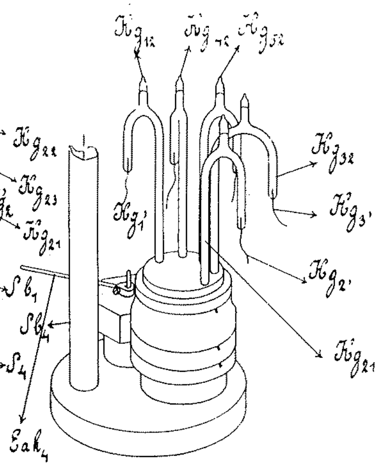
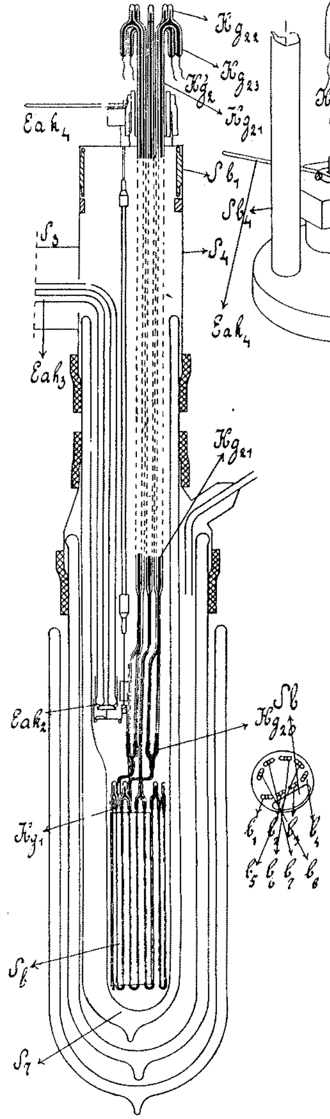
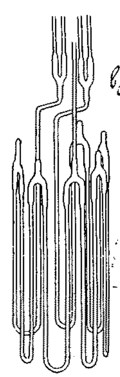


Fig. 3.





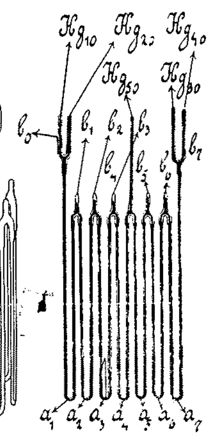


Fig. 4. Fig. 2. Fig. 1.

Communication No. 124c.

KAWA, 22 February 1913, pp. 1284-1302.

Communications - Leiden 133a

H. KAMERLINGH ONNES. *Further experiments with liquid helium.* H. *On the electrical resistance of pure metals etc.* VII. *The potential difference necessary for the electric current through mercury below* 4°.19 K.

§ 1. *Difficulties involved in the investigation of the galvanic phenomena below* 4°.19 K. In a previous Communication (No. 124*c* of Nov. 1911) we related that special phenomena appeared when an electric current of great density was passed through a mercury thread at a temperature below 4°.19 K., as was done to establish a higher limit at every temperature for the possible residual value of the resistance. Not until the experiments had been repeated many times with different mercury threads, which were provided with different leads chosen so as to exclude any possible disturbances, could we obtain a survey of these phenomena. They consist principally herein, that at every temperature below 4°.18 K. for a mercury thread inclosed in a glass capillary tube a "*threshold value*" of the current density can be given, such that at the crossing of the "threshold value" the phenomena change. At current density below the "threshold value" the electricity goes through without any perceptable potential difference at the extremities of the thread being necessary. It appears therefore that the thread has no resistance, and for the residual resistance which it might possess, a higher limit can be given determined by the smallest potential difference which could be established in the experiments (here $0.03 \cdot 10^{-6}$ V) and the "threshold value" of the current. At a lower temperature the threshold value becomes higher and thus the highest limit for the possible residual resistance can be pushed further back. As soon as the current density rises above the "*threshold value*", a potential difference appears which *increases more rapidly than the current*; this seemed at first to be about proportional to the square of the excess value of the current above the initial value, but as a matter of fact at smaller excess values it increases less and at greater excess values much more rapidly.

It appears that the phenomena at least for the greater part are due to a heating of the conductor. It has still to be settled whether this heating is connected with peculiarities in the movement of electricity through mercury, which for a moment I thought most probable in connection with various theoretical suppositions (comp. § 4), when this metal has assumed its exceedingly large conductivity at low helium temperatures; or whether it can be explained by the ordinary notions of resistance and rise of temperature of a conductor carrying a current, perhaps with the introduction of extra numerical values for the quantities that influence the problem. A further investigation of this with mercury in the most obvious directions, such as cooling the resistance itself with helium, presents such difficulties that I have not pursued it, as it would not be possible to prepare the necessary mercury resistances by the comparatively simple process of freezing mercury in capillary tubes. When I found (Dec. 1912) that, as I shall explain in a
2 following Comm., (see VIII of this series, Comm. N°. 132*d*) tin and lead show similar properties to mercury, the investigations were continued with these two metals. Thus the experiments with mercury which are described below may be regarded as a first complete series.

Various circumstances combined to make even the investigation of the mercury inclosed in capillary tubes difficult. A day of experiments with liquid helium requires a great deal of preparation, and when the experiments treated of here were made, before the latest improvements in the helium circulation were introduced, there were only a few hours available for the actual experiments. To be able to make accurate measurements with the liquid helium then, it is necessary to draw up a programme beforehand and to follow it quickly and methodically on the day of experiment. Modifications of the experiments in connection with what one observes, must usually be postponed to another day on which experiments with liquid helium could be made. Very likely in consequence of some delay caused by the careful and difficult preparation of the resistances, the helium apparatus would have been taken into use for something else. And when we could go on with the experiment again, the resistance sometimes became useless (e. g. § 3) because in the freezing the fine mercury

thread separated, and all our preparations were labour thrown away. Under these circumstances the detection and elimination of the causes of unexpected and misleading disturbances took up a great deal of time.

§ 2. *Confirmation of the sudden disappearance of the resistance at* 4°.19 K. *and first observations concerning the potential phenomena at low temperature.* The first experiments which showed the phenomena to be discussed were made in October 1911, with the resistance
described in the previous Comm. (No. 124*c*). 3

α. Before discussing them let us consider for a moment the measurements which were made with this resistance at 4°.23 K. and add something to what we said about them in the previous Comm. [1]). In the measurements which we are considering we could take advantage [2]) of the presence of Hg_5 to measure the portions between Hg_1 and Hg_5 and between Hg_5 and Hg_4 separately and afterwards the two in series. The result was $Hg_1Hg_5 = 0.0518$ Ω, $Hg_5Hg_4 = 0.0617$ Ω, together 0.1135 Ω. This gave a necessary check on the determination of both in series $Hg_1Hg_4 = 0.1142$ Ω [3]). These values, considering that they belong to about 65 Ω (calculated for solid mercury at 0° C.) correspond pretty well to the results obtained in the experiments in May 1911 Comm. No. 122*b*,
July 1911, viz. that a resistance of about 40 Ω (calculated for 4
solid mercury at 0° C.) becomes 0.084 Ω at the boiling point 4°.25 K.

[1]) For a survey of the observations concerning mercury at the lowest temp. in three figs. with rising scale the reader is referred to Rapport du Comité Solvay, Nov. 1911, fig. 11, 12 and 13 (in which read 13 for 12, and 12 for 13), Leiden Comm. Suppl. N°. 29.

[2]) The measurements with a view to which the tube Hg_5 was added (see Plate I in Comm. No. 124*c*) were not made then, but postponed till later. (See § 5). They were to enable us to judge of the dependence on the section.

[3]) The resistance at the boiling point of hydrogen was 3.27 Ω. A further Comm. will refer to the difference of the ratio of the values at 273° K. and 20° K. to those in previous measurements, which is here of no consequence and is due to different ways in which the mercury freezes. In the experiments described here similar differences were constantly found.

It should be mentioned that the glass was tested at all temperatures for its insulation and also that when the potential difference at the terminals was found to be zero, it was always ascertained that the resistance of the galvanometer circuit which served to measure the P. D. had not changed materially.

β. In these experiments the validity of OHM's law was confirmed above the point where the almost sudden disappearance of the resistance begins which was treated of in the previous Comm. by one measurement at a current strength of 3 and another of 6 milliampères which within the limits of accuracy gave the same result (0.0837 at 3, and 0.0842 at 6 m.A.). In connec-
5 tion with the experiments in Comm. No. 122*b* July 1911 we may mention that they were made with a resistance of a different kind to that [1]) which was used for the experiments in Oct. 1911, viz. the one which appears in the Plate of Comm. No. 123 as Ω_{Hg} (of about 40 Ω calculated for solid mercury at 0° C.). Narrow tubes alternately going up and down were connected by expansion heads (as in the Plate in Comm. No. 124*b*) and connected to platinum leading wires by fork shaped turned down wide pieces [2]), which can be seen distinctly on magnification on the Plate in Comm. No. 123 (where the resistance is shown in the cryostat).

γ. After this digression about the change in the resistance between ordinary temperature and the boiling point of helium, let us return to the experiments in and below the region of the sudden fall of resistance, which as has been said at the beginning of this § were made with a mercury resistance with mercury leads, and which were treated of in § 3 and fig. 1 of the previous
6 Comm. (Dec. 1911) about the resistance at helium temperatures (experiments of Oct. 1911).

[1]) This was a ramification of solid mercury threads consisting of a U divided at both ends, allowing measurements as well by the method of CALLENDAR as by the potentiometer method.

[2]) In the resistances which were used for the first experiments with mercury, the platinum leading in wires were simply sealed into the wider portions of the resistance tube at the ends (the expansion heads). When the mercury cannot be poured into the tube in vacuo but has to be boiled in the tubes in order that they may afterwards be exhausted without any chance of the mercury separating there is some fear of platinum amalgam being formed which might penetrate into the current circuit. In order to prevent this the wide ends of the tubes are according to a suggestion of Mr. G. HOLST, made fork shaped the prongs which contain the sealing place being turned down. In this manner mercury leads may in general be replaced by platinum leads without any trouble being experienced with regard to the resistance of the current circuit. By a comparison with experiments with mercury leads it had been found that the mercury-platinum contacts could be allowed in the potential circuit.

At 4°.20 K. we find ourselves in the higher part of the almost sudden change. In the case that we are now about to treat it had almost become complete. With a current of 7.1 m.A. it was a considerable time before the condition became stable. When this had taken place, the resistance of $Hg_1 Hg_4$ was found to be 0.000746 Ω [1]).

At a further cooling of the mercury to 4°.19[5] K. with the same strength of current the result was only $Hg_1 Hg_4 < 1.4.10^{-5}\ \Omega$.

δ. At 4°.19 K. we come into the lower part of the region with which this Comm. deals in particular. The strength of the current 7
had to be increased to 14 m.A. to give a perceptable potential difference at the ends of the resistance but even then it remained doubtful. It became distinct at a current strength of 0.02 amp. and was then $2.5.10^{-6}$ V. At 0.023 amp. it became 5.10^{-6} V, and at 0.0288 amp. 16.10^{-6} V.

When the mercury thread was cooled by helium which evaporated at a mercury pressure of 40 cm. that is at about 3°.65 K., with a strength of current of 0.49 amp. there was no potential difference to be observed at the extremities, the current had to be increased to the threshold value of 0.72 amp. to make the potential difference observable.

