Citation:

H. Kamerlingh Onnes, Further experiments with liquid helium. II. On the electrical resistance etc. VIII. The sudden disappearance of the ordinary resistance of tin, and the super conductive state of lead, in: KNAW, Proceedings, 16 II, 1913-1914, Amsterdam, 1914, pp. 673-688 an *ideal mixture*, again leaving molecular rotations and intramolecular motions out of account, may be easily derived if GIBBS' theorem, according to which the entropy of such a mixture is obtained by calculating the entropy for each component as if it were present by itself in the volume occupied by the mixture and adding the values so obtained, is supposed to remain valid when the equipartition laws no longer hold. We then obtain:

α. for *low temperatures*

$$S = aT^3 V^2 \Sigma \frac{M_1^3}{c_1}, \quad \ldots \ldots \ldots \quad (16)$$

β. for *high temperatures*, retaining the first term which gives a deviation from the equipartition laws:

$$S = Nk \left\{ \frac{3}{2} \ln \beta T V^{2/3} + \frac{3}{2} \Sigma c_1 \ln M_1 - \Sigma c_1 \ln c_1 + 4 + \frac{1}{700} (\beta T V^{2/3})^{-2} . \Sigma c_1^{7/3} M_1^{-2} \right\} \quad \ldots \ldots \quad (17)$$

If at constant volume the temperature continually decreases, at sufficiently low temperatures (for densities of the order of magnitude of the normal density at extremely low temperatures, cf. Suppl. N°. 30*a* § 5*b*) a positive deviation from the equipartition value begins to develop itself. This deviation finally causes the entropy for a mixture also to approach to 0 proportionally to T^3 as shown by (16) instead of becoming $-\infty$.

Physics. — "*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.*" By Prof. H. KAMERLINGH ONNES.

(Communicated in the meeting of May 31, 1913).

§ 13 [1]. *First observation of the phenomena. a.* 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 from our experiences

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[1] The §§, tables and figures are numbered successively to those of Comm. VII of this series. (These Proceedings May and June 1913).

with gold and platinum (see Comm. N°. 119, III and Comm. N°. 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 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 mm^2. 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 each other. Leading wires of tin fastened to the up turned ends of the wire, were led downwards through the liquid and attached to copper wires. With these resistances immersed in liquid helium the

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[1]) KAMERLINGH ONNES and BENGT BECKMAN. Comm N°. 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.

sudden disapparance 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

$$\frac{w_{3^\circ 8\,K}}{w_{273^\circ K}} < 10^{-7}.$$

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[1]) 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 accompanied 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 superconducting, 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.

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[1]) 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.

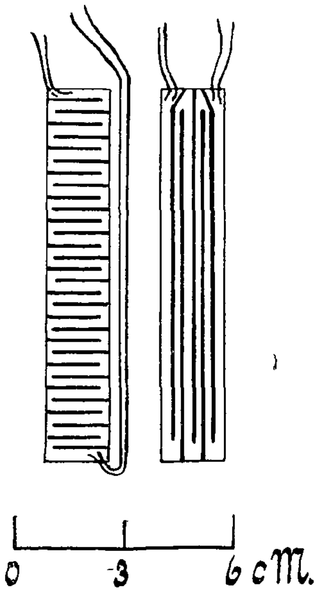

Fig. 8 Fig. 9

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 amalgamated tinfoil becomes more easily superconducting 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.

a. 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

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

increase of resistance and decrease of the temperature coefficient, 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 [1]), moreover, it causes thin wires to go into angular forms [2]). 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 [3]) with two

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[1]) 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. N⁰. 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. N⁰. 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 mm.) was drawn out further than ours (0.1 mm.) (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.

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

[3]) 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.

sentinel wires W_{SA} and W_{SB} [1] of 0.8 m. length and about 0.02 mm^2. section, wound round a glass tube and insulated with silk. We found, (Febr. 1913) [2]:

TABLE VIII.

Resistance of a bare tin wire at, and a little below 3°,8 K.
Section of w_C: 0.0097 mm^2.

