

Resistivities of rubidium and potassium at helium temperatures

B. N. Aleksandrov, O. I. Lomonos and E. D. Semenova

Physico-technical Institute of Low Temperatures, Ukrainian Academy of Sciences

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The resistivities of Rb and K are measured between 1.6 and 5.1 K for samples of various purity ($R_0/R_{290} = 1.1 \times 10^{-2} - 1.2 \times 10^{-2}$ for Rb and $R_0/R_{290} = 5.7 \times 10^{-4} - 1 \times 10^{-3}$ for K). It is found that the relative resistivity of Rb can be described by the formula $\delta T = \delta_0 + AT^4$ for $T \leq 3.3$ K. With increasing temperature, the dependence of δ on T decreases and tends toward $\delta(T) = BT^3$ at ~ 5 K. For K, the resistivity can be described by the equation $\delta T = \delta_0 + AT^5$ through the helium temperature region.

INTRODUCTION

On the basis of the recently published researches of MacDonald et al.,^[1,2] it has been considered as established that the Bloch law ($\rho \sim T^5$) is observed for all alkali metals at low temperatures, and the resistivity law $\rho \sim T^6$ at helium temperatures has been observed only in Na. In these researches, the dependence of ρ on T for Rb has been studied in the temperature range 1.5–20 K on a sample having $\delta_0 = \rho_0/\rho_{290}^* = (1.8-3.2) \times 10^{-2}$,^[1] and in the interval 2.7–5 K on a sample having $\delta_0 = 2.63 \times 10^{-3}$.^[2] In the first paper, it was shown that $\rho \sim T^{4.5}$ in the temperature range 1.8–3 K and $\rho \sim T^{1.94}$ in the range 4.5–20 K. In the second, it was reported that $\rho \sim T^5$ in the temperature range 2.7–5 K. It was shown in the same studies that for potassium the Bloch law is observed in the temperature range $4 \text{ K} \leq T \leq 7 \text{ K}$ on samples with $\delta_0 = (2-7) \times 10^{-3}$.

With the availability of purer metals, the possibility arose of a more thorough study of the temperature dependence of resistivity. Quite recently, it was shown that for Cs with $\delta_0 = 1.1 \times 10^{-4}$ the resistance $\rho \sim T^3$ at $1.6 \leq T \leq 5.16$ K (and not $\rho \sim T^5$),^[3] and for potassium with $\delta_0 = (1.2-1.7) \times 10^{-4}$, $\rho \sim T^6$ ^[4] for $1.5 \leq T \leq 5.2$ K and $\rho \sim T^7$ for $2 \leq T \leq 4.5$ K. Thus, different authors observed two strongly differing dependences of ρ on T for potassium in the same temperature range for metal samples with almost identical δ_0 . All this suggests that the dependence of ρ on T in alkali metals at low temperatures is far from completely understood. Therefore, just such an investigation is of great scientific interest, since it offers an opportunity for scrutiny of singularities in the scattering of conduction electrons in alkali metals. Unfortunately, theory cannot yet predict this dependence completely (especially at low temperatures); and much space is therefore devoted to experimental studies.

Since impurities heavily mask the true scattering inherent to metals of high purity, it is therefore of interest to study carefully the dependence of the resistivity ρ on T for metals as their chemical and physical purity increase, i.e., with decreasing residual resistivity ρ_0 . Our purest Rb has a value of $\delta_0 \sim 1 \times 10^{-3}$, i.e., smaller by a factor ~ 2.5 than in MacDonald et al.^[2] The value $\delta_0 \sim 1 \times 10^{-3}$ for Rb can be regarded at the present time as the lowest for Rb.^[6] If it is taken into account that for Rb the Debye temperature is very low ($\Theta \sim 60$ K), then a decrease of δ_0 by a factor of 2.5 should measurably facilitate establishment of the actual character of the electron scattering at helium temperatures (from 0 to 5 K), in which the resistance of our Rb changes by a factor of about 2. Our potassium samples were, to judge from their δ_0 , 3.5–4.5 times dirtier than

those of Tsol and Gantmakher^[4] and Ekin and Maxfield,^[5] but 4–12 times purer than those of MacDonald et al.^[1,2] Therefore, it was of interest to make clear the temperature dependence of ρ for potassium with an intermediate value of δ_0 .