ε. The highest limit of the value which the residual resistance can have in the case of the lowest temperature, is therefore in these last experiments again considerably reduced by the application of stronger currents, viz. in this case (3°.65 K.) to 10^{-9} of the resistance at 0° C. (calculated for solid mercury) while in Comm. No. 122*b* June 1911 at 3° K. it could only be put at $< 10^{-7}$. 8

§ 3. *Appearance of the same potential phenomena in a revised arrangement of the experiment.* The appearance of the peculiar phenomena immediately above the "threshold value" of the current, gave rise to the question whether the just established limit would not have to be put lower when it should be possible to avoid the disturbances, which might still exist, and perhaps showed themselves

[1]) Here and in the following we speak repeatedly of resistance, without wishing to give it beforehand any other meaning than: calculated by OHM's law from the strength of current and the pressure difference observed.

in the above mentioned phenomena. The most obvious thing in the first place was to prevent the possibility with great current density of heat, developed in places in the main circuit where the temperature is higher, penetrating to the resistance that is being measured. By this, from both ends, the thread would be brought over part of its length above the vanishing temperature, which would immediately cause considerable potential differences. In this connection we thought
9 particularly of JOULE heat. PELTIER heat, which we had noticed before (Comm. No. 124*c*) but which for the present we attributed to impurities in the mercury in the legs, and assumed to be present only in the neighbourhood of the transition from solid to liquid, I took to be as far as possible excluded by the fact that the whole current system was of pure solid mercury at the very low
10 temperatures. Now this belief may be untrue, because owing either to tension caused by a difference of expansion to that of glass which it seems can be fairly great as the mercury sticks to the glass, or through the contact between crystals of different kind or size, even in the purest mercury considerable thermopowers may possibly appear. But then they have their seat, as shown by the previous experiments, chiefly in places above the temperature of liquid air and PELTIER heat in these places need not be feared. To avoid disturbances of the sort to which we referred the experiment

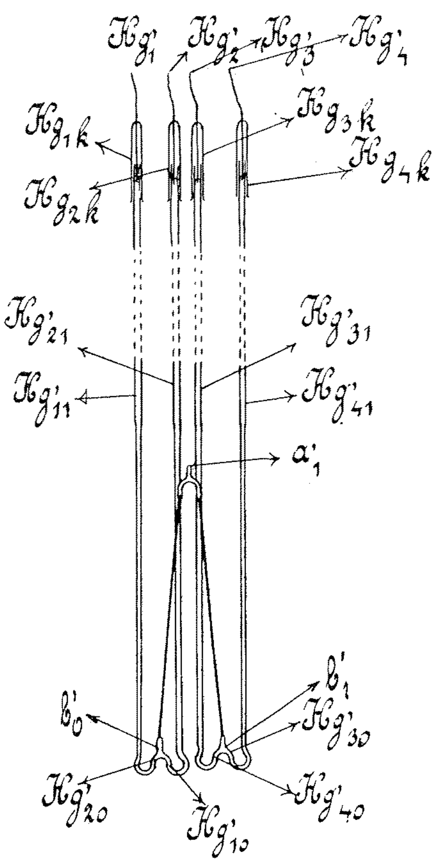


Fig. 2.

was repeated with resistances of such a kind that the conduction of any kind of heat from a part of the apparatus where there was higher temperature was made very difficult. The accompanying figure, which should be compared with figs. 1 and 2 on the Plate in the previous Comm. N⁰. 124*c*. (VI of this series) shows the form chosen. The mercury threads which lead the current to and from the apparatus, run first through the liquid helium downwards, before they come out into the widened parts of the resistance. The potential wires do the same [1]). Close to the surface of the liquid the leading wires can be thin on account of the low temperature. There were two resistances of the same kind in the cryostat, one of 50 Ω and the other of 130 Ω, the section of the tubes was about 0.004 mm² and 0.0015 mm². They were intended to investigate the influence of the section of the tubes upon the phenomena examined, a thing thad had been aimed at already before (see § 2) but did not succeed and the preparation of the narrowest one in particular had given great difficulties. It gave way during the experiment, so that the question of the influence of the section had again to be solved later on (see § 5). The experiments which were of chief importance for the matter under consideration were made in Dec. 1911 with the smallest of the two resistances, the section of the narrow resistance tube was here a little smaller than the mean in the resistance which was used for the experiments in Comm. No. 124*c*.

On the whole the results were the same as by previous measurements. Although great care [2]) was again given to the distillation of

[1]) Corresponding parts are indicated by the same letters, modified parts by the addition of an accent. A small additional improvement was further introduced into the contacts at the upper end, the four leading tubes were simply left open (which made it easy to add mercury which the contraction during the freezing made necessary), and bell shaped tubes *Hgk* were placed over the extremities in which the platinum wires *Hg'* etc. are sealed which connect the resistance to the current sources and the measuring apparatus. Platinum amalgam (see note 2. p. 6) need not be feared in this case, so that the complication of the inverted forks was superfluous.

We do not need here to enter into particulars of precautions such as the protection of contacts against changes of temperature, and others which have reference to the special circumstances under which the resistance measurements were made.

[2]) In § 9 it in demonstrated that in repeating the experiments less precautions would have been sufficient.

the mercury with the help of liquid air [1]), the mercury legs, as has been observed, gave considerable thermo-power; the legs with the smallest thermo-power were chosen as potential wires [2]).

There was some indication that the resistance of the mercury in narrower tubes falls a trifle less than in wider ones, when the tubes are cooled to 4°.25 K. (boiling point of helium). The new experiments also raised the question whether the almost sudden changes were found at a slightly different temperature of the bath in the narrower than in the wider tubes. But all this concerns particulars which can probably be explained by differences of crystallization and of heating by the current.

That the almost sudden change begins at 4°.21 K. [3]) and ends within a fall of 0°.02, was again confirmed with a resistance of about 50 Ω (calculated for liquid mercury at 0° C.).

Concerning the threshold value of current and the potential differences appearing at higher currents, i.e. the phenomenon to which the investigations were especially directed this time (Dec. 1911) results were obtained which correspond pretty well with the previous ones (Oct. 1911) if we assume that the origin of the phenomenon is in the resistance itself, and at the same time make the natural assumption that the potential difference increases with the current density, and

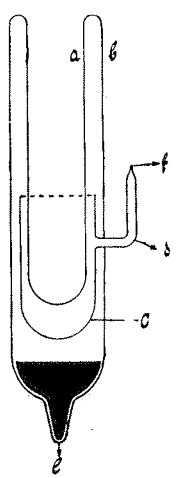


Fig. 2.

[1]) In the distillation the mercury was not heated above 65° and 70° C. while the cooling was done with liquid air. In order not to have to wait too long to procure a sufficient quantity it was done in an apparatus shown in fig. 2 at $^1/_3$ of the actual size. The mercury is brought into the double walled tube *a b* (with the reception beaker *c*), which was sealed off below at *e*. It is exhausted through tube *d*, while the mercury is warmed and then sealed off at *f*.

The lowest part is immersed in warm water; in the hollow *a* liquid air is poured. In 3 hours about 2 cm³. goes over; the condensed mercury in *c*, is afterwards poured out at *f*.

[2]) It amounted to only 12 microvolts, and this was compensated. The seat of these E.M.F. (up to 340) is to be found principally in the portion above hydrogen temperature.

[3]) This means more precisely 0°.04 below the boiling point of helium.

with conductors joined in series is equal to the sum of the potential differences in each of these conductors. This is shown in the table, in which both series of observations are combined, and holds both for the minimum value of the current at which the potential

TABLE I.

Potential difference of the extremities of mercury threads carrying a current.

Temperature.	Current density in ampères per mm².		Potential difference in microvolts.	
	October 1911.	December 1911.	October 1911 $l = 7 \times 20$ cm.	December 1911 $l = 20$ cm.
3°.65 K.	0.49 × 190		0	
		0.510 × 260		0
	0.56		0	
		0.665		0.5
	0.72		7 × 1.14	
		0.890		4.7
		1.10		12.7
4°.19 K.	0.010		0	0
	0 014		7 × 0.017	
		0.016		0.4
	0.020		7 × 0.36	
	0.023		7 × 0.71	
		0.024		4.7
	0.028		7 × 2.3	

difference appears, and the value of the potential difference at a given excess value of current and a given temperature.

For we must remember that the previous resistance consisted of 7 U-shaped tubes not all precisely similar, averaging 37 Ω, and the present one of one U-shaped tube of 50 Ω, while the lengths of the tubes did not differ much. The appearance of the potential difference was therefore, on our supposition, to be expected in the last case at a slightly smaller current than in the first; on the other hand, the greater length which was partly compensated by a greater section, made it probable that in the Oct. experiments the potential difference at the same temperature and current would be a few times larger, though not as much as seven times.

§ 4. *Questions to which the experiments give rise.* There were not sufficient data to make out whether the resistances used really differed as much as was thought as regards the opportunity of receiving heat through heat conduction from elsewhere, in particular JOULE heat. It would however have to be regarded as a curious coincidence that this conduction of heat in conjunction with other causes had led to such a close correspondence in the phenomena observed. It seemed much more probable that the phenomena were to be accounted for not by disturbances from outside, but by resistance arising in the thread itself.

Where such a remarkable change in the condition of the mercury takes place as is shown by the disappearance of the ordinary resistance, the appearance of a "threshold value" dependent on the temperature naturally gave rise to the question, if we had to do with a deviation from OHM's law [1]) for mercury below 4°.19 K. The electron theory, supplemented by the hypothesis in Comm.
1 12 No. 119, that the resistance is caused by PLANCK's vibrators [2]), and by the more special hypothesis that the electrons move freely

13 [1]) I hope to return to the new and important theory of WIEN, in a further comm.

[2]) LENARD has recently given two important papers on the conduction of electricity by free electrons and carriers, which intend with a third paper to make a whole of his highly interesting researches on the interaction of electrons and atoms and the theory of metallic conduction. This gives to the latter a new and very promising base. In the first paper Ann d. Physik 40 p. 414,
14 1913 he comes to the result making use of the great conductivity of metals at helium temperatures (Comm. N⁰. 119) that OHM's law is only valid within narrow limits for metals at very low temperatures comp. further VIII § 16 of
15 this Serie. [Note added in the translation].

through the atoms as long as they do not collide with the vibrators and are reflected as perfectly elastic bodies at the surface of the conductor, indicates causes which might work in that direction. The distance which the free electrons travel between two collisions at which they give off energy derived from the electric force, might become comparable to the dimensions of the conductor below
4°.19 K. (compare Comm. No. 119 Feb. 1911 § 3, last note); the 16
speed which they acquire in the electric current is perhaps no longer negligible compared to the velocity of the heat movement; for a certain current density at each temperature it might be just sufficient to bring the vibrators into motion, which otherwise below 4°.19 K. are stationary [1]). Considering all this, we may not take it as a matter of course, that OHM's law will still hold below 4°.19 K. and a further investigation of this will be interesting, if it only proves that this is actually the case.

As long as the contrary is not experimentally proved, we shall however adhere to this law, because we have first to try to refer the phenomena as much as possible to already known ones and so far under appropiate suppositions from the domain of known phenomena the results obtained did not seem incompatible with OHM's law.

Various possibilities presented themselves at once. A very small residual resistance evenly distributed throughout the whole thread might remain, which might be peculiar to the pure metal as such
(§ 12*α*), or might be the consequence of an admixture (mixed crystals) 17
evenly distributed through the metal. It might also be that the pure metal in the particular condition in which it comes below 4°.19 K. and in which the atoms perhaps form one whole together,
does not possess any resistance at all, but that somewhere (§ 11) in 18
the thread through some peculiarity a section is sufficiently heated by great current density, to bring the temperature of the

[1]) At the great current densities that were attained in some of the experiments (see § 7), (they went up to 1000 Amp. per mM²) the question arises if even the change in the resistance of the conductor through its own magnetic field of the current through the conductor should be considered, as it might be the case, that the resistance in the magnetic field for mercury in this condition was much greater, just as it alters with the temperature for some other substances, and has been found to increase for mercury at hydrogen temperatures (KAMERLINGH ONNES and BENGT BECKMAN, Leiden Comm. N⁰. 132*a*.)

thread locally up to the vanishing point. In either way an ordinary resistance could be formed somewhere, which, when the strength of current is further increased, gives rise to an accelerated heat evolution and an increased development of resistance.

§ 5. *Further investigation of the potential difference phenomena, in particular at temperatures slightly below the vanishing point.* It was considered desirable in the first place, to investigate the influence of the thickness of the thread upon the temperature, at which the fall of resistance occurs, and also upon the more or less sudden disappearance of the resistance.

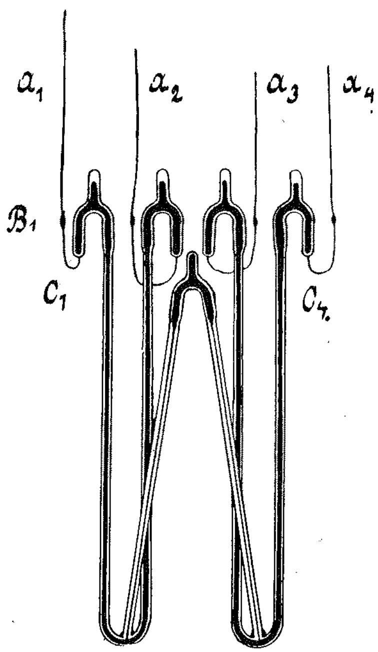


Fig. 3.

The resistance apparatus with which the experiments (Jan. 1912) for this purpose were made differed from those of Dec. 1911 only in this, that in the two pairs of mercury threads which serve for the measurement of the resistance of the mercury (two current leads and two potential threads) the pieces that were above helium temperature were replaced by copper wire, in this way that the mercury legs were cut off and sealed up, and in the sealed up ends, as in the resistances of Oct. 1911, platinum wires were sealed in, which were in their turn joined to copper leads [1]). During the experiments all these contacts were immersed in liquid helium, compare fig. 3. This change was made since

[1]) The wires were made comparatively fine, to prevent the liquid helium from evaporating too quickly from the conduction of heat Besides the conduction of heat from above the absorption of radiated heat by the metal in the transparent apparatus was avoided. Later on, when the various circumstances could be better surveyed, leads were constructed which could carry a strong current without causing too much evaporation.

it had been shown that the kind of lead had little influence on the phenomena, so as to be free from the troublesome thermo-currents in the potential wires, when these were of mercury from the resistance which was immersed in helium to where the ordinary temperature began, and all four were replaced in order to be free in the choice of the pair of threads which were to be used as potential wires or as current leads. The thermo-powers were now only about 10 microvolts.

The experiments of Jan. 1912 were made with two mercury threads, one with a resistance of about 50 Ω, the other of about 130 Ω. These resistances were joined up in a circuit with a milliammeter, which could be shunted, and to each of them one of the coils of a differential galvanometer was connected as a shunt. By using only one coil at a time the resistance of each of the mercury threads could be measured separately; by connecting the two coils in the opposite direction the change in the ratio of both with the temperature could be investigated as long as the difference was small.

