

The temperatures read from the curve represented by this formula, *viz.*:

0.1	0.94
.05	.87
.02	.80
.01	.75
.005	.70
.002	.65
.001	.62

are even lower than those found by rectilinear extrapolation. So the results, as I said, indicate that with the linear extrapolation we were on the safe side.

Differences of some hundredths of a degree such as occur between the results of Professor PORTER and of myself are after all to be considered as within the limit of uncertainty of the experimental data from which we have to start.

COMMUNICATIONS

FROM THE

PHYSICAL LABORATORY

OF THE

UNIVERSITY OF LEIDEN

BY

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N^o. 160^a.

H. KAMERLINGH ONNES and W. TUYN. — Further experiments with liquid helium. Q. On the electrical resistance of pure metals etc. X. Measurements concerning the electrical resistance of thallium in the temperature field of liquid helium.

(Translated from: *Verslag van de Gewone Vergadering der Wis- en Natuurkundige Afdeling der Kon. Akad. van Wetenschappen te Amsterdam*, 28 October 1922, Deel XXXI, pp. 467—474).

H. KAMERLINGH ONNES and W. TUYN. — *Further experiments with liquid helium. Q. On the electrical resistance of pure metals etc. X. Measurements concerning the electrical resistance of thallium in the temperature field of liquid helium.*

§ 1. *Object of the research. Method of preparing the resistances.* The place of thallium in the periodic system of elements, between the super-conducting metals mercury and lead, made it seem probable that it would become super-conducting at helium temperatures.

We had at our disposal only rods of thallium from KAHLBAUM¹⁾. From this Mr. P. J. v. D. BAAN, instrumentmaker of the Phys. Lab., extruded wires of 0.2 and 0.5 m.m. thickness; they were bright at first, but quickly became tarnished and grey in colour. At the distance of a few c.m. from the ends of each wire a second short wire was melted on in a small gas-flame; during this process the thallium was protected from oxidation by a layer of melted candle grease. The wire was then wound bifilarly upon a porcelain tube with a double screw thread baked into it, (these tubes were made by the Königliche Porzellan Manufaktur, Berlin and have been mentioned before in Comm. N^o. 152c § 2) and then the four thallium ends were each soldered to a copper wire, previously attached to the tube. To prevent further oxidation the resistance thus prepared was enclosed in a glass tube by the chief glassblower of the Phys. Lab. Mr. O. KESSELRING in the following manner. The ends of this tube through which the copper wires protuded were platinised, coppered, provided with copper caps

¹⁾ According to a letter from the firm the thallium contained the usual amount of lead; about other impurities nothing was said. The same letter said that the firm did not prepare any "extra" pure material. M. LEVIN (Z. S. f. An. Chem. 45 (1905), p. 31) states that KAHLBAUM-thallium contains 99,91% Tl, N. KURNAKOW, S. ZEMCZUZYNY and V. TARAKIN (Z. S. f. An. Chem. 83 (1913), p. 200), only say that they used pure Tl from KAHLBAUM.

and sealed up (see also Comm. N^o. 133*d*, p. 60). To remove the oxidation on the *Tl*-wire the resistance was rinsed through the opening at the other end of the glass tube and dried by a moisture absorber and carbon tube; a tap attached to this end of the tube was then closed. By means of a Töpler pump and a suitable arrangement of glass connecting pieces the resistance was then twice rinsed with helium and finally helium to a pressure of 51 c.m. was admitted; after this the glass tube was sealed at the narrow part provided for the purpose. (For the final form see fig. 1 of Comm. N^o. 160*b*). In this way in Dec. 1916 were prepared *Tl*-VIII-1916, diameter 0.2 m.m., with a joint in the bifilar wire, and *Tl*-IX-1916, diameter 0.5 m.m.

§ 2. *Zero determinations.* For determining the zeros, the resistances were placed in glass tubes filled with liquid paraffin (owing to the war conditions no isopentane could be had) or

TABLE I.

DATUM.	Tl.-VIII-1916.	Tl.-IX-1916.
Jan. 5 th 1917.		1.149 ₀ Ω
Jan. 6 th 1917.	4.439 Ω	
	Immersed in liquid air.	
Jan. 8 th 1917.	4.441 ₃ Ω	
	Immersed in O ₂ liq. and H ₂ liq.	
Jan. 30 th 1917.		1.150 ₇ Ω
Febr. 2 nd 1917.	4.447 ₃ Ω	
Febr. 6 th 1917.	4.448 Ω	1.150 ₃ Ω
Febr. 13 th 1919.	4.446 Ω	
Febr. 19 th 1919.	4.446 Ω	
Febr. 20 th 1919.		1.150 ₂ Ω

with distilled benzine; the tubes were closed by corks, over which a layer of paraffin was laid. They were placed in ground ice, and the first measurement was made two hours later and repeated with intervals of about half-an-hour. The method of

measuring used is either that of overlapping shunts in accordance with KOHLRAUSCH, or that of the compensation of the potential at the terminals of an unknown and a known resistance, connected in series, by means of a compensation apparatus free of thermoforces in accordance with DIESSELHORST and provided by O. WOLFF. Enclosing the wires in an atmosphere of helium proved to be completely sufficient. The results of the zero point determinations are found in Table I; they are partly due to Dr. J. M. BURGERS, now Professor at Delft.