EXPERIMENTAL RESULTS AND THEIR DISCUSSION

The temperature dependence of resistivity of five Rb samples and three K samples was measured in the range 1.6–5.2 K, as was described previously.^[7] The resistance was measured by a potentiometric method using an R-348 compensator with a circuit sensitivity of 5×10^{-8} V. Rubidium and potassium of purity $\sim 99.99\%$ were contained in glass capillaries of diameter 0.5 and 1.2 mm and length 22 and 45 mm, into which were sealed potential and current leads in the form of platinum or molybdenum wire (of diameter 0.3 and 0.5 mm, respectively), as had been done previously for cesium.^[1] The measurement current at helium temperature was equal to 3 A, and at room temperature, 65 mA. The maximum error of a single measurement of relative resistivity $\delta T = RT/R_{290}^*$, for the purest sample of Rb, No. 4, amounted to 0.1% at 5 K and 0.15% at 1.6 K, while for sample No. 1, it was 0.17 and 0.3%, respectively. The error of a single measurement for the purest sample of K amounted to 0.2% for the entire range of helium temperatures.

Both pure metals wet glass very well; therefore, upon cooling from 17°C to 4.2 K mechanical stresses appeared in them. To remove these, the samples were maintained at a temperature of 77–100 K for two days. At these temperatures, which are close to the temperature of the onset of recrystallization $T_{rec} = 60-100$ K, the samples were annealed, after which values of δT were obtained that were reproducible.

The results of the measurements of the resistance of Rb are shown in the form of graphs in Figs. 1 and 2, and in Table I. As analysis of the curves showed, for all the samples of rubidium at helium temperatures, there was no single law of dependence of ρ on T , nor did the Bloch law $\rho(T) = \alpha T^5$ appear in any form. Since the exponent n in the dependence $\rho \sim T^n$ usually increases with increasing purity for normal metals,^[8] we should have been able to find $\rho \sim T^5$ on samples that were purer than in^[2] if this law is actually observed. However, our experimental results do not confirm such a dependence. The conclusion of MacDonald et al.^[2] that the Bloch law is observed in Rb, as also in Cs, is in error and evidently resulted from insufficient care in carrying out the experiments for Rb (there were only four points in the temperature range 2.7–4 K).

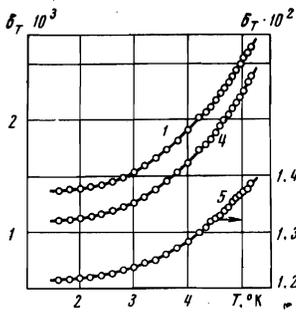


FIG. 1. Dependence of the relative resistivity δ_T of Rb on the temperature: sample No. 1— $\delta_0 = 1.35 \times 10^{-3}$, No. 4— $\delta_0 = 1.085 \times 10^{-3}$, No. 5— $\delta_0 = 1.21 \times 10^{-2}$.

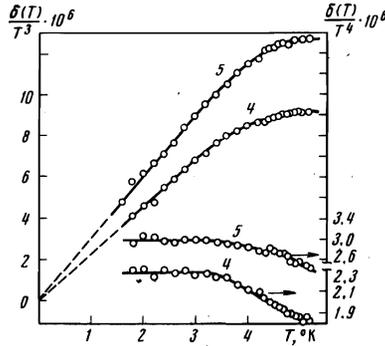


FIG. 2. Dependence of the ratios $\delta(T)/T^3$ and $\delta(T)/T^4$ on the temperature for Rb (samples No. 4 and t).

As follows from Fig. 2, the ideal relative resistivity $\delta(T) = \delta_T = \delta_0 = AT^4$ for $T \leq 3.3$ K. Upon an increase in temperature, the dependence of δ on T decreases and tends toward $\delta = BT^3$ in the range near 5 K. Using the graphical dependence $\rho(T)$ for Rb from [2], we established that $\rho(T) \sim T^{3.1}$ in the temperature range $5.5 \leq T \leq 8$ K, which (if we take into account the error in taking the points from the graph) is in excellent agreement with our data in Fig. 2. Table II gives the values of the constants A and B , δ_0 , $\delta_{1.6^\circ}$ and the values of the change in the resistance of Rb from 4.2 and 5.1 K to 0 K, whence it follows that the resistance of the pure metal decreases between 5 and 0 K by a factor ~ 2 . The values of δ_0 and A for all samples were obtained by reduction of the experimental data by the method of least squares on a computer. The maximum departure of the computed values of the resistivity from the experimental amounted to 0.13% at 2 K and 0.8% at 3 K.