The ratio

$$\left(\frac{W_{130}}{W_{50}}\right)_{T=290^\circ} = \frac{128.4}{50.4} = 2.55$$

became, through cooling to the boiling point of helium

$$\left(\frac{W_{130}}{W_{50}}\right)_{T=4^\circ.25} = \frac{0.0542}{0.0249} = 2.18.$$

The ratio changed, as had been found before, and as could be readily explained by a slightly different manner of freezing of the mercury in the two tubes.

On changing the current strength at 4°.25 K. we found

Current in Amp.	W_{130}	W_{50}
0.006	0.0545	0.0251
0.010		0.0250^5
0.016		0.0249
0.030	0.0549	0.0260 [1]).

[1]) As regards the deviation at 0.03 amp. of W_{50}, we may perhaps conclude from the comparison of the ratio of the resistances at $T = 290^\circ$ K. and $T = 4^\circ.25$ K. in both resistances, that there is a thinner place in the thread W_{50} by which a greater heating takes place locally at temp. above the vanishing point, than would be expected from the average section.

Up to currents of 0.03 amp. therefore it is confirmed that there is no reason to assume a deviation from Ohm's law above the vanishing point.

On lowering the temperature from the boiling point to where the disappearance of the resistance begins, this ratio remained unchanged according to the observations with the differential galvanometer; from that point downwards the resistance in which the current density was smaller, disappeared more quickly.

Although the resistance in the experiments disappeared gradually, yet the way in which it disappears gives the impression that the change in resistance of the mercury with the temperature occurs suddenly and that the gradual disappearance of the potential is due to the fact that the thread is only gradually cooled over its whole length to below the vanishing point, and only that part which is below this temperature looses its resistance.

It was again confirmed that at temperatures some tenths of a

TABLE II.

Resistance of mercury threads carrying current in the neighbourhood of 4°.2 K.

T	3.7 amp./mm² W_{130}	1.6 amp./mm². W_{50}
4°.24 K.	0.0532	0.0244[5]
4.22	459	182
216	314	0.0069
214	264	34
213	190	13
210	128	0.0003
207	0.0087	1
205	50	1
201	46	0.0000
196	21	0.0000
190	0.0005	0.0000
180	0.0000	0.0000

degree below the vanishing point no resistance was found up to very high current densities. Table III may be compared with Table I. In W_{130} the centrur density could be raised to 400 amp. per sq. mm. without the least resistance being perceptable. The highest limit for the resistance is hereby put back at 3°.6 K. to $< 4.10^{-10}$ of the value at 0° C. (in the solid state) and reduced to about half of that to which we could go down in the January experiments.

TABLE III.

Potential differences at the extremities of mercury threads carrying a current. $l = 20$ cm.

$\pi r^2 = 0.0016$ mm² for W_{130}

$= 0.004$ „ „ W_{50}

Temp.	Current density in amp. per mm².		Potential difference in microvolts.	
	W_{130}	W_{50}	W_{130}	W_{50}
3°.6 K.	375	160	0	0
	490		0.27	
	500		2.12	
	625	260	12.9	0

For W_{50} at a strength of current of 1 amp. the current density which in W_{130} appeared to be the threshold value was not yet reached. A stronger current was applied. But now a special disturbance arose: on raising the current to 1.5 amp. so much Joule heat was generated by the current in the platinum wires joining the mercury leg, that this reached the thin mercury thread and brought it up to a temperature above the vanishing point. All this was accompanied by a rapid boiling of the helium, while the ammeter showed a strong falling off of the main current corresponding to a decided rise in the resistance. From the readings it could be seen that the resistance of W_{50} had risen to that which it has at hydrogen temperature This time it seemed most probable that the potential differences could be attributed entirely to heat introduced from outside, so that if this could be prevented it would be possible to bring at these lowest temperatures the highest limit for the possible residual resistance still nearer to zero.

§ 6. *Experiments with an apparatus arranged so as to be sure that no heat penetrates to the thread from places at a higher temperature than that of the vanishing point.*

A mercury resistance was made, suitable for observing the potential changes, when a current of 3 amp. went through the same mercury thread as in the last experiments, and to make certain that the disturbances which had occurred would be impossible. The mercury thread *C*, see fig. 4, at the ends of which the potential was to be measured was for this purpose lengthened at both ends by an auxiliary mercury thread of larger section. We will call these auxiliary threads *A* and *B*.

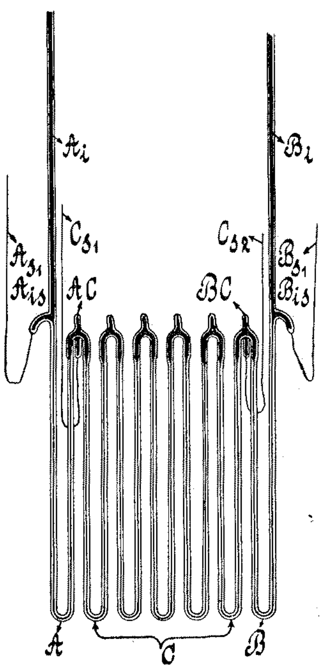


Fig. 4.

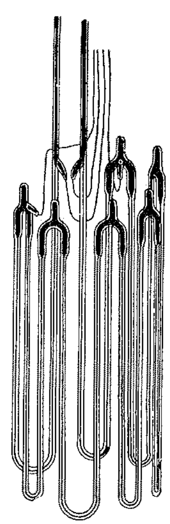


Fig. 5.

By measuring the potential difference at the extremities of both auxiliary threads it could be ascertained that any heating above the vanishing point could not be the consequence of the introduction of heat which had entered the extremities of the resistance *C* which was to be examined through conduction. For this heat could only enter through the sentinel wires, and these could only become dangerous for the experiment after betraying a heating above the vanishing point by showing a potential fall.

On the ground of the experience in the last experiments, the connecting wires carrying the current in to the resistance (compare the diagrammatical fig. 4 and the perspective fig. 5) were again of mercury, in order to prevent Joule heat being transported to the resistance while sealed in platinum wires to which copper wires were soldered served as potential wires. The sentinel thread *A* had at the ordinary temperature about 35 Ω, the sentinel thread *B* about 36 Ω resistance, the resistance *C* consisted of five threads in series of about 80 Ω resistance each and with a combined resistance of about 390 Ω at ordinary temperature.

At the boiling point of helium $W_{SA} = 0.01831$ Ω, $W_B = 1.01285$ Ω, $W_C = 0.1773$ Ω. The observations were as shown in Table IV.

We had therefore not succeeded, as had been our intention in giving a larger section to *A* and *B* than to *C*, in managing that if *C* should show potential difference, it would do so before *A* and *B* did it. Only if this had happened would it have shown that the heat that brought *C* to a temperature above the vanishing point was developed inside *C*. And the potential which now appeared in *C* can again be ascribed to heat conduction through *A*. The experiment shows very clearly that accidental circumstances in the freezing of the mercury threads play a part in the determination of the "threshold value" of the current density, and that in calculating with the average section of the tube in which the thread is frozen, only a lower limit can be given for this.

Possibly the mercury in *A* and *B* was only frozen in an unfavourable form, and therefore greater local current densities or worse exchange of heat had arisen than the average.

TABLE IV.

Resistance of a mercury thread just below 4°.20 K.

$\pi r^2 = 0.0025$ mm² for W_C

Temp.	W_{SA}	W_{SB}	W_C
	current density 2.5 Amp. p. mm² in W_C		
4°.24			0.163 Ω
4 .234			0.161
4 .230		0.011	0.158
4 .222		0.0078	0.0774
4 .208	0.0022	0.0025	0.00775
4 .192	0.000024		0.000024
4 .185	0.000012		$< 10^{-6}$
	current density 12 Amp. p. mm² in W_C		
4 .185	0.000071	0.000153	$< 10^{-6}$
	current density 20 Amp. p. mm² in W_C		
4 .185	0.000117		0.000048

§ 7. *Repetition of the experiment with the same apparatus.* We obtained more favourable results from another freezing. First a few results may be given, which were obtained by measurements at different strengths of current at 4°.25 K., that is at a temperature above the vanishing point. These results gave an opportunity of judging to what degree heat can be given off by the mercury thread closed up in a glass capillary or flows off along the extremities.

From the increase of resistance at greater current strength, the rise of temperature was deduced on somewhat simplified suppo-

sitions, at which the equilibrium between the JOULE heat and the heat given off to the outside is established. The result for the resistance and the average rise of temperature of C was:

current	resistance	rise of temp.
0.006 amp.	0.1928	0°.
0.006 „	0.1932	0°.
0.356 „	0.2149	0°.12
0.500 „	0.2410	0°.25

The average rise of temperature was calculated by the formula got by separate determinations

$$W_T = W_S (1 + 0.9\,(T - T_s))\ ^{1)}$$

in which T_s represents the boiling point of helium.

It follows from these determinations that per degree of difference of temperature between mercury thread and bath 0.057 calorie is given off per second. If we assume that all the heat goes through the glass, that the mercury touches the glass everywhere, and that we only have to consider the narrow capillary, then we find with $d_i = 0.056$ mm, $d = 2.07$ mm, $l = 100$ cm, for the conductivity of glass $k = 0.00033$, while at ordinary temperature $k = 0.0022$.

The loss of heat through the glass must therefore by cooling to the boiling point of helium have become much less than at ordinary temperature, which might possibly be the consequence of the mercury only touching the glass at a few places besides in the bends.

The application of the data obtained at temperatures below the vanishing point is in the nature of the matter uncertain, as we do not know whether, with the galvanic change in the mercury, there may not be another change in the thread, which would bring about a further change in the giving off of heat.

With regard to the appearance of potential differences at the extremities of the thread, we found the data contained in Table V.

At 3°.6 K. the current at which a potential difference would appear in the sentinel wires could not be measured, as, before

[1]) See the fig. in Comm. No. 124. Dec. 1911.

TABLE V.

Strength of current at which the potential difference appears at the extremities of a mercury wire carrying a current below 4°.2 K.
$\pi r^2 = 0.0025$ mm² for *C*.

Temp.	*A*	*B*	*C*
4°.18 K	0.0535	0.0615	0.034
4 .10	0.232	0.317	0.172
3 .60			1.068
3 .28			1.646
2 .45			2.56

the current had reached this value, the resistance *C* was heated to above the vanishing point along too great a length.

What we were aiming at was however attained in these experiments of Feb. 1912. It is established that heat is produced in *C* by raising the strength of current sufficiently, and that the heat is not conducted to it from *A* and *B*, since *A* and *B* were at a lower temp. than the vanishing point as appeared by the absence of potential fall in them. It is developed in the thread itself.

Table VI may be subjoined concerning the experiment at 2°.45 K corresponding to Tables I and III.

At the same moment that the galvanometer which measures the potential difference at the extremities of the thread is deflected, the strength of current in the main circuit falls from $i = 2.84$ amp. to $i = 1.04$ amp. which corresponds to an increase of resistance $\Delta W = 2.44\ \Omega$ in the circuit, from which it appears that the resistance is heated nearly to the temperature of hydrogen by the remaining current, of 1 amp. nearly.

If we take the last described experiments together, we have been able by them on the one hand to raise the current density to the enormous value of about 1000 amp. per mm², without any heat being developed in the wire. This threshold value for

TABLE VI.

Potential difference at the extremity of a mercury thread carrying a current below 4°.2 K.
$\pi r^2 = 0.0025$ mm²

Temp.	current density in amp. per mm²	Potential diff. in microvolts.
2°.45 K.	944	< 0.03
,,	1024	0.56
,,	1064	1.5
,,	1096	6.3
,,	1120	very large

the current density brings the highest limit for the possible resistance of mercury in the peculiar condition into which it passes below 4°.19 K. and particularly when it is cooled to 2°.45 K. still further back, and the ratio of the resistance at 2°.25 K. to that of solid mercury at 273° K. becomes $\frac{W_{2°.45\ K.}}{W_{273°\ K.}} < 2.10^{-10}$.

On the other hand it is proved that the *development of heat* which appears at a still higher strength of current, *hat its origin in the thread itself.*

§ 8. *Influence of the current density upon the manner in which the resistance in mercury threads disappears.* What has been related above can all very well be reconciled with the view (see § 5) that the disappearance of the ordinary mercury resistance at 4°.19 K. occurs quite suddenly, and in a thread that has been cooled to below that temperature, as soon as the "threshold value" of the current density is exceeded, somewhere heating occurs which carries the thread at that place to above that temperature, at first over a scarcely perceptible length but at higher currents over a rapidly increasing distance, by which ordinary resistance is generated in this part of the wire. With these larger currents the thread then comes in a state on which there is no uncertainty, it assumes over its entire length the new temperature equilibrium of a thread carrying a current, which equilibrium is determined above the vanishing point in the usual way. In order to improve the comprehensive view that may be formed on the ground of Table IV combined with Table II in which latter the different current densities do not refer to the same wire, further experiments were made in June 1912, which show how with the same thread the resistance disappears at different current densities.

The thread had a section of about 0.003 mm²., at the boiling point of helium the resistance was 0.1287 Ω. The experiments were made with a falling temperature, with current densities of 1.3,

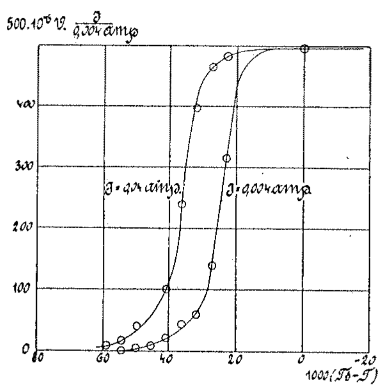


Fig. 6.