§ 3. *Measurements in liquid helium; determination of the vanishing point temperature.* The resistances were placed in the cryostat provided with a stirring apparatus shown in Comm. N^o. 124*c*, fig. 4. For determining the amount of their resistance the second method mentioned in § 2 was used. The measurements were always made with both directions of current in the circuit of the resistances, care being taken that to each of them the direction of the current in the compensation apparatus corresponded. Moreover, in measurements below the vanishing point temperature the galvanometer was observed when the current was reversed in the circuit of the resistances only (this betrays superconductivity more quickly): in the case of superconductivity there must be no change of position observable.

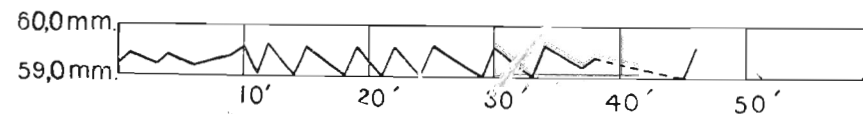


Fig. 1.

The temperatures are determined by the measurements of the vapour pressure of the helium bath, the connection between pressure and temperature having been derived graphically from the results in Comms. N^o. 119 and N^o. 147*b*. Close to the vanishing point temperature the pressure of the bath was followed with the kathetometer (June 5th 1919); we give in fig. 1 the diagram of a series of observations (in this field of temperature 1 m.m. pressure corresponds to about 0.01 of a degree).

TABLE II.

Vapour-pressure in local m.m. Hg.	T.	$W_{\text{TI-VIII-1916}}$	$W_{\text{TI-IX-1916}}$	$w_{\text{TI-VIII}} = \left(\frac{W}{W_0}\right)_{\text{TI-VIII}}$	$w_{\text{TI-IX}} = \left(\frac{W}{W_0}\right)_{\text{TI-IX}}$	$\Delta w = W_{\text{TI-VIII}} - W_{\text{TI-IX}}$
273.09 K.		4.446 Ω	1.150 ₂ Ω	1.00000	1.00000	
4.24		0.0075	0.0009 ₆	0.0016 ₂	0.0008 ₄	0.0008 ₄
3.33		0.0039	0.0008 ₃	0.0015 ₃	0.0007 ₂	8 ₃
2.49		0.0037	0.0007 ₅	0.0015 ₁	0.0006 ₅	8 ₂
2.42		0.0037		0.0015 ₁		
2.38		0.0036 ₃	0.0007 ₈	0.0015 ₀	0.0006 ₈	8 ₂
2.34		0.0036	0.0007 ₆	0.0014 ₃	0.0006 ₆	8 ₃
2.33		swings from 0.006 ₆ to 0.002	swings about 0.0007	swings from 0.0014 ₃ to 0.0004 ₃	swings about 0.0006	
59.3		0.00000	0.00000	0.00000	0.00000	
58.6	2.32					

In spite of the fact that the wires were not in contact with the liquid helium, in the measurement of their resistances the galvanometer reacted with surprising rapidity to the changes of the bath. The results are given in Table II.

From this table it appears that a constant difference Δw exists for all temperatures; in spite of this additive resistance¹⁾ of *TI-VIII-1916* with regard to *TI-IX-1916* both become superconducting at the same temperature. The behaviour of *TI-VIII-1916* confirms the experience gained with *Pb*-wires (Comm. N^o. 133d § 15), that joints in a wire do not affect its becoming super-

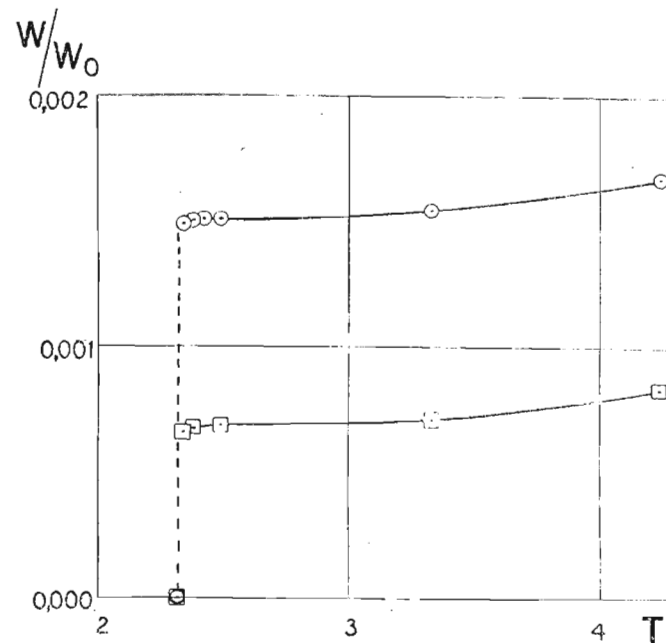


Fig. 2.