The constants B were estimated for each sample from graphs similar to Fig. 2, where the initial slope of the straight line gives the value of the quantity A . For the first four samples, which have neighboring values of δ_0 , $A = 2.3 \times 10^{-6}$ and $B = 9 \times 10^{-6}$, and for the dirtiest sample, No. 5, the coefficient $A = 3.0 \times 10^{-6}$ and $B = 12.8 \times 10^{-6}$. Like the constant α in Bloch's law, which increases with increasing δ_0 , as was found for Cd, Sn, [8] Al, [9] and In, [10] the constants A and B also increase with δ_0 , i.e., they depend on the purity of the metal, although not very strongly (see Table II).

Attention is drawn to the fact²⁾ that for Rb, as for Cs, there is no dependence $\rho(T) \sim T^5$, either in the "pure" form or in the form of an additional term. For both metals, there is some form of a $\rho(T) \sim T^2$ or T^4 dependence. However, while the coefficient of T^3 for Cs is ~ 100 times greater than that for T^4 , this difference in the coefficients is only fourfold for Rb.

The dominant term at helium temperatures is the term $\sim T^3$ for Cs and the term T^4 for Rb, evidently be-

TABLE I

T, °K	$\delta_T \cdot 10^4$	$\delta(T) \cdot 10^4$	T, °K	$\delta_T \cdot 10^4$	$\delta(T) \cdot 10^4$	T, °K	$\delta_T \cdot 10^4$	$\delta(T) \cdot 10^4$
0	1.085	--	2.8	1.23	1.421	4.22	1.74	6.603
1.6	1.10	0.15	3.0	1.27	1.841	4.410	1.84	7.593
1.8	1.11	0.262	3.2	1.32	2.372	4.590	1.950	8.669
2.0	1.12	0.3724	3.4	1.39	3.028	4.750	2.05	9.703
2.2	1.14	0.5172	3.6	1.46	3.772	4.895	2.16	10.737
2.4	1.16	0.7655	3.8	1.54	4.531	5.035	2.32	11.703
2.6	1.19	1.048	4.0	1.63	5.483	5.16	2.38	12.972

TABLE II

Sample No.	d, μ	$R_{200} \cdot 10^4$, ohm	$\delta_0 \cdot 10^4$ (calc)	$\delta_{1.6^\circ} \cdot 10^4$ (exp)	$A \cdot 10^6$, deg ⁻⁴	$B \cdot 10^6$, deg ⁻³	$R_{4.2}/R_0$	$R_{5.1}/R_0$
1	1.22	0.463	1,350	1,37	2,35	9,5	1,5	1,92
2	1.24	0.5038	1,300	1,32	2,07	7,94	1,45	1,83
3	0.51	1,56	1,200	1,21	2,26	9,0	1,55	2,00
4	0.54	1,45	1,085	1,10	2,29	9,30	1,6	2,17
5	1,23	0,507	12,1	12,15	3,0	12,8	1,07	1,14

TABLE III

Metal	n	ΔT	$\delta_0 \cdot 10^4$	T_{res} , °K	°K	Purity (in %)
Li [1,2,13]	5—4,55	11—20	3—5	6—8	370	99,95
	3,5	10—30				
Na [1,2,14,15]	3,4—2,5	65—90	0.3—0.4	4	165	99,95
	1,26	200—300				
	6	4—9				
	5	8—13				
	4,85	8—20				
	3	30—40				
K [1,2,4,5,10,14,18]	2,2	50—60	0.7	5—6	100	$\sim 99,99$
	1,26	150—300				
	7	2—4,5				
	6	1,5—4,2				
	5	2,2—3,5				
	5*	2,5—5,16				
	5	4—7				
	3	10—20				
Rb [1,2]	4*	$\leq 3,3$	1.08	1.5	60	99,99
	3*	5—8				
	2,2	9—20				
	1,95	4.2—20				
Cs [1—3]	3	1,5—8	0.113	1.5	40	99,995
	2,7	4,5—6,5				
	1,69	8—20				
		10—20				

*Data of the present paper.

cause of the difference in the Debye temperatures for the two pure metals. Inasmuch as the Debye temperature for Cs is $\Theta = 40$ K and for Rb $\Theta = 60$ K, then the temperature region where $\delta \sim T^4$ is already clearly evident for Rb, while for Cs it is only beginning to appear (a small coefficient for T^4), although δ_0 for Cs is only one-tenth the δ_0 for Rb. Upon a further significant decrease (by another factor of 10) of δ_0 for Rb, the Bloch law can also appear at $T \leq 4$ K, and in the case of Cs, it can appear at lower temperatures, probably at $T \leq 2-2.5$ K.