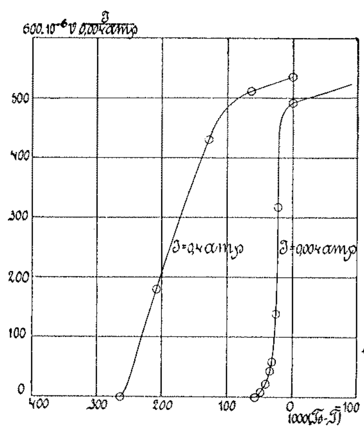


Fig. 7.

13 and 130 amp. per mm². (strength of current 4,40 and 400 milliamp). The phenomena are shown in the accompanying figs, upon which the numerical values are distinct enough to make it unnecessary to print a table. Fig. 6 allows a comparison between the phenomena at 0.004 amp. and 0.04 amp., fig. 7 at 0.004 amp. and 0.4 amp. The ordinates represent the potential fall in micro-volts divided by the strength of the current, expressed in 0.004 amp., the abscissae the difference of the temp. T with that of the boiling point $T_s = 4°.25$ K. in thousandths of a degree. The unit of the scale of the abscissae in fig. 7 is five times as large as in fig. 6.

At 0.04 amp. the curve continues with diminishing values of the ordinate to lower temperatures than are shown on the fig.; at 4°.11 K., when the experiment had to be stopped, the resistance was not quite 0, we found $0.2.10^{-6}$ V. The intersection with the horizontal axis in fig. 7 is probably drawn too sharp; at 3°.96 K. the potential difference was $< 0.03.10^{-6}$ V.

The whole gives one the impression that the lower temperature of the bath at greater strength of current is required (a comparison of 0.004 and 0.04 amp. shows that an almost constant shift of temperature would change the potential differences per unit of current in the one case into those of the other) to cool the part of the thread that has an ordinary resistance strongly enough to prevent it imparting its temperature to the part which is below the vanishing point, and to prevent the temperature in the latter part from being raised above the vanishing point by the greater local development of heat.

With the same thread in the manner of table III the results of table VII were found, in which experiments are included with a second thread with a section of about 0.012 mm².

It appears that in the thread W_I, to which the experiments just quoted refer, local heating takes place more easily at the same current density than in W_{130} (see § 5). The fact that the latter thread gives off heat more readily also explains why in W_{130} a greater current density checks the disappearance of the resistance less than in the case of W_I (June 1912).

As regards the threshold value of the current density for different temperatures with the same thread, it would seem from Table VII and Table V roughly speaking to change linearly with the temperature, if the fall below the vanishing point is not too small, and if we leave out of account a term for JOULE heat which only appears distinctly at a higher current strength. This naturally suggests that we are dealing with a PELTIER-effect raising the temperature till the vanishing point of resistance (e. g. connected with different forms of crystallisation or tensions); (the simultaneous cooling of the opposite contact has no effect on the resistance which is already practically zero and remains zero when further cooled). As regards the threshold value of the density at a given temperature for different threads this appears (comp.

TABLE VII.
Potential differences at the extremities of mercury threads carrying current.

Temp.	Current density in amp. per mm²		Potential difference in microvolts.	
	w_I	w_{II}	w_I	w_{II}
3°.6 K.		129		0.5
		141		very large
	363		0.3	
	412		3.8	
	429		12.1	
	431		very large	

§ 6 and Table IV) to be rendered uncertain by accidental circumstances. But it deserves notice that it was also found very high in very narrow capillaries.

(To be continued).

KAWA, 22 March 1913, pp. 1388-1391

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H. KAMERLINGH ONNES. *Further experiments with liquid helium. H. On the electrical resistance of pure metals etc.* VII. *The potential difference necessary for the electric current through mercury below* 4°.19 K. (continuation).

§ 9. *Experiments on impurities as a possible source of disturbances.* Although the greatest care was always bestowed upon the purification of the mercury, the explanation of the appearance of a residual resistance that offered itself the first for closer investigation was the influence of impurities. These may give an "additive mixture resistance" to the metal which changes little with the temperature and is proportional to the amount of impurity. To such an additive resistance I ascribed the fact (Comm. No. 119 1
and Suppl. N⁰. 29) that the resistance of very pure platinum and very pure gold did not disappear at helium temperatures as I expected with absolutely pure metals. Now the experiments had realized the expectation, that mercury could be so far freed from impurities, as to make the resistance practically nothing. But if one may judge by the additive resistance which even very pure gold exhibits, then with the residual resistance of mercury which is only perceptable at the threshold value of current density for the lowest temperatures, it would be a question of an impurity of the order of a millionth of the trace that could possibly be present in the most carefully purified gold. And it was a priori doubtful if the mercury could be procured in so much greater a state of purity than gold. [1])

The experiment was therefore repeated with solid mercury in which I believed a very small quantity of an other metal to be present. After being distilled in a vacuum by means of liquid air, the mercury was in one case brought into contact with gold and

[1]) On difficulties inherent in the supposition of a resistance equally distributed throughout the thread which apply also to our present case of additive mixture resistance see § 11.

the other time with cadmium, after which it was mixed with a larger quantity of pure mercury. To my surprise with the mercury that had been treated in this way, the resistance disappeared in the same way as with pure mercury [1]; much of the time spent on the preparation of pure mercury by distillation with liquid air, might therefore have been saved, without the experiments on the sudden disappearance of the resistance which were made with mercury prepared in the ordinary way with double distillation giving other results.

Even with the amalgam that is used for the backing of mirrors, the resistance was found 0 at helium temperatures. Later Dec. 1912 it was found that it disappeared suddenly, as with the pure mer-
3 cury but at a higher temperature [2].

Where the influence of impurities, in the form of mixed crystals in the solid mercury, seems to retire into the back ground, the next most natural supposition is that less conductive particles, separated out of the mercury during the freezing, or coming amongst the mercury crystals in some other way, bring a resistance into the path of the current. But if we do not assume that a thread of perfectly pure mercury can possess a residual resistance itself, this theory of the origin of the potential differences is not very probable, because in a resistance-free path of current, only by a closing of the whole section by an ordinary conductor is resistance produced. Particles of the sort we mean, as also other casual circumstances, for instance the manner of freezing and small cracks, can influence the magnitude of the threshold value of the current density derived from the experiments, but the values found for this quantity, although they vary, differ so little, that in addition to the causes mentioned we must assume for a *thread* of pure mercury the existence of a residual resistance which we will call a "microresidual" resistance, to distinguish it from the
4 "additive mixture" resistance to be attributed to impurities.

[1]) Perhaps not even a quantity of the order of a thousand millionth of zinc or gold is absorbed in solid mercury. The application of the sensitive test of the disappearance of the resistance may be of value for the theory of solid solutions. Of course in our argument we only deal with absorption in a form which comes into consideration for the resistance (mixed crystals).

[2]) This part of the text is changed in the translation in accordance with the
5 facts see § 13γ in VIII of this series.

§ 10. *Experiments on the possible influence of contact with an ordinary conductor upon the superconductivity of mercury.* In the 6 ← first use of "superconductivity"
reasoning, that we have just given it is assumed that the laws of current division between two conductors which touch each other also hold when one of the conductors consists of mercury below 4°.19 K. But this assumption might not be correct. In the line of thought of § 4 and taking into account the heat motion which takes the electrons now to the inside and then to the surface of the conductor, a pushing forward of the electrons in the galvanic current through a superconductor without performance of work seems only possible, when its surface only comes into contact with an insulator, which reflects the electrons with perfect elasticity. If the electrons can hit against the atoms (or more accurately the vibrators) of an ordinary conductor, they will of course give off work in this collision. Thus a thread of superconducting mercury, if an ordinary conducting particle were present anywhere in the current path, could show resistance at that spot, even although the particle did not entirely bar the section which was otherwise free from resistance.

These considerations lead to the following experiment. A steel capillary tube, supplied with connecting pieces in which were platinum wires for measuring the resistance, was carefully filled with mercury at the air pump. The measuring wires were immersed in the mercury, without touching the current wires. According to the ordinary laws of current distribution the resistance of this composite conductor should disappear below 4°.19 K. Whether the mercury is in a glass or a metal capillary makes no difference to the conduction. Thus for instance, if one was to coil up such a steel capillary filled with mercury, and press the coils against eachother without insulating them, the coil could still serve as a magnetic coil below 4°.19 K.; the coiled up mercury thread would be resistance-free, and the steel would take the part of the insulator, which otherwise separates the different windings of the current path in a magnetic coil. On the other hand if the above reasoning is correct, a mercury thread, that is provided with a close fitting steel covering should retain its resistance below 4°.19 K. though the current is lowered below the threshold value.

In several experiments with the above mentioned steel capillary,

in accordance with the last conclusion, the resistance of the mercury
thread did not disappear. Yet we must not conclude from this
that the remaining resistance is given to the mercury by the
contact with the steel. There only needs to be one little gapin the
mercury which extends over the whole section, to cause the appea-
rance of ordinary resistance of the amount according to the poten-
tial difference. If the resistance had disappeared in the experiments,
there would on the other hand have been room for the question
whether there had been contact between the steel and the mercury.
With mercury in a steel capillary the result of the experiment
remains always doubtful. We may therefore mention here, that
afterwards when it was found that the resistance of tin dissappeared
suddenly too, we succeeded in making a less doubtful experiment
than is possible with mercury, with a flattened out constantin wire,
which was covered with a thin layer of tin [1]). The resistance of
the layer of tin disappeared with a weak current and at a low
temperature, while the constantin remains an ordinary conductor
at that temperature.

Thus we may for the present adhere to the usual laws of
current division, and in this extreme case continue to assume that
in so far as the appearance of the potential difference is to be
explained by a local heating in consequence of a local change in
difference of the chemical nature of the conductor from pure
mercury this disturbance must extend over the whole section of
the current path. Thus the conclusion drawn in § 9 concerning
7 the probability of the existence of a microresistance remains valid.

(*To be continued*).

[1]) It is to be noted, however, that the current density in the thin layer had
8 to be made very weak. Comp the following part of this Communication VIII, § 16.

H. KAMERLINGH ONNES. *Further experiments with liquid helium.* H. *On the electrical resistance of pure metals etc.* VII. *The potential difference necessary for the electric current through mercury below* 4°.19 K. *(continued).*

§ 11. *Local nature of the loss of heat by a mercury thread
enclosed in a glass capillary carrying a current, when the tempe-
rature sinks below* 4°.19 K. While the supposition that the thread
should accidentally consist of some other substance than mercury
for a small part of its length, is in contradiction to the regularity
of the potential phenomena, yet on the other hand the supposition
that the mercury thread has a microresidual resistance similar to
the ordinary resistance in OHM's law (therefore independent of
the strength of current, see § 4), gives rise to no less difficulties [1]). 1
Such a microresistance proper to the mercury will be evenly 2
distributed over the whole thread. If we calculate from the poten-
tial differences observed during the warming up at low tempera-
tures and the strength of current to which they belong, the
resistance of the thread under the conditions of the experiment,
then we find that the thread, when the threshold value of the
strength of current is only very slightly exceeded, must for a
part of its length be partly heated distinctly above the vanishing
point. Let us take for example the experiments of Dec. 1911 in
table I. We find from the threshold value of the current at 4°.19K., 3
that the resistance of the thread at this temperature may be put
at $< 3.10^{-6}\,\Omega$. In the experiment at 3°.65 K. we find that
when the strength of current rises to 1 amp. the resistance,
$11.5.10^{-6}\,\Omega$, was already distinctly greater than when the whole
thread was at 4°.19 K., while the ends must still be at 3°.65 K. The

[1]) Besides those mentioned in § 9, the difficulties here treated also present 4
themselves if we try to explain the potential phenomena by an even distribution
of additive mixture-resistance.

portion that comes above the vanishing point by this heating, as it assumes ordinary resistance, need only be very small to produce the potential differences observed; in the case in point only 0.1 mm. If we assume that the giving off of heat to the bath may be calculated by the same data as were found for it above the vanishing point in § 7, then we find that, if the whole surface of the thread were at the mean of the temperature of the bath and of the vanishing point, the loss of heat per second should be about 20000 microjoules, while in reality only 14.0 microjoules, or about 1400 *times less*, are given off.

We conclude from this that the rise of temperature in the thread, which is in a bath of a temperature below the vanishing point is only local. If there were anywhere else a rise of temperature (although of a smaller amount) the thread must have ceased to give off heat to the glass to a perceptible degree, except at certain points. The heat could therefore only flow to the extremities or the remaining points of conduction. This might be the consequence, for instance, of the mercury having come away from the glass everywhere except at the places indicated. But this is contradicted by the fact that in freezing the mercury adheres to the glass, and that immediately above the vanishing point the contact has not yet ceased. The supposition that everywhere where the temperature remains above the vanishing point (and perhaps close to it) the mercury thread gives off heat, and does not where the temperature is lower, is confirmed by the way in which the resistance disappears below the vanishing point (see Table II and fig. 7). If we determine, from the proportion of the resistance remaining to that just by the vanishing point, the length of the portion of the thread which is at the temperature of the vanishing point then the JOULE-heat that it must give off at the existing strength of current corresponds more or less to that which is to be expected at the assumed difference of temperature of bath and vanishing point if the heat is given off to the glass over the whole length of that portion; more or less, for there remain unexplained and apparently systematic differences, with which perhaps the difference of the curves for different strengths of current in fig. 7 is connected.