T	w_{SA}	w_{SB}	w_C
	Current density 0.61 amp./mm^2 in C.		
3°.85 K.	$6.84 . 10^{-3}\,\Omega$	$6.50 . 10^{-3}\,\Omega$	$69.6 . 10^{-3}\,\Omega$
.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./mm^2 (and higher?)		
1°.6	0	0	0

With a coil of 252 windings of tin wire insulated by picëin (see § 16) of 0.014 mm^2. 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:

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[1] 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.

[2] 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 improbable 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		
.12^5			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/mm^2.

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., was very small here and there. 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

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

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).

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 it 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

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

1000 windings (resistance at ordinary temperature, 290° K., 773 Ω) insulated by silk soaked in liquid helium. We found: (See table XII p. 681).

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.

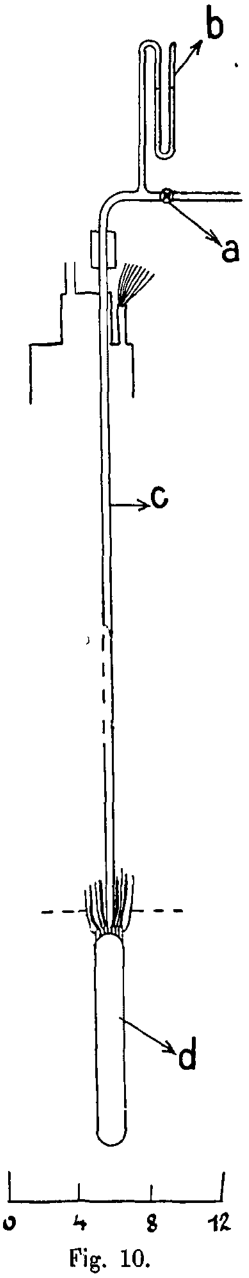

Fig. 10.

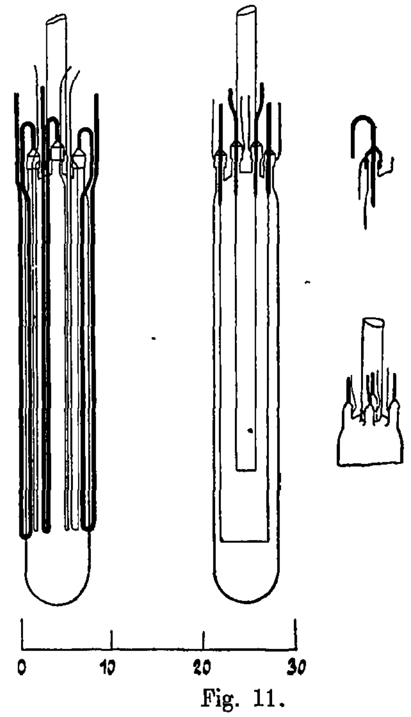

Fig. 11.

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 consists (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 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 $^1/_{70}$ mm².

T	Current density in amp/mm²
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.*

a. Our results with tin and lead make it seem probable that

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[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 their being provided like the lead wires with sealed on thicker ends.

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 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 piceïn, 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 $^1/_{7.0}$ 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

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[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.

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. (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, particularly 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]).

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[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 Févr. 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 centrimetres, 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. centimetre, 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 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

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. § 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 temperatures near the ordinary temperature [2], or at least not without a change of direction, would be able to do this better if the foil were

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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 new form.

1) Comp. note 3 p. 1113. Leiden. Comm. N^0. 119. Febr. 1911.

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

superconductive. 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 stated already in § 13*a*, and further investigation has confirmed it and also extended 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 degree 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 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. § 12a, note 1 p. 118) 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

$$\text{with mercury} \quad \frac{w_{2^{0}45K}}{w_{273^{0}K}} < 2.10^{-10}$$

$$\text{tin} \quad \frac{w_{1^{0}8K}}{w_{273^{0}K}} < 6.10^{-10}$$

$$\text{lead} \quad \frac{w_{1^{0}8K}}{w_{273^{0}K}} < 0.5\ 10^{-10}$$

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 thanks 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.