ELECTRICAL RESISTANCE OF CESIUM AT LOW TEMPERATURES

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The temperature dependence of the resistance of a sample of very pure cesium with a relative resistivity $\rho_0/\rho_{293} = 1.13 \times 10^{-4}$ was investigated between 1.65 and 5°K and between 14 and 20.4°K. It was found that, at $T \ll 8°K$, $\rho \propto T^{3.1}$. The dependence of ρ on T was attributed to residual impurities. Between 4.2 and 0°K, the resistance of cesium decreased by a factor of 10, which indicated a fairly high degree of purity of metallic cesium.

It has been reported in several experimental papers[1-4] that alkali metals obey Bloch's law, according to which the resistivity $\rho \propto T^5$. This law is obeyed by lithium with $\delta_0 = 4 \times 10^{-3}$ at $T \leq 20°K$,[1] by sodium with $\delta_0 = 3 \times 10^{-4}$ at $T \leq 15°K$,[1] by potassium with $\delta_0 = 2 \times 10^{-3}$ at $T \leq 8°K$,[1-3] by rubidium with $\delta_0 = 2.6 \times 10^{-3}$ at $T \leq 5°K$,[1] and by cesium with $\delta_0 = (2-3) \times 10^{-3}$ at $T \leq 3°K$.[1,4] [1)]

Since an increase in the purity of a metal may alter the nature of the temperature dependence of the resistance at low temperatures, because of changes in the contributions of the various scattering proceeses to the resistance,[5,6] it seemed desirable to investigate the temperature dependence of the resistance using much purer metals. The present paper reports the results of measurements of the resistance of very pure cesium with a relative residual resistance ~16 times lower than the value reported in [1,4]. The measurements were carried out in the liquid helium and liquid hydrogen temperature ranges. The pure cesium (≥99.995%) was prepared at the Institute of the Chemistry and Technology of Rare Elements of the Kolan branch of the USSR Academy of Sciences, by successive vacuum rectification and vacuum distillation. Spectroscopic analysis of the pure cesium established the presence of 4×10^{-3}% Rb, 2×10^{-3}% Na, 4×10^{-4}% K, and traces of Si, Ca, Mg, Fe, and Al.

The resistance of cesium was measured in thick-walled cylindrical glass capillaries, which were filled with the metal in high vacuum and then sealed. The electrical leads (two current and two potential leads) were platinum wires of 0.3 mm diameter sealed into the glass. The distance between the potential probes was 120–60 mm and the diameter of cesium columns was 2.0, 1.0, or 0.4 mm. The electrical resistance was measured by a compensation method using an R-306 potentiometer and an M 17/3 galvanometer in a circuit whose voltage sensitivity was $\sim 5 \times 10^{-8}$ V. The measuring current at room temperature was 0.06 A, while at liquid helium temperature the current was 3 A for a sample of 2 mm diameter, 0.6 A for 1 mm diameter, and 0.06 A for 0.4 mm diameter. The measurements at 1.7°K showed that the resistance increased by ~25% in a longitudinal magnetic field of ~2.5 kOe. Hence, we concluded that the influence of the magnetic field of the measuring current could be ignored. The error of the resistance measurements was ~0.5% at 5°K and ~5% at 1.65°K. In the liquid hydrogen range, the error was less than 0.01%.

All the measurements were carried out in a metal cryostat using a technique described earlier.[7] The error in the determination of the temperature was ±0.003° at 5°K and ±0.01° at $T \leq 2.5°K$. All the samples were cooled slowly (in 1–2 hours) in order to prevent, or at least reduce, the cold working of the cesium samples during cooling from room temperature to ~77°K (by 200 deg) because of a difference between the linear expansion coefficients of the metal and glass, which was wetted by cesium. When such slow cooling was employed and temperatures were fairly high [compared with the temperature of the onset of recrystallization, equal to $(0.2-0.3)T_{m.p.} = 66-100°K$], the cold working of cesium should be partly relieved by annealing. The next stage of cooling from 77 to 4.2°K was carried out rapidly (in 5–10 min).

The results of the measurements of the relative resistance $\delta_T = R_T/R_{293}$ in the helium range of temperatures are presented in Fig. 1 and the ideal resistance $\delta(T) = (R_T - R_0)/R_{293}$ in the helium and hydrogen regions is shown in Fig. 2. The experimental points, representing the relative resistances of all five samples of cesium, fitted a single curve at helium temperatures, irrespective of the sample diameter. The results of measurements obtained for each sample could be reproduced satisfactorily after several days.

The dependence of δ_T on T obtained in the helium range of temperatures, 1.65–5°K, obeyed an empirical equation $\delta_T = (0.113 + 1.37 \times 10^{-2} T^{3.1}) \times 10^{-3}$. [2)] The power exponent of T in this equation was determined with an error of ±0.05. The deviations of the experimental points from the empirical curve did not exceed 1.2%. It is evident from Fig. 2 that the same $\delta(T)$ law should be obeyed also above 5°K, approximately up to 8°K. The results obtained disagreed entirely with those reported in [1,4], where the dependence $\rho \propto T^5$ was

[1)] Here, $\delta_0 = \rho_0/\rho_{293} \approx R_0/R_{293}$, where R_0 and R_{293} represent the electrical resistance of the same sample at 0 and 293°K.