In supposing, however, that the development of heat which

brings a part of the thread to the temperature of the vanishing point is of a local nature, we give up the supposition that the microresidual resistance is evenly distributed over the thread. Assuming the whole of the path of the current to be of pure mercury, there could possibly only be an *apparent microresidual resistance*, in consequence, for instance, of the mercury not being homogeneous, or not free from mechanical tension. These disturbances would then be the cause of threads showing a resistance throughout, while the pure homogeneous tension-free mercury would have an imperceptible microresidual resistance.

If we remember that with lead the increase of resistance by pressure [1]) becomes less at low temperatures, and has almost disappeared at hydrogen temperatures, then it is not probable that tensions, although they could cause PELTIER-effects, and although their regularity corresponds to that of the phenomena, should really play a part in the disturbances.

It would be more natural to suppose a lack of homogeneity in the thread, which might be the consequence of difference of the state of crystallization. When we turn down a block of very pure KAHLBAUM-lead on the lathe, we can sometimes see a moiré effect on the surface, which indicates different alternating states of crystallization, each of which extends over more than a centimetre. In this way a thread of solid mercury might consist of a series of differently crystallized portions, the dividing surfaces of which would be at the same time usually cross sections of the thread.

At a dividing surface of this kind, a local heating such as we have treated above, might take place, at the expense of current energy. For instance a transitional resistance might give an apparent microresidual resistance to such a dividing surface. But the relation between the threshold value of current density and the temperature of the bath, points (see § 8) rather to a PELTIER-effect at this transitional place. We should then have to imagine that when the current density reaches the threshold value, the temperature at the dividing surface between two states of crystallisation, even if not high enough to occasion a thermo-

1) H. KAMERLINGH ONNES and BENGT BECKMAN. Comm. No. 132*b*. Nov. 1912.

electric force equal to the potential difference observed, yet reaches the vanishing point, and that, therefore, by further increase of the current density ordinary resistance must appear at this dividing surface. The length of the thread which takes an ordinary resistance would then increase with the excess of the development of heat above that which produces locally the vanishing point temperature; it would be further determined by the circumstances under which the excess of the heat developed would be given off. When we compare the potential difference observed in the different cases, there are one or two things that seem to confirm this supposition [1]).

Taking all this together, we are brought back to the idea that the potential phenomena must be ascribed to "*bad places*", although in a different sense to that in § 9. But the regularity of the phenomena remains a weighty objection to this hypothesis [2]). For although, with the explanation of the local development of heat by a difference in the states of crystallization, the difficulty disappears which in the explanation by foreign resistances arose out of the circumstance that the whole section must be blocked up, still the appearance of a dividing surface between two states of crystallization is governed by chance. In any case, to come to an explanation on this principle, we should have to assume, that there are various PELTIER-places of the kind meant in each mercury thread of any length and that they are not too unevenly distributed.

But in this manner we would add a new indefinite hypothesis to the one which has to be tested and it is only by a complete quantitative working out of a perfectly definite theory that the question with which we are dealing can be answered: for the answer involves some far-reaching inferences. If we might assume that the potential phenomena in mercury-threads at a current density exceeding the threshold value are entirely due to disturbances then, on account of the systematic connection of the potential phenomena, there would be every reason to assume that we get a truer idea of the actual degree of conductivity of the superconductive mercury, the lower the temperature at which we determine the threshold value of current density of a thread [1]). And as at the lowest temperatures the disturbances still have an influence, although a smaller one, the actual conductivity would therefore have to be placed higher, perhaps a good deal higher, than the value found in § 7, which was already $0,5 \,.\, 10^{10}$ times that at the ordinary temperature, in other words the conductivity of the super-conducting mercury might *practically* be considered *infinite*.

1) Too indefinite to be published.

2) The existence of a microresidual resistance is also made probable by that the ratios between the resistances for the mercury in the capillary tube and the frozen mercury thread at 4°.25 K. seems to run parallel to the threshold values, so that the difference of the threshold values might be ascribed to differences of the local deviations of the cross sections from the mean.

Treal

§ 12. *Failure of the relations of* WIEDEMANN *and* FRANZ *and of* LORENZ *with super-conductors. α.* If the conclusion concerning the non giving off of heat to the glass by a mercury thread below 4°.19 K. which we discuted in § 11, were applicable we should arrive at a different view concerning the potential phenomena, from that arrived at above. If the mercury has an appreciable real micro-residual-resistance, so that heat is developed throughout the thread, and if we need not take any account of apparent micro-residual-resistances, the distribution of temperature in the part of the wire that is below the vanishing point, is governed by the ordinary formula for the rise of temperature of a wire conveying a current without external conduction of heat.

Let us keep as near as possible to the well known ordinary case in order to show the nature of the phenomena that are to be expected in the case in point, and for the sake of simplicity, as it is principally a question of order of magnitude, let us assume that below the vanishing point the ratio of the electric conductivity k to that of heat λ, is given by the same formula as holds approximately above the vanishing point, with the difference that the constant has a different value 10^7 times smaller, so that while above the vanishing point:

$$\frac{\lambda}{k} = aT \quad \text{with } a = 0.023.10^{-6} \text{ (watt. ohm. degree}^{-1}\text{)}.$$

1) In this train of thought there is no reason for not supposing that the conductivity assumes its large value immediately below the vanishing point.

below the vanishing point

$$\frac{\lambda}{k} = a'T \qquad \text{with } a' = a.10^{-7}.$$

We arrive at the low value which we ascribe to a' amongst other things in consequence of the fact that λ remains of the same order of magnitude below the vanishing point as above it, as appears when with the supposition that all the heat in the experiments is developed in the middle of the thread and only flows away at the extremities, we deduce an upper limit for the heat conductivity [1]).

With the assumption indicated the maximum temperature T_{max} of a thread, the extremities of which are at the temperature T_b, with a potential difference of E volts at the extremities is determined by

$$T^2_{max} - T^2_b = \frac{1}{4a'} E^2.$$

From this formula can be seen at once that the well known property of good conductors, that comparatively small potential differences, when external heat conduction is excluded, produce considerable heating, which may even lead to melting, becomes enormously more prominent in the superconducting condition.

In fact we find that at the smallest potential difference E of 0.5 microvolts, which is only a little above that which at 2°.45 K. is first observed, such comparatively great heating can take place, that even at the lowest values of T_b, T_{max} rises to 4°.20 K. At higher bath temperatures of course smaller potential differences are sufficient to reach the vanishing point, or at the same potential difference a' can be placed ~~lower~~ higher, at 4°.18 K. for instance $a' = a.\ 10^{-5}$.

[1]) This conclusion is confirmed by preliminary determinations of the heat-conductivity of mercury above and below the vanishing point made by Mr. G. HOLST and me. We conclude from these that this constant does not undergo any considerable change at the vanishing point, and the same is true for the specific heat, which we have also investigated, however important the vanishing point may be for the electric conduction.

[Our preliminary yet very uncertain values are: for the conductivity between 4°.5—5° K., $k = 0.25$ cal. cm. sec., between 3°.8—4°.2 K., $k = 0.46$ cal. cm. sec., for the specific heat between 4°.2—6°.5 K., $C_p = 0{,}0014$ and between 3°—4° K., $C_p = 0.00053$. (Added in the translation)].

With the rough estimation of a' given, and assuming that the mercury thread where its temperature has fallen below the vanishing point gives off no heat to the glass [1]), we can, therefore, whithout the assumption of heating caused by local disturbances, predict phenomena such as threshold value of the current density and the differences of potential, that appear at greater current densities.

At current strengths below the threshold value, the thread will all along be in the condition of superconduction, without external heat conduction, at current densities above the threshold value this only exists for portions below the vanishing point temperature; for the portion of the thread that is above the vanishing point, the regime of ordinary conduction with loss of heat at the surface comes in its place [2]). In this way there can, however, be no question of the deduction of the law of dependence of the threshold value on the temperature, because it is determined by the temperature function, which we have arbitrarily assumed as constant a' while we have seen that in the train of reasoning followed it might have very different values at different temperatures, from $a' = 10^{-5}a$ to $a' = 10^{-7}a$. And it is very questionable if, when the necessary data are known for working out the sketch taking note 1 into consideration, the potential phenomena would correspond quantitatively to those observed. For the supposition with regard to the absence of external conduction of heat, upon which the theory in this § is based, might be untrue. (Cf. § 16 δ of VIII).

It would be of great importance [3]) to cool by immediate contact the thread over its whole surface with liquid helium; if the potential phenomena are to be ascribed to a real micro-residual resis-

[1]) This calls our attention to the question of the distribution of temperature along a thread through which a current passes without external conduction of heat for different laws of dependence of λ, k and T. Laws might be imagined, which would cause the rise of temperature to run through the values from 0 to $T_{max} - T_b$ practically within a very small length of the thread, in which case the heating by a microresidual resistance could not be distinguished from a heating caused by a local disturbance. For the present, however, we adhere to the simpler supposition that the thread gives off no heat to the glass.

[2]) The divergence of the lines for 0.4 and 0.004 amp. in fig. 7 may also indicate the transition from the one regime to the other.

[3]) Less, when the particular circumstances mentioned in note 1 might exist.

tance of the mercury, then the threshold value of the current density could probably be raised considerably higher than was now possible. This is too difficult with mercury. Thus for further experiments the use of tin and lead (see § 1) was indicated, these metals being more easily manipulated than solid mercury, and with them the conditions of the external conduction of heat being more easily regulated [1]). We shall treat of these investigation in future papers.

β. We may here add a few remarks concerning the super-conducting condition.

The experiments described above leave no doubt that for mercury below 4°.19 K. there is no question of an approximate validity even as regards the order of magnitude of the relations established by WIEDEMANN and FRANZ and by LORENZ. The failure of this relation between λ, k and T indicates a difference between the super-conducting and the ordinary conducting state which may be regarded as a *characteristic difference* of both.

According both to § 11 and to § 12α, we come to a conductivity of mercury which is say 10^{10} times as great, or even more, than that at the ordinary temperature. If we assume that the number of free electrons per unit of volume at the transition from the ordinary to the super-conducting condition undergoes no important change, and then calculate according to the ordinary electron theory from the conductivity the free path of the electrons, we arrive at values which are comparable to the *lengths* of the mercury threads used in the experiments, in fact are considerably larger [2]). With such large free paths there would be every reason to believe that the peculiarities of the movements of the electrons pointed out in § 4, which are not consistent with OHM's law, would begin to play a part (which perhaps might resemble a PELTIER-effect such as seems to reveal itself in the potential phenomena). It is, however, questionable

[1]) The purity of both can probably not be made so high as that of mercury so that disturbances from a trace of additive admixture resistance in the super-conductive state do not seem impossible.

[2]) Taking the free path at ordinary temperatures at 10^{-7} cm., it becomes 10^{2} cm. at 2°.45 K., yet taking no account of the decrease of the number of free electrons. We do not consider collisions of the electrons mutually, as these would cause microresidual-resistance phenomena.

whether the whole hypothesis developed in § 4 in connection with Comm No. 119, concerning the movement of free electrons through the metal and which is also mentioned in § 10, must not be replaced by an essentially different one for the super-conducting condition, according to which the movement of the electrons is carried on by the current for considerable distances, but each separate electron which takes part in the progress, only moves one molecular distance.

To illustrate this idea we may take as an example the well known case of the propagation of a blow by a row of billiard balls which just touch eachother. In a super-conductor the flow of electricity might consist in this, that an electron jumping across on to an atom of the super-conductor from one side causes an electron on the other side of the atom [1]) to jump into the next atom, etc. till finally at the further end of the superconducting wire as many electrons would be carried away in the direction of the current, as were thrown in at the beginning [2]).

[1]) To express it more accurately, in the same layer of atoms taken across the path of the current, more passes over in a given time than is sent out (or thrown back) through the same layer in the same time to the side from which the electrons taken up come. We here give only the simplest possible sketch, to characterise the super-conducting condition.

[2]) The taking up of an electron on one side of an atom and the giving off on the other side of one to another atom, would then be accompanied by a moving up of the electrons (through or) over the surface of the atom, by which each electron moves along a part (if the number of electrons on the surface of an atom is large, then a small part) of the diameter of the atom. The connection of the electrons of two different atoms with each other and with these atoms probably does not differ very much from the connection between the electrons of one atom with each other and with the atom, so that the passing of an electron from the one atom to the other in the super-conducting state would be similar to the movement of the electrons in a single atom. The conductivity of the super-conductor would thus be that of the atoms united into one continuous whole (see § 4).

If the numerous electrons in the atom, which belong to the framework of it, in the described process only pass on the blow from the one electron that jumps onto the atom, onto the one that is given off without themselves taking part in the movement and if the moving electrons are the valency electrons, then our hypothesis, although arrived at by a different road, may be regarded as an application to the super-conducting state of the hypothesis of STARK concerning the movement of the framework of the valency electrons along the

The migration speed is thereby propagated through the super-conductor without the performance of work [1]). If the super-conducting metal is converted into an ordinary conducting metal by heating above the vanishing point, (if the point is not much exceeded it will still be strongly conducting) then, according to this hypothesis the OHM resistance is due to the action of the vibrators (between the atoms) which bring the atoms to a distance from eachother such that the electrons cannot jump from one atom to another without doing work, but in traversing the space made by the vibrators between the atoms give off some of the electric energy taken up by them [2]). The representation given of the conduction in the super-conductors seems thus to be most easily combined with the conduction theory developed by LENARD.

