  $\Theta_D$  and  $E_F$ .

The measurements were made on a beryllium sample with a resistivity ratio  $\rho_{300\text{ K}}/\rho_{4.2\text{ K}} = 11.5$ . From a comparison with the samples used by Watts,<sup>[4]</sup> which had  $c = 0.4\%$  and a resistivity ratio  $\rho_{300\text{ K}}/\rho_{4.2\text{ K}} = 30\text{--}40$ , it can be assumed that the sample employed by us had  $c \cong 1.5\%$ . This yields for the estimates  $T_1 = 21\text{ K}$ ,  $T_2 = 4\text{ K}$  and  $\Delta\rho_{\text{min}}/\rho_0 = -4 \times 10^{-4}$ . The sample was cut by the electric-spark method<sup>(1)</sup> from a single crystal (in which quantum oscillations of the resistivity, the Shubnikov-de Haas effect, and thermoelectric power were observed, and the values of the magnetic frequency coincided with those known for beryllium), in the basal plane (to make the samples stronger, since beryllium is brittle and cleaves along the hexagonal plane), in the form of a "serpentine" with transverse dimensions  $0.3 \times 0.1\text{ mm}$ . The cut sample was glued with BF-2 adhesive to a bulky sample from the same single crystal, with dimensions  $2 \times 8 \times 24\text{ mm}$ . The housing of a TSG-2 germanium resistance thermometer, calibrated in the range  $2\text{--}30^\circ\text{K}$ , was soldered to this bulky sample with Wood's alloy. The junction of a thermocouple (Au + 0.07% Fe—Chromel P, model S-7050, Thor Cryogenics LTD) was also attached to the sample. The sample was placed in a cooper capsule, the temperature of which could be varied in a wide range with the aid of a heater. The accuracy with which the temperature was measured in the region  $T < 30^\circ\text{K}$  was  $0.05^\circ\text{K}$  at  $T > 30\text{--}0.5^\circ\text{K}$ . The sample resistivity was measured with the four-contact method using an R-348 double potentiometer of accuracy  $2 \times 10^{-5}$ .

Figure 1 shows the measurement results. The small deviation of the points at  $T \lesssim 4^\circ\text{K}$  is due apparently to slight overheating of the sample by the measurement current ( $I = 190\text{ mA}$ ): the upper points correspond to points in liquid helium, and the lower in helium gas. On the upper curve (c) the same results are plotted in coordinates  $\rho = \rho(T^5)$  for  $T < 50^\circ\text{K}$ .

It can be stated that the behavior of the observed  $\rho(T)$  dependence agrees with the results of the theory,<sup>[1]</sup> qualitatively, and even quantitatively in order of magnitude. Generally speaking, we cannot exclude here a priori the possible influence of the Kondo effect, nonetheless, for a number of reasons, it can be assumed that it does not manifest itself here in this case. First, this sample had a much lower magnetic-impurity content,  $C_m \ll C$ , amounting to about

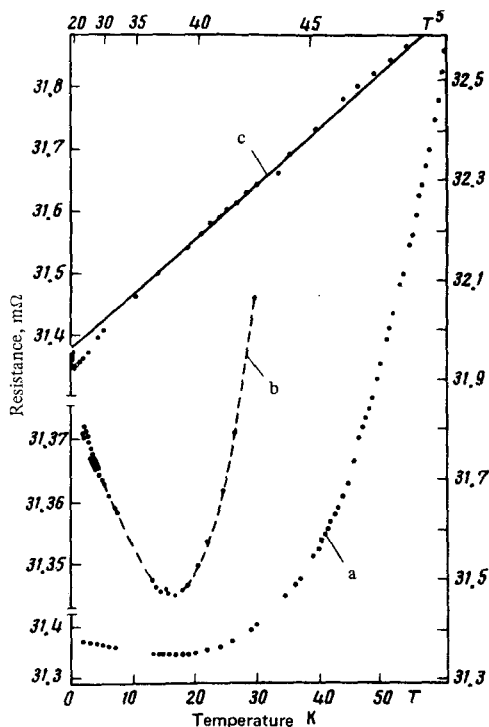


FIG. 1. a) Temperature dependence of the resistivity of beryllium sample ( $\rho_{300\text{ K}}/\rho_{4.2\text{ K}}=11.5$ ); b) the same dependence in a larger scale; c) the same dependence plotted as a function of  $T^5$ . The lower temperature scale is for curves a and b, and the upper scale for curve c.

10<sup>-2</sup>%. Second, the behavior to the left of the minimum is very difficult to reconcile with the logarithmic dependence customarily observed in the Kondo effect, and on the other hand, to the right of the minimum the negative resistivity increment relative to the Bloch law  $\Delta\rho \sim T^5$  vanishes in a very narrow temperature interval; this does not agree with the Kondo effect, but follows naturally from the theory of<sup>[1]</sup>. Although it is difficult to compare this section, in view of the low accuracy, with the logarithmic law (1), it can be explained as being due to the narrowness of the interval between the first and the second quantum temperatures in beryllium.

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<sup>1</sup>A. N. Kozlov and V. N. Flerov, Tez. NT-19, Minsk, 1976, p. 200.

<sup>2</sup>J. Kondo, Solid State Physics **23**, 184 (1969).

<sup>3</sup>Guenter Ahlers, Phys. Rev. **145**, 419 (1966).

<sup>4</sup>B. R. Watts, Proc. R. Soc. Lond. **A282**, 521 (1964).