The law $\rho \sim BT^3$ at $4.2 \leq T \leq 8$ K for Cs^[3] evidently corresponds to the resistivity of the pure metal, i.e., on a further decrease in δ_0 this dependence on T does not change above 3.5—4 K and pertains to its transition region. The same can be said of the cubic law for Rb in the region $5.1 \leq T \leq 8$ K, although the decrease in δ_0 , in contrast with Cs, should have some effect on this dependence (B decreases somewhat and the temperature range ΔT remains practically unchanged).

Some indirect evidence in favor of the above is provided by Table III, where values of n in the dependence $\rho(T) \sim T^n$ are given, as well as the temperature interval ΔT in which the given law is observed and the temperature T_{res} at which it can be assumed that $\rho T = \rho_0$ for all alkali metals, according to the published data. It is seen that with decreasing Θ , the interval ΔT where

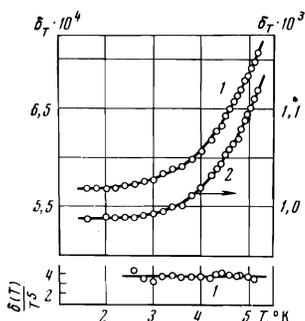


FIG. 3. Change in the relative resistivity δ_T of Ca and the ratio $10^8 \cdot \delta(T)/T^5$ with temperature. Sample No. 1— $\delta_0 = 5.7 \times 10^{-4}$; No. 2— $\delta_0 = 9.8 \times 10^{-4}$.

$\rho \sim T^5$ becomes narrower, shifting in the direction of lower temperatures. Similar remarks can be made about the dependence $\rho \sim T^3$ and, while Bloch's law appears sufficiently clearly for Li and for Na of purity $\sim 99.995\%$, then for Cs with $\Theta \sim 40$ K a purity $\sim 99.995\%$ is insufficient for all the processes of scattering that are characteristic for Li, Na and K to appear. The dependence $\rho \sim T^4$ for Rb below 4 K and for Cs below 2.5 K (where Bloch's law should appear), is evidently connected with insufficient purity of both metals and is the result of superposition of the scattering of electrons by phonons and inelastic scattering on impurities.^[11,12]

Figure 3 shows the dependence of δ_T on T for both samples of K (the purest with $\delta_0 = 5.7 \times 10^{-4}$ and the dirtiest with $\delta_0 = 9.8 \times 10^{-4}$). Processing of the curves for all three samples of potassium showed a dependence $\delta(T) \sim AT^5$ for $T \leq 5$ K, which is clearly seen from the graph of the dependence $\delta(T)/T^5$ on T for the purest sample (Fig. 3). The coefficient A is almost identical for all samples and is equal to $\sim 3.9 \times 10^{-8}$, which is in excellent agreement with $A = 3.8 \times 10^{-8}$ for K with $\delta_0 = 2.7 \times 10^{-4}$.^[10] Neither $\rho \sim T^6$ ^[4] nor $\rho \sim T^7$ ^[5] was observed. This is possibly connected with the fact that our samples were 4.5–3.5 times dirtier than those of^[4,5].

Thus, at the present time, the Bloch law has been observed only for Li, Na and K among the purest alkali metals available. With increase in purity, this law will evidently also appear in Rb and Cs. Furthermore, it can be expected that the strongest power-law dependences of ρ on T ($\rho \sim T^6$, T^7), which are observed for Na and K, will also appear in the other three alkali metals, while in

the case of Rb and Cs, at very low ($\leq 1-2$ K) temperatures, when it becomes possible to reduce the quantity δ_0 significantly (by an order of magnitude or more).

¹⁾The samples of rubidium and potassium were prepared by É. P. Lokshin and O. S. Ignat'evich at the Institute of the Chemistry and Technology of Rare Elements of the Kola Branch, Academy of Sciences USSR at Apatity, to whom we express our thanks.

²⁾It was mistakenly reported previously^[3] that the experimental data satisfy the dependences $\delta_T = \delta_0 + \alpha T^3 + \beta T^4$ and $\delta_T = \delta_0 + \alpha' T^3 + \beta' T^5$ in the same degree. In actual fact, only the first dependence is found to be in good agreement.

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