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shearing surfaces of the metal crystals. It thus shows the usefulness of the fundamental idea of STARK. As in the above hypothesis this idea is supplemented by the notion of the free moving electrons of the original electron theory viz. the jumping across of the electrons, the connection with the electron theories of the ordinary conducting state, especially with that of LENARD, is maintained.

1) In so far as we may disregard microresidual resistance.

2) We will not discuss whether this happens through electrons with migration speed being taken up and electrons without migration speed being given off or by elastic collision of the electrons against the surface of the atoms between which they move backwards and forwards: through energy of ordered motion being transformed into energy of unordered motion. We must remark that for the explanation of the super-conducting state the assumption that in contrast to non elastic collision in ordinary, only elastic collision takes place in the super-conducting state is inadequate. As LORENTZ has taught us (comp. REINGANUM, Heidelb. Akad. 1911, 10 p. 7) even with elastic collision the above mentioned transformation must take place and show itself as development of heat.

By the transition from the superconducting state to the ordinary in proportion as the atoms begin to vibrate separately in larger numbers and room is made for the movement of the electrons between the atoms, the mechanism develops which leads to the approximate relations of WIEDEMANN and FRANZ and of LORENZ. The communication of the movement of the electrons inside the atoms to each-other perhaps plays a chief part in the conduction of heat. The continuity of the heat conduction above and below the vanishing point would then be explained by the small change which the process undergoes when the peculiar connection of the atoms which makes super-conduction possible, is destroyed.

The change of the distance between the atoms also clearly plays a part in the change of the resistance at the melting point.

In my rough sketch (Comm. N⁰. 119) of the application of the quanta-theory to the electron-theory of conductors, in order to judge whether the hypothesis that resistance is caused by vibrators (the electrons otherwise moving freely through the metal with speeds in accordance with the kinetic theory of gases [1])) is well adapted to deduce the change of resistance with temperature, I put the mean free path of the free electrons inversely proportional to the mean amplitude of PLANCK's vibrators, which disturb them in their movements, while this mean amplitude was calculated by the formula which PLANCK at the time gave for the mean energy of the vibrators. The way in which mean values were introduced by this (comp. the reasonings in WIEN's theory, which clearly show the deficiencies of mine) could not allow us to expect more than a qualitative representation. Yet, as is rather remarkable, a close agreement was obtained with the observations between the ordinary temperature and that of liquid hydrogen. It is more difficult to judge of the suitability of the new hypothesis for reproducing the observations with metals above the vanishing point. According to the note at the end of Comm. N⁰. 119 the energy of the vibrators would also determine the increase of the volume of the metal from $T = 0$. The mean distance of the surface of the atoms may thus perhaps be taken proportional to the square of the mean amplitude calculated according to PLANCK's just mentioned formula. We may perhaps further conclude that the idea of the condition above the vanishing point at which we arrived starting from the new hypothesis concerning the super-conducting state, will appear to be not unsuitable, and in any case gives no ground for objecting to the last named hypothesis.

On both assumptions, however, the assumption that the free path is continuously described by the same electron, and also the other that it is broken by the movement being transferred

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1) KEESOM (this same Report, Suppl. No. 30*b*) has come to the important conclusion, by the application of the quanta-theory to the free electrons in a metal (considered as a monatomic gas) that at low temperatures the velocity of the free electrons becomes independent of the temperature, and has called this field of temperature the "WIEN field."

over a distance from one electron to another, a difficulty arises in the explanation of ordinary resistance, because PLANCK's previous formula has been replaced by a new one. In the discussions at the Conseil SOLVAY [1] (Oct. 1911) I pointed out that according to the theory developed in Comm. N°. 119, if we introduce the new formula, and further calculate in the same way, i. e. with only one frequency, the resistance could not fall below a certain value determined by the "internal temperature" (according to $\frac{h\nu}{2} = \frac{1}{2} k\beta\nu$ and $\beta\nu = 200°$ K. for silver 100° K.) multiplied by $\sqrt{T}$, while above $T = 0$ (for various metals above helium temperatures) it seems to become practically nothing. We must therefore adhere to the old formula [2]) for calculating the amplitude, or rather, accepting the new formula on account of the more satisfactory representation that it gives in many respects, we must assume that the amplitude of the vibrators that comes into consideration for the determination either of the free path of the electrons through the metal or of the distance between the atomic surfaces (the part of the path between their old and their new positions, upon which the electrons experience resistance in their movement from one atom to another) [3]) is only determined by that part of the energy of the vibrators, which is dependent on the temperature. In addition, in order to explain the existence of the super-conducting state one would have to assume that when the excess of the energy above the zero point energy has fallen to the small value which corresponds to the temperature of the vanishing point, the resistance to the motion of the electrons between the atoms suddenly becomes zero [4]).

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1) La théorie du rayonnement et des quanta. Rapports et discussions de la réunion à Bruxelles sous les auspices de M. SOLVAY. Paris 1912 p. 129.

2) As WIEN does in his theory. Sitz Ber. Ak. d. Wiss. Berlin 1913. p. 200.

3) We may remark that it is not necessary that when an electron jumps over with resistance the whole surplus velocity which it has to propagate should be lost.

4) Perhaps the distance of the surfaces of neighbouring atoms has then become equal to that of two neighbouring electrons in the same atom (comp. note 2 p. 43) and the connection of the electrons of two atoms similar to that of the electrons in one and the same atom (comp. the speculations on "atom-fast" compounds in KAMERLINGH ONNES and KEESOM, Encyclop. d. Math. Wissensch. V 10, Leiden Comm. Suppl. No. 23 Nr. 57).

In the reasonings of Comm. N°. 119 it was assumed that all vibrators in the metal have the same frequency. As the resistance is mainly determined by $e^{-\frac{\beta\nu}{T}}$ one need only assume as the single difference between the super-conducting condition and the normal that the frequency of the vibrators is say four times higher in order to find at the vanishing point a micro-residual resistance 10^4 smaller than the ordinary resistance at the same temperature and at 2° K. one which is 10^9 times smaller. But against this explanation it may be adduced that in order to bring the formulae of Comm N°. 119 into agreement with the observations at the lowest temperatures the frequency has to be taken lower as the temperature falls [1]). WIEN in taking into account in the calculation of the free path of the electrons all the frequencies which play a part in the specific heat has succeeded in explaining this peculiarity: the resistance according to his theory diminishes at very low temperatures only as T^2 or as $T^{5/2}$, (depending on the choice of a subsidiary hypothesis). But then it becomes much more difficult to explain the extremely small value of the possible micro-residual resistance by considering the super-conducting metal simply as a metal with slightly modified properties. It thus seems as if at the vanishing point something occurs by which the small frequencies lose their influence on the resistance although they continue to play a

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1) As I pointed out at the discussion of the Conseil SOLVAY (l. c. p. 298) one might suppose considering that the vibrations take place in the system of mutually connected molecules that there are two kinds of vibrations, a longitudinal and a transversal kind. Perhaps above the vanishing point only two vibrations play a part in the resistance, a transversal and a longitudinal one, so that according to PLANCK the small frequency becomes prominent at the lower temperatures, and at the vanishing point this frequency changes into a very high one, so that the original higher one assumes the more important part.

A rotation in opposite senses of two neighbouring atoms with small frequency above the vanishing point, might perhaps, by the atomic surfaces overlapping below the vanishing point, change into a rotation with high frequency. [The caloric investigation of what happens in passing the vanishing point will throw light on this question. As to the specific heat above and below the vanishing point compare the addition to note 1 page 40].

part for the specific heat. The spectrum of the frequencies of the vibrators which are operative in the resistance would thus become limited to a few higher frequencies or at least be cut off on the side of the small frequencies, in the same way as this happens according to Debije on the side of the high frequencies [1]).

[1]) This raises the question whether above the vanishing point also the small frequencies do not in some way lose their influence on the resistance all the more the smaller they are.

COMMUNICATIONS

FROM THE

PHYSICAL LABORATORY

OF THE

UNIVERSITY OF LEIDEN

BY

H. KAMERLINGH ONNES,

Director of the Laboratory.

N°. 133ᵈ.

H. KAMERLINGH ONNES. Further experiments with liquid helium. H. On the electrical resistance etc. (*continued*) VIII. The sudden disappearance of the ordinary resistance of tin, and the super-conductive state of lead.

(*Translated from: Verslag van de Gewone Vergadering der Wis- en Natuurkundige Afdeeling der Kon. Akad. van Wetenschappen te Amsterdam*, **31 Mei 1913**, p. 137—153).

Eduard IJdo — Printer — Leiden.

H. KAMERLINGH ONNES. *Further Experiments with liquid helium. H. On the electrical resistance etc. (continued). VIII. The sudden disappearance of the ordinary resistance of tin, and the super-conductive state of lead.*

§ 13 [1]). *First observation of the phenomena. α.* Passing from the investigation of the super-conductive state of mercury to that of the change in the resistance of various other metals when they are cooled to helium temperatures, although I hoped to find more super-conductors, I did not think it likely, judging by our experiences with gold and platinum (see Comm. N⁰. 119, III and Comm. N⁰. 120, IV of this series) that we should be able to get more than a systematic survey of different cases of additive admixture-resistance (see Comm. VII of this series § 10). Very soon, however, the surprising results with tin and lead were obtained, which we mentioned in Comm. VII § 1 and § 12.

In the first place on Dec. 3rd 1912 we investigated a wire of pure tin, and perceived that this metal too, at helium temperatures became super-conducting.

The tin was of the specially pure kind supplied by KAHLBAUM. It was melted in a vacuum and poured into a glass capillary U-tube. The capillary tube had tin branches at either end, by which the conducting wires and the measuring wires were attached. The resistance at the ordinary temperature, 290° K., was 0.27 Ω.

We found that at the boiling point of helium a small ordinary resistance $1{,}3 . 10^{-4}$ Ω remained. At 3° K. this had disappeared ($< 10^{-6}$ Ω) and when the field of temperature between 4°.25 and 3° K. was gradually gone through, we found that the disappearance took place suddenly at 3°.78 K.

In order to be better able to judge of the micro-residual resistance, we tried to make a tin wire of greater resistance, in the same way in which we had formerly succeeded in making a long

[1]) The §§, tables and figures are numbered successively to those of Comm. VII of this series.

thin lead wire [1]). A steel core was covered with a substantial layer of pure tin, and turned down on the lathe. Then with a razorshaped chisel a thin spiral shaving was cut off [2]). This method, which seemed preferable to drawing (comp. § 14*a*) by which the metal might undergo a greater change, yields without difficulty wires of 0,01 mm². section. Several of these wires were then joined into one long wire by melting them on to eachother, during which it was necessary to carefully avoid the possibility of oxide being introduced into the surfaces to be united. The tin wires, one of which 1.75 m. long had a resistance of 19.2 Ω, and the other 1.5 M. long a resistance of 6,7 Ω, were wound upon glass cylinders, between a spiral of silk thread which separated the windings of the tin thread from eachother. Leading wires of tin fastened to the up turned ends of the wire, were lead downwards through the liquid and attached to copper wires. With these resistances immersed in liquid helium the sudden disappearance was observed when the temperature fell to 3°.806 K. (boiling under 47 cm. mercury pressure). At 3°.82 K. the resistance of one was still 0.0183 Ω, of the other 0.00584, at 3°.785 K. of both $<10^{-6}$ Ω. In this case too the highest limit for a possible micro-residual resistance was thus very low. We may put $\frac{w_{3°.8\,K.}}{w_{273°\,K.}} < 10^{-7}$.

Besides the sudden disappearance of the resistance of the wire, we also observed, as in the mercury thread, that for each temperature below the vanishing point a threshold value for the current density [3]) determined by this temperature, (in the case of the last mentioned wire the threshold current was 0.28 amp. at 3°.785 K.) could be fixed, below which the current passes without any perceptible fall of potential, and above which it is accom-

1) KAMERLINGH ONNES and BENGT BECKMAN. Comm. No. 132*c*. Dec. 1912.

2) A few of the tin wires first made did not become super-conducting; the inferior method of working the metal had perhaps caused additive admixture resistance, or more probably very insufficient continuity of material.

3) Concerning the dependence of the threshold value upon the dimensions of the wire and the conditions under which the heat is given off, further investigation is needed.

panied by potential phenomena, which (see § 14) increase rapidly with the increase of the excess of the current above the threshold value In a word, the tin wire behaves below the vanishing temperature of the tin, 3°.8 K., qualitatively precisely the same as a thread of mercury below the vanishing point of that metal.

β. Lead of KAHLBAUM, made into a wire in the same way as the tin, 1.5 m. long and 10.8 Ω resistance at ordinary temperature, when it was immersed in liquid helium appeared to be super-conducting, without the necessity of reducing the pressure at which the helium boiled. When the temperature was raised as far as the cryostat permitted, that is to 4°. 29 K. (the pressure was raised 11 cm. mercury above 76 cm.) the lead remained super-conducting. The temperature at which the ordinary resistance of the lead disappears will probably, as indicated in § 15, not be far above the boiling point of helium.