○ *TI-VIII-1916*.□ *TI-IX-1916*.

conducting. The unsteadiness of the resistance at 2°33 K. is caused by the pressure variations of the bath over a range of 0.6 m.m. Hg, corresponding to about 0.006 of a degree; in this field of temperature thallium is in the same condition as is shown for mercury in Comm. N^o. 133a p. 24, fig. 6. At a current

¹⁾ If this additive resistance is taken constant, it becomes 0,00083 $W_0 = 0,0037 \Omega$; we must assume in the meantime that it is largely due to the joint.

strength of 3.1 m.A. through the resistances the resistance falls, thus, within a smaller temperature range than in mercury; a similar difference had been found earlier between mercury and tin¹⁾. At $T = 2^{\circ}.32$ K. all measurable resistance has disappeared.

§ 4. *Highest limit of a microresidual resistance.* This limit is found from the quotient of the smallest observable potential difference and the threshold value of the current, it being assumed that Ohm's law still holds. We found:

April 15th 1919, for *Tl-VIII-1916* $\frac{W}{W_{273^{\circ}\text{K.}}} < 14.10^{-10}$ at $p = -2.3$ m.m. Hg and

May 27th 1919, for *Tl-IX-1916* $\frac{W}{W_{273^{\circ}\text{K.}}} < 24.10^{-10}$ at $p = -2.6$ m.m. Hg.

The difference in the results may be due to the inequality of temperature, but more to the difference of current threshold value of the two wires (see further § 5). If the value $\frac{W}{W_{273^{\circ}\text{K.}}}$ for thallium is compared with that for other super-conductors (Comm. N^o. 133d, p. 67) the retrogression of the limit caused by a greater decrease of temperature below the vanishing point temperature would seem to be recognisable in the measurements on wires of different metals, as has been ascertained already by measurements on one wire of one metal. But we must point out that this general conclusion cannot be drawn before the value of the threshold current as a function of $T_{\text{vanishing point}} - T$ and of the dimensions of the wire is known and after it has been ascertained whether a returning resistance is due to a single "bad place", or whether it is distributed over the whole length of the wire.

§ 5. *Threshold value.* At some temperatures we tried to determine the threshold value of the current, that is the strength of the current which again generates a measurable potential difference at the ends of the wire. The results are given in Table III.

¹⁾ This comparison is defective, for as yet the fall of resistance in mercury, tin and thallium has not been observed on wires of the same diameter by using the same strength of measuring current. [Note added in the translation].

TABLE III²⁾:

Date.	Resistance.	Diameter in m.m.	Section in m.m. ²	ρ_{He} in local m.m. Hg.	Temperature ¹⁾ in K.	Threshold value in amp.	Current density in Amp. per m.m. ²	$\frac{i}{r}$ in Amp. in m.m.
April 25 th 1919	Tl-VIII-1916	0.2	0.031	2.3	1.3 ₆ K.	1.5 ₇	50.0	15.7
May 27 th 1919	Tl-IX-1916	0.5	0.196	2.6	1.8 ₆	3.6 ₀	18.4	14.4
"	"	"	"	55 à 56	2.29	0.25 ₂	1.3	1.0
June 5 th 1919	"	"	"	54	2.28	0.62 ₅	3.2	2.5
"	"	"	"	58	2.31	0.12 ₆	0.6	0.5

¹⁾ The two first temperatures in this table are derived graphically by means of a formula slightly differing from that given in Comm. N^o. 159 p. 35.

²⁾ Referring to § 3 concerning the heat conductivity of helium vapour, yet the threshold values might have been found greater, when the resistances would have been surrounded *directly* by liquid helium. [Note added in the translation].

The two first observations in this table show that for wires of different diameter at the same temperature the quantity $\frac{i}{r}$ seems to be much more a constant than the current density. The latter quantity occurs in the expression for the magnetic field at the surface of the wire through which a current passes. F. B. SILSBEE¹⁾ drew special attention to the influence of this field. The determination of the threshold value of the magnetic field for thallium by means of external fields, and the comparison of it with H , derived from the observations in Table III by means of $H = \frac{2i}{r}$, (the *Tl*-wires therefore being regarded as straight), must prove whether both strengths of field are equal, and that therefore the magnetic field is the primary factor in the disturbance of super-conductivity. Then the "bad places" referred to more than once, are the places with the smallest diameter; the returning of the resistance caused by a current occurs first in these places only. The above mentioned experiment with thallium is prepared and also a similar one on a more extensive scale with the more easily manipulated tin; it must not be forgotten, that at the return of the resistance at great strengths of current such a development of heat soon takes place, that first the wire and if this melts the galvanometer is in danger; this makes the determination of large current threshold values rather risky.

If we assume, that in super-conductivity the current runs only in an extremely thin layer at or along the surface of the wire and that each element of a section of this layer ceases to be super-conducting at a certain current saturation dependent upon the temperature, integration over the whole layer yields the threshold current and for wires of different diameter we get the constancy of $\frac{i}{r}$. The assumption of current saturation along the surface does not, however, explain the connection, suggested by SILSBEE, between the threshold values of the current and the magnetic field.

¹⁾ F. B. SILSBEE, *Scient. Pap. Bur. of Stand.* N^o. 307 (1917).

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