[2)] We are grateful to A. I. Bezrukiĭ for the calculation, using an M-20 computer, of the coefficients in all the empirical equations quoted in the present paper.

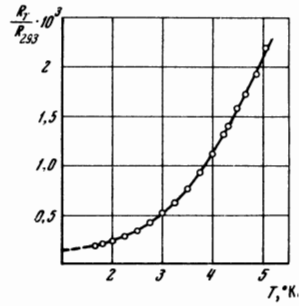

FIG. 1. Temperature dependence of the relative resistance $\delta_T = R_T/R_{293}$ of cesium.

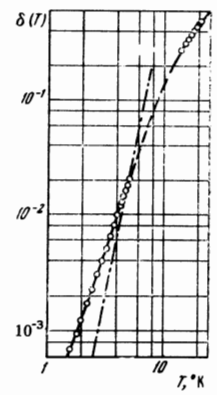

FIG. 2. Ideal temperature dependence of the resistance, δ(T), of cesium. The chain straight line shows the slope for the law $\delta(T) \infty T^5$.

found to apply in a very narrow range of temperatures (from 2 to 3°K) in the case of cesium with $\delta_0 \approx \delta_{2.5}$, which was 16 times more impure than our material.

It is worth noting our observation of a tenfold decrease of the resistance between 4.2 and 0°K. This is in full agreement with an earlier suggestion that $R_{4.2}/R_0$ of cesium, which has a low Debye temperature and a low melting point, should increase considerably when the concentration of impurities is reduced.[7] Moreover, this very large change in the resistance between 4.2 and 0°K indicates that the ratio $\delta_{4.2}$ for cesium with $\delta_0 \sim 1 \times 10^{-4}$ cannot be used as a measure of its purity. To estimate the purity of cesium with this value of δ_0, we must know the ratio $\sim\delta_2$, i.e., we must determine the resistance at temperatures lower than 4.2°K.

No available theory predicts $\rho \propto T^{3.1}$ and, therefore, we attempted to represent the experimental temperature dependence of the resistance in the form of the following sums of three terms:

$$\delta_T = \delta_0 + AT^2 + BT^4, \quad \delta_T = \delta_0 + AT^2 + BT^5,$$
$$\delta_T = \delta_0 + AT^3 + BT^4, \quad \delta_T = \delta_0 + AT^3 + BT^5.$$

Such an expansion was the next step, after a two-term expression, in the approximation of the experimental data to the theory. The power exponents of T, ranging from 2 to 5, were selected on the basis of the following considerations. It is well known that the term with T^5 is due to the scattering of electrons by phonons and the term with T^2 is due to the scattering of electrons by electrons. According to Pytte,[8] the term with T^4 represents the inelastic scattering of electrons by phonons (in which momentum is lost). Finally, the term with T^3 may be associated with the influence of the sample size, when the diameter d is considerably less than the mean free path λ.[9]

It was found that the first two expansions were unsuitable, while the last two expansions fitted the experimental points almost equally well with an average deviation from calculated points not greater than 2.4–2.5%. These expansions were of the form

$$\delta_T = [0.103 + 1.52 \cdot 10^{-2} T^3 + 1.97 \cdot 10^{-4} T^4] \cdot 10^{-3},$$
$$\delta_T = [0.113 + 1.5 \cdot 10^{-2} T^3 + 1.65 \cdot 10^{-4} T^5] \cdot 10^{-3}.$$

However, bearing in mind that the deviation of the experimental points from a curve described by two-term expansion was only half the deviation found in the three-term case, we concluded that $\delta_T = \delta_0 + AT^3$ [1] was still the best representation of the experimental results.

Thus, the results obtained did not yield any definite conclusions about the nature of the scattering of conduction electrons in cesium at low temperatures and consequently the cause of the dependence close to $\rho \propto T^3$ was not clear.

This temperature dependence could be accounted for by a strong effect of the dimensions on the resistance ($d \ll \lambda$),[9] by the complexity of the Fermi surface, or by an anomalous phonon spectrum of cesium at helium temperatures. However, none of these explanations could be used in our case since the dimensions had no influence on the resistance, the Fermi surface differed little from a sphere, and—according to the temperature dependence of the specific heat[10]—the phonon spectrum of cesium had no anomalies at low temperatures. We had to assume that the temperature dependence of the resistance was the result of the superposition of two processes: the scattering of electrons by phonons and the inelastic scattering of electrons by impurities, which depended on temperature (because the Matthiessen rule was not obeyed).[11, 12] Assuming that this explanation was correct, we had to conclude that the purity of cesium was still insufficient for investigations of this kind, in spite of the very low value of its residual resistance.

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