Whether this disappearance, as with mercury and tin, also takes place suddenly, has yet to be investigated. For temperatures below 14° K., where lead has still a relatively high ordinary resistance, and above 4°.3 K. where it has disappeared, we do not yet possess a satisfactory cryostat. At the temperature just mentioned of 4°.29 K. we found that the threshold value of the current was not yet reached at 1.3 amp.

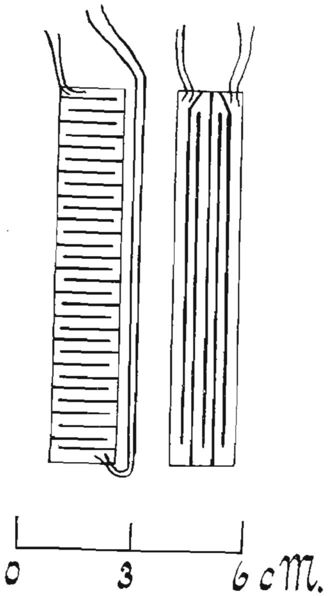

Fig. 8. Fig. 9.

γ. Besides lead and tin, amalgamated tin foil was investigated. We examined a layer of it spread out on a mirror glass, in which layer grooves were made in the manner shown in fig. 8. In helium boiling at atmospheric pressure, it appeared to have lost the ordinary resistance (2.3 Ω at 290° K.). At 4°.29 K. we found

0.12 amp. for the threshold value of the current, and a potential of 1.3. 10^{-6} volt, at 0.30 amp. 19.8. 10^{-6} volt, and at 0.363 amp. 34.6. 10^{-6} volt.

It is worth noticing that this tinfoil becomes more easily super-conducting than either tin or mercury. Perhaps the soft tin-amalgam, though a solid solution (of mercury in tin), has this property. This would only need to become a continuous whole in order to provide a nonresisting path for the current beside that of the free mercury (comp. § 9) or tin that might be present in the tin foil.

§ 14. *Further investigation of tin.* The further investigation of tin and lead does not form by any means a complete whole yet. Several of the measurements we had in view were failures, so that the results attained are very disconnected; nevertheless, in connection with our experiments with mercury, I think them worth communicating.

α. Methods of working the tin. In the previous § we said that working the tin into a spiral shaving did not interfere with the sudden disappearance of the resistance. What is of even more importance is that the rolling out of the wire to a thickness of 0.01 mm. has not any influence upon the super-conducting state either, so that we may feel confident that a very thin nonresisting tinfoil could be made [1]).

We must remark that in working tin, heating must be avoided. The increase of hardness which is caused in the drawing of metals by the compression and stretching, which is accompanied by an increase of resistance and decrease of the temperature coëfficient, is removed in gold and platinum for instance, by heating. With tin, on the other hand, heating is injurious, it causes the resistance to increase [2]), moreover, it causes thin wires to go into angular

[1]) The resistance of commercial tin foil, pasted on glass and cut out as in fig. 9, appeared not to become zero.

[2]) According to TAMMANN and his school, the crystals are shattered by wire drawing, and arranged in such a way that in the cases meant the resistance increases. By heating, larger crystals are again formed, and the resistance resumes its original value. In the investigations of KAMERLINGH ONNES and CLAY, (Comm. No. 99*b*, § 4, June 1907), it is pointed out that the additive resistance of platinum and gold wires is always found greater by continued drawing even after heating to glowing. We attributed this to the acquiring of admixtures through the drawing. In gold it is possible to test for such small quantities of admixture as are here of importance. In gold wires carefully drawn by HERAEUS, (Comm. no. 99*c* § 2, June 1907), under repeated treatment with acids, larger quantities of admixtures were found in proportion as the resistance fell less at reduction to hydrogen temperatures At the same time it is possible that the drawing itself has an influence. HENNING (Ann. d. Phys. 1913), thinking as we do, attributes the difference found with his platinum thermometers in the temperature coefficient from that found by us, to a larger amount of admixtures in our thermometer. The difference becomes greater still, when we consider that HENNING's wire (0.05 m.m.) was drawn out further than ours (0.1 m.m.) (which is of importance in the application to thermometry). As mentioned above and as we found confirmed in comparing the wires Pt_I (0.1 mm.) and Pt_d (0.05 mm.), thinner wires fall less in resistance, a result by which we also explained, l. c. why HOLBORN's thick wires (0.2 mm.) showed a greater fall than ours. Our wires were at the time most carefully drawn by HERAEUS from the purest platinum supplied by him. The platinum obtained by HERAEUS later on may have been even purer. Improvement may also have been made in the method of drawing the wires.

forms [1]). The threads we used were, therefore, not heated after being worked, and showed regular curvatures when bent.

β. Potential phenomena in the super-conducting state. The following observations allow us to judge of the highest limit of the possible micro-residual resistance, and of the potential differences above the threshold value of the current density just below the vanishing point. They were made with a branching tin wire exactly like the one used in the experiments with mercury of Table IV and V in Comm. VI of this series, § 6 and 7. The resistance consisted of a principal wire W_C 4 M. long, and mainly 0.0097 mm². section [2]) with two sentinel wires W_{SA} and W_{SB} [3])

[1]) Where broken, tin wires exhibit comparatively large crystals. See also § 15, note 1.

[2]) In this investigation the section is deduced from the length of the wire and the resistance at ordinary temperature. We only ascertained, whether this agreed approximately with the result of direct measurement. The values given are therefore only to be considered as rough mean values.

[3]) The object of the sentinel wires was the same as in VII § 6. We had namely calculated on sending much stronger currents through than we actually did, and on that supposition it was necessary to make sure that no JOULE heat penetrated to the wire from elsewhere.

of 0.8 M. length and about 0.02 mm². section, wound round a glass tube and insulated with silk. We found, (Febr. 1913) [1]):

TABLE VIII.

Resistance of a bare tin wire at, and a little below 3°.8 K. Section of w_C: 0.0097 mm².

T	w_{SA}	w_{SB}	w_C
	Current density 0.61 amp./mm². in C		
3°.85 K.	6.84 . 10^{-3} Ω	6.50 . 10^{-3} Ω	69.6 . 10^{-3} Ω
.82	5.50	0.90	34.9
.79	2.82	0.03	1.23
.785	1.5	0	0
.78	0.7	0	0
.75	0.15	0	0
.74	0.02	0	0
.72	0	0	0
	Current density in C 154 amp./mm². (and higher ?)		
1°.6	0	0	0

With a coil of 252 windings of tin wire insulated by picëin (see § 16) of 0.014 mm². section, (with pieces of 0.02, 0.012 and 0.03) and 79 Ω resistance at ordinary temperature 290° K., the disappearance of the resistance was followed, at three different current strengths as in § 8 was done with mercury. We found:

[1]) In one of the sentinel wires W_{SA} there is obviously a thinner place which causes locally a much greater current density than the mean. Probably the same case occurs here as in the experiments with mercury in Table IV, but here the disappearance of the resistance at lower temperature makes it improbably that the tin wire should be interrupted by a foreign resistance.

TABLE IX.

Disappearance of the resistance of a tin wire, under reduced giving off of heat, at different currents.

T	0.004 amp.	0.04 amp.	0.4 amp.	0.6 amp.	1.0 amp.
3°.82 K.	0.0533 Ω	0.0535 Ω	0.0536 Ω		
.805	500	534	536		
.79	488	533			
.785	425				
.78	162	508			
.765	0.00137				
.75	0.00005	0.0039			
.74	1	14	0.0532		
.72	0.000000	0.00025			
.70					
.68		0.000012			
.66		0.000000	0.0050		
.64					
.54			38		
.42			22		
.28			10		
.12⁵			0.0002		
2.69			0.000012		
.35			0.000000		
1.6				0.000000	great

This table gives in general the same as fig. 6 and 7 of § 8. The disappearance of the resistance extends over a much larger field of temperature than with the mercury thread, probably because the giving off of heat is considerably reduced by the winding up of the wire protected by picëin; which is probably also the reason why at the lowest temperature the strength of the current cannot be raised above 0.8 amp. and the threshold value of the current density therefore only reaches 56 amp/mm².

γ. Experiments concerning the influence of the contact with an ordinary conductor of a metal which can become super-conducting, upon its super-conducting properties, were in continuation of those of § 10 made with tin in two different ways, first with a german silver tube, which was tinned, and through the layer of tin of which a spiral was cut, and second with a constantin wire which was tinned. In the first experiment the resistance did not disappear, in the second, as already said in § 10, it did; from which we conclude that the continuity of the layer of tin in the first case was not sufficient. In the second experiment the threshold value was, however, also very low, even at the lowest temperature 1.°6 K. it remained below 0.095 amp. for the bare wire immersed in liquid helium. It is simplest to assume in the mean time, that the layer of tin becomes super-conducting, but that the section of it, which was: deduced from the resistance 0,0125 mm²., according to measurements down to 0,1 mm²., here and there was very small. There was in this case no reason to suppose a want of contact between tin and constantin, as in the corresponding experiment with mercury between it and the steel.

§ 15. *Further examination of lead.* In the first place we will mention a few experiments on the heating of a wire which was at a temperature below the vanishing point, which correspond to those in Table VI for mercury. The lead resistances were arranged exactly like the tin resistances described in § 14, the bare wires were wound upon glass between silk. With a wire of 0.025 mm². section (10.8 Ω resistance at ordinary temperature) containing six joints, which were made with a miniature hydrogen flame, we ascertained that joints do not interfere with the experiments. The results (Febr. 1913) with one of the wires (92 Ω at ordinary temperature) are contained in Table X (the observations were confirmed later on repetition).

TABLE X.

Potential differences in a lead wire carrying a current $l = 6$ m., section $= 0.014$ mm².

T	Current density in amp./mm².	Potential difference in microvolts.
1°.7 K	560	0.0
	645	0.2
	675	3.5
	695	5
	710	6
	720	10
	750	19
	791	± 40
	> 790	very great

A similar experiment with the wire containing six joints at less low temperature gave:

TABLE XI.

Threshold value of current density for bare lead wire of section 0.025 mm².

T	Threshold value in amp. mm².
4°.25 K.	> 420
	< 940

At a current density of 940 the wire was dammaged (calefaction?) and upon repetition it appeared that is was broken.

Similar conditions of external conduction of heat to those of the tin coil described in § 14, prevailed in a lead wire (see § 16) of 1000 windings (resistance at ordinary temperature, 290° K., 773 Ω) insulated by silk soaked in liquid helium. We found:

TABLE XII. Potential difference in a lead wire carrying a current with reduced external conduction of heat. $l = 55.5$ m. section $= 0.014$ mm².		
T	Current density in amp./mm².	Potential difference in microvolts.
4°.25 K.	33	0.03
	36	0.65
	38	1.75
	40.2	7.35
	41.3	22.0
1°.7	60	3.7

Judging by this we may perhaps estimate that the lower limit of the threshold value at 4°.25 K given above cannot be raised much, and that the vanishing point for lead lies at about 6° K.

Further, measurements were made with lead wires placed in a vacuum, the object of which is obvious by § 12. The apparatus which served for this consist (see fig. 10 and fig. 11, face view and diagram of *d* with detail figures) of a glass reservoir immersed in liquid helium, carried by a long narrow glass tube fixed into the lid of the cryostat. The reservoir *d* can be evacuated through the tube *c* (the tap *a* allows it then to be connected to a tube filled with charcoal which is immersed in liquid air); through the indicator gauge *b* we can make sure that the apparatus is not cracked in cooling.

In the apparatus shown in the fig. there are two lead wires (see diagram); we were only able to do the measurements with one. Four short tubes are blown into the upper part of the reservoir to receive the lead wires (see detail figures); upon these tubes after platinizing and copperplating caps are soldered with tin into

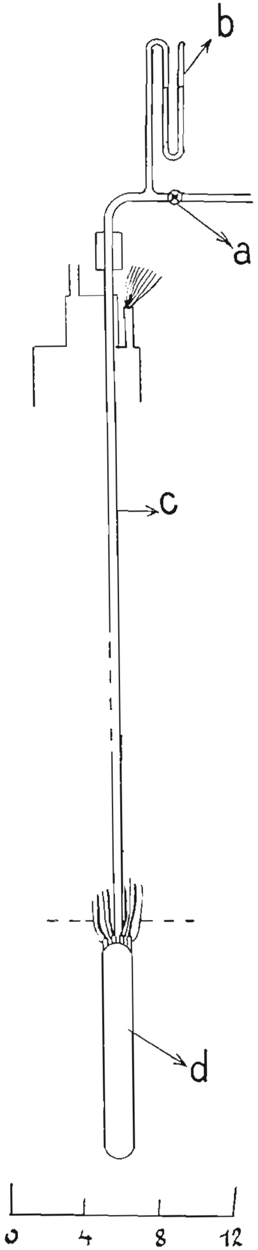

Fig. 10.

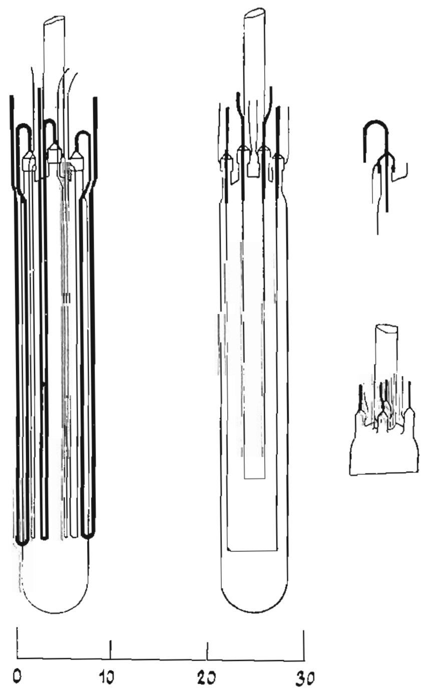

Fig. 11.

which the thicker top ends of the wires are soldered with WOOD-metal [1]).

Rolled out lead wires are fastened to the wires that project from the covers, and run down along the reservoir, insulated from each other with silk and then up again through the liquid helium.

We found with a part of the wire of Table XI:

TABLE XIII.

Threshold value of current density of a lead wire in vacuo; section $^1/_{70}$ mm^2.

T	Current density in amp./mm^2.
4°.25 K.	> 270

The experiment is incomplete as the threshold value was not reached.

We made similar apparatus with tin wire; the observations with tin in vacuo have, however, not succeeded yet.

§ 16. *Remarks in connection with the experiments with tin and lead.*

α. Our results with tin and lead make it seem probable that all metals, or at least a class of them, if they can be procured sufficiently pure, pass into the super-conducting state when reduced to a low enough temperature. Perhaps in all it would also be suddenly. But the additive admixture-resistance which can be caused by mere traces of admixtures, will in general make the detection of the phenomena a difficult one.

β. A number of experiments with resistance-free conductors

[1]) It is not possible to solder tin wires into the covers with WOOD-metal: as coming in contact with the tin the melted WOOD-metal, as it seems, penetrates by capillary action amongst the tin crystals which makes the wire brittle and break in two. The tin wires must therefore be melted to the tinned covers, which is possible, by them being provided like the lead wires with sealed on thicker ends.

of which several suggest themselves at once, now that we can use the easily workable super-conductors tin and lead, can be undertaken with good prospect of success [1]).

In this way the preparing of nonresisting coils of wire, with a great number of windings in a small space, changes from a theoretical possibility into a practical one. We come to new difficulties when we want not only to make a nonresisting coil but to supply it as a magnetic coil with a strong current [2]).

I have been engaged for some time making a preliminary estimation of these difficulties/ (3)

The coils mentioned in § 14 and § 15 were made chiefly for this purpose. The first of tin wire insulated with picëin, contained on 1 cm. length in a layer of 7 mm. thickness 300 windings of $^1/_{70}$ mm^2. section (the resistance at ordinary temp. was 79 Ω). While a current of 8 amp. could be sent through the wire before it was wound when immersed in liquid helium, without reaching the threshold value of current density (see § 14) the coil came to the threshold value at 1.0 amp. The number of ampere windings per cm^2. of a section through the axis was about 400. The second coil was wound of lead wire of $^1/_{70}$ mm^2. section, and contained in a length of 1 cm. 1000 windings in a layer of 1 cm. thickness. The resistance at ordinary temperature was 773 Ω. The insulation of the wires in each layer was obtained by silk threads, between the different layers a thin piece of silk was placed. I thought that the liquid helium penetrating into the coil through this texture would cause the heat to be given off more easily all over the coil, while it was not certain (comp. the remarks about mercury in glass in § 7 and § 11 Comm VII of this series) that the picëin remained adherent to the tin wire everywhere. Through this coil a current of 0.8 amp.

[1]) In our first paper about the disappearance of the resistance of mercury we mentioned that this opened a new field of experiment. That mercury is liquid at ordinary temperature was, however, a serious hindrance to entering it.

[2]) A coil of this kind one would wish to place in the interferrum of a very large electromagnet of WEISS, in the same way as the auxiliary coils contemplated by him, in order to further raise the field. The field that is added by the coil would in that case have to be greater than what would be sacrified by enlarging the interferrum to make room for the cooling appliances.

[3]) A possible difficulty was pointed out in note 2 § 4.

(see § 15) could be sent, without the threshold value being reached. The number of ampere windings per cm^2. was then about 800. If the disturbing potential phenomena had not been greater than with the shorter wire of the same section which was washed by liquid helium over its entire surface, and if the difficulty mentioned in note ~~2 § 4~~ does not come into play, it would have been possible to supply this coil with up to 9000 ampere windings per cm^2. If, therefore, the potential phenomena which frustrated this in the experiment reported, in accordance with the opinion expressed in Comm. N^0. VII of this series, particulary in § 11, may be ascribed to "bad places" in the wire, and if we may therefore be confident that they can be removed (for instance by fractionising the wire) and if moreover the magnetic field of the coil itself does not produce any disturbance (note ~~2 § 4~~) then this miniature coil may be the prototype of magnetic coils without iron, by which in future much stronger magnetic fields may be realised than are at present reached in the interferrum of the strongest electromagnets [1]).

[1]) J. PERRIN (Soc. d. phys. 19 Avril 1907) made the suggestion of a field of 100000 gauss being produced over a fairly large space, by coils without iron, cooled in liquid air. CH. FABRY (Journ. d. Phys. Febr. 1910) worked out this idea. He finds that the energy absorbed in such a coil, in watts is represented by the formula

$$W = \rho \eta \, a H^2 K^{-2}$$

where a is a length in centimetres, which determines the size of the coil, for a cylindrical one the radius of the internal space, η the ratio of the metallic area in a section through the coil at right angles to the windings to the area of this section, K a purely numerical coefficient, which depends upon the form of the coil, and which in cylindrical coils with wire of equal section does not differ much from 0,18, ρ the specific resistance of the metal of the windings in ohms. centrimetre, H the magnetic field in gauss.

In order to get the desired field of 100000 gauss in a coil with an internal space of 1 cm. radius, with copper as metal, and cooling by liquid air 100 kilowatt would be necessary, putting K at 0,20 and η at 1,5 (which last number might well be 6 times as large). The electric energy supply, as FABRY remarks, would give no real difficulty, but it would arise from the development of JOULE heat in the small volume of the coil to the amount of 25 kilogramme calories per sec. which in order to be carried off by evaporation of liquid air would require about 0,4 litre per second, let us say about 1500 litres per hour.

We may add to FABRY's objection that the preparation of 1 litre of liquid air

γ. Certainty that the potential phenomena observed are due to such imperfections in the wire would be of no less value for another tempting group of experiments. As soon as the super-conductivity of mercury was established, the question forced itself upon me, in connection with the great value which according to the electron theory of metals is ascribed to the free path of the electrons [1]) (comp.

per hour is at present to be reckoned as requiring not much less than $^1/_2$ K. W. According to this standard, 7 times as much work would be necessary for the cooling than for the current. By a judicious use of the cold of the vapours this number can be reduced, but the proportion will remain unfavourable.

Moreover, as FABRY shows, the dimensions determined by a, to make it possible for the heat to be carried off, would need to be much larger, by which at the same time the amount of liquid gas used becomes greater. The cost of carrying out PERRIN's plan even with liquid air might be about comparable to that of building a cruiser!

If we calculate in the same way the cooling with liquid hydrogen in the case of silver and if we assume that the resistance of silver (according to KAMERLINGH ONNES and CLAY) at the boiling point of hydrogen is 0,009 of that at the ordinary temperature, we arrive at a more favourable figure, namely, that at $a = 1$ cm., 700 liters of liquid hydrogen would be needed per hour, but the ratio of cooling work and electric work becomes more unfavourable yet, putting the preparation of a litre of liquid hydrogen in the same way as above at $1\,^1/_2$ K. W. But the figure for liquid hydrogen would also on the ground mentioned above have to be considerably increased. Although an installation which will give as much liquid hydrogen as is necessary for the cooling could be made after the pattern of the present Leiden plant, it would be of such an extraordinary size that with liquid hydrogen also, the method described perhaps involves more difficulties than a further increase of the size of the coil, in order to be able to cool with running water (as introduced by WEISS) while this method also has its advantages with a view to the use of the field.

The possibility of using the super-conductors tin and lead, gives a new departure to the idea of PERRIN of procuring a stronger magnetic field by the use of coils without iron. With super-conductors no JOULE heat needs to be carried off (or at any rate only 10^9 times less than with ordinary conductors) and thus with currents below the threshold value the difficulties mentioned above disappear. If the conditions mentioned in the text can be fulfilled, then even a coil of 25 cm. diameter of lead wire, constructed as the one in § 15, immersed in helium, could give a field of 100000 gauss, without perceptible heat being developed in the coil. Some such apparatus could be made at Leiden if a relatively modest financial support were obtained. In the mean time this remark may serve to put the problem of very strong magnetic fields which are becoming indispensable for various investigations in a new form.

[1]) Comp. note 3 p. 26. Leiden. Comm. No. 119. Febr. 1911.

§ 12 β), whether electrons moving at speeds by which they cannot penetrate a thin plate, e. g. a LENARD's window of solid mercury, at the ordinary temperature [1]), or at least not without a change of direction, would be able to do this better if the foil were super-conductive. Now that super-conducting plates of tin and lead can be made the experiments on this subject are made practicable, and the plan of making these has assumed a promising form, since I have obtained the prospect of doing it with LENARD himself, which I highly value. If the potential phenomena are caused by local disturbances, we may expect that in experiments with thin plates, by a correct choice of the places to be experimented upon, they will be of little importance. If, as might be imagined according to § 4, the potential phenomena are connected with peculiarities in the movements of the electrons, then they would be of prime importance in phenomena such as we have here under consideration.

δ. The correspondence of the potential phenomena in tin and lead to those in mercury is very striking. As regards tin, it was remarked upon in § 13α, and further investigation has confirmed it and also extented to lead. All the considerations with regard to them for the case of mercury can thus immediately be applied to tin and lead. On the other hand the latter may serve to elucidate the doubtful points in mercury.

With the bare tin wires at 4°.25 K. measurements were made which acquaint us with the amount of heat, given off to the liquid helium above the vanishing point; whether it is proportional to the surface of the wire, as is to be expected, when the heat is mainly given off to the liquid, could not be settled yet. With the rolled out tin wire, with which the various measurements were successful, it was great, which corresponds to the fact that here the ratio between the heat-conveying surface and the heat developed is very favourable. It was estimated at 0.5 watt per 1 difference of temperature. Still at 1°.6 K., 1.4 microwatt caused a local rise of temperature to the vanishing point. As in § 11 we deduce from this that the whole development of heat is local. The hypothesis that in this way „bad places" show themselves

[1]) Whether the same electron passes through, or whether the movement is carried from the one to the other, does not affect the experimental question.

is confirmed by the fact that through a wire like this at the boiling point of helium, therefore above the vanishing point, a current of 9 amp. could be sent, and all the Joule heat was absorbed by the liquid helium, while with a current only a little stronger the wire gave way (presumably by the forming round the wire of a vapour bubble in the helium, which caused calefaction in the wire).

The different threshold values for the bare lead wire and the lead coil § 15, and for the bare tin wire and the tin coil § 14, may throw light upon the influence of more or less easy conditions of heat loss. The phenomena at the disappearance of the resistance with the bare tin wire with sentinel wires make the hypothesis followed out in § 12 improbable, namely that the mercury below the vanishing point comes away from the glass or at least does not give off heat to it at a difference of temperature. The correspondence of the disappearance of the resistance in the tin wire with sentinel wires and in the mercury thread is explained most simply by assuming a local rise of temperature in both, while for both below the vanishing point the same opportunity remains for giving off heat, but does not take place owing to absence of rise of temperature.

Here, therefore, the "bad places" mentioned in § 11 (comp. § 12α, note 1 p. 41) would again remain as the sole explanation. It is however suspicious that in the coil of lead wire at 1°.6 K. 56 amp./mm^2. was found as the threshold value, while with lead in a vacuum 270 amp./mm^2. at 4°.26 K. was reached without a trace of potential phenomena.

Finally we point out that the threshold values of current density far below the vanishing point in the wires of the three different metals differ very little. We found for the highest limit of the possible micro-residual resistance determined by the threshold value in proportion to that at the ordinary temperature

$$\text{with mercury} \quad \frac{w_{2^\circ.45\,\mathrm{K.}}}{w_{273^\circ\,\mathrm{K.}}} < 2.10^{-10}$$

$$\text{tin} \quad \frac{w_{1^\circ.8\,\mathrm{K.}}}{w_{273^\circ\,\mathrm{K.}}} < 6.10^{-10}$$

$$\text{lead} \quad \frac{w_{1^\circ.8\,\mathrm{K.}}}{w_{273^\circ\,\mathrm{K.}}} < 0.5\ 10^{-10}$$

In view of so much correspondence and such regularity of the character of all the potential phenomena, it still remains doubtful whether besides the disturbances which we have adduced to explain them, there may not be at the bottom of them peculiarities in the movement of the electrons, which may be more clearly revealed by the experiments indicated in γ.

Having completed the series H of my experiments with liquid helium I wish to express my thank to Mr. G. Holst, assistant at the Physical Laboratory, for the devotion with which he has helped me, and to Mr. G. J. Flim, chief of the technical department of the cryogenic laboratory, and Mr. O. Kesselring, glassblower to the laboratory, for their important help in the arrangement of the experiments and manufacturing of the apparatus.