THE

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AND THE QUANTA.

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ON THE

ELECTRICAL RESISTANCES

By M. KAMERLINGH ONNES.

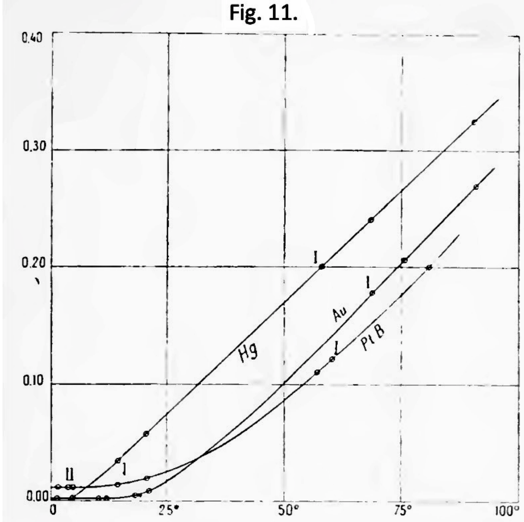
Translated from the original text in French by Dirk van der Marel, 20.09.2021

I believe I should attribute the limit value for the electrical resistance of aluminum, found by M. Nernst, to impurities of this metal. I have observed influences of this kind for platinum and gold by operating down to the temperature of liquid helium [1]. It results from research which I carried out formerly with the collaboration of Mr. Clay at the temperature of liquid hydrogen that the limit resistance will be all the smaller as the metal is more pure. Mercury can be obtained more easily than other metals in the state of extreme purity. You can go so far in this direction that there is no longer any resistance due to impurities. The resistance of extremely pure mercury becomes practically zero and it would probably be the same for perfectly pure platinum or gold.

In this connection, I would like to give some indications about my research on the resistance of mercury down to extremely low temperatures.

1. See Communic. fr. the physical Laboratory at Leiden, N^{os} 119, 120, 123.

Fig. 11.



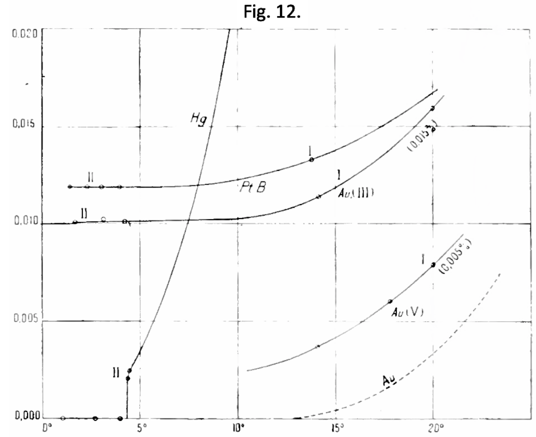
This research is part of a series of projects that stared long ago on the peculiarities which appear in a large number of phenomena at temperatures close to the melting point of hydrogen and below this point. I generally attributed these peculiarities to a kind of freezing of electrons on atoms. Observation of the resistance of mercury can perhaps provide more precise indications on this subject. Probably, we will have to consider this freezing of electrons on atoms as corresponding to the stopping of certain Planck oscillators.

Figure 11 shows the variations, with temperature, of the resistance of platinum, gold and mercury below -100^o C.

For solid mercury, we have accepted as resistance at 0^o C, the value obtained by extrapolation of the experimental results below -100^o .

The figure contains first of all the results obtained previously by Mr. Clay and me down to the temperature of liquid hydrogen ; the corresponding points are marked I. The curve relating to mercury does not yet reach, at the temperature of liquid hydrogen, the inflection point which is found on the others and which seems to reveal for metals the existence of corresponding states. The curves relating to the two other metals already show in liquid hydrogen a very clear curvature, which approaches the abscissa and which should, according to my previous views conform to those of Kelvin and developed in a way by Koenigsberger, be followed by a rise when cooling down to even lower temperatures. The figure is completed by the results of my research, marked II, at the temperature of liquid helium. When I made the experiment on platinum, at the temperature of liquid helium, I had well thought that instead of showing the expected increase, the resistance could, when the temperature approaches absolute zero, tend towards a limit value or even towards zero. However, my surprise was very great when I noticed that in the vicinity of the temperature of liquid helium, the resistance of the platinum wire Pt B in the figure, became

Fig. 12.



independent of the temperature, as shown in figure 12 (including the scale is 5 times greater) : all the more so since, from the influence of the impurities shown by the curves relating to various gold samples, it must be concluded that the resistance of the pure metals (including in the figure the curves for gold with various amounts of impurities and the dotted line accepted for pure gold) would already be practically (i.e. up to values which are attributable to unavoidable impurities) zero at temperatures above absolute zero (see figure 13 in which the resistance scale is 20 times greater).

These new results do not allow to suppose that the free electrons freeze on the atoms, but seem to indicate that the obstacles to the movement of the electrons disappear. The fact that this disappearance occurs above absolute zero suggested an application of quantum theory analogous to that made by Einstein and Nernst to explain the disappearance of specific heat. It suffices to admit that the obstacles to the movement of electrons in pure metals come from the agitation of Planck's oscillators. From this point of view, one could predict the approximate variation of resistance as a function of temperature by introducing Planck's considerations into the Riecke-Drude-Lorentz theory. The influence of the obstacles must also be considered as proportional to the speed or the amplitude of the movement of the oscillators, therefore proportional to $\sqrt{E}$ where E is the energy defined by Planck's formula.

From this follows

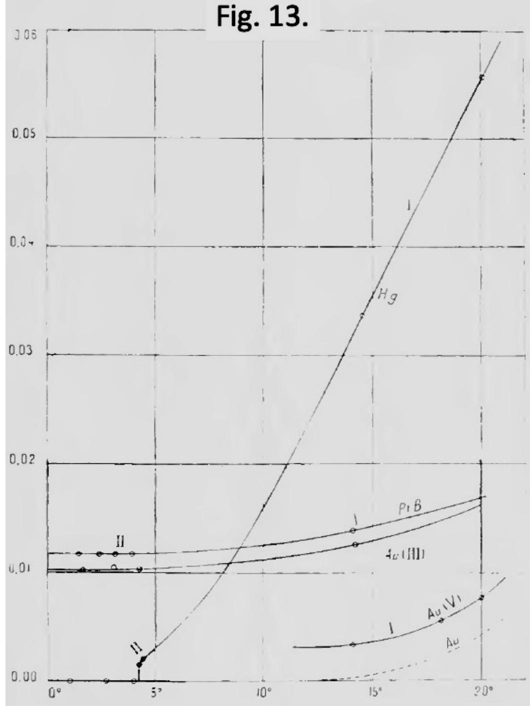
$$\frac{W_1}{W_{273}} = \frac{\sqrt{273}\sqrt{E_{273}}}{\sqrt{T}\sqrt{E_T}}$$

with

$$E_1 = \frac{\beta\nu}{e^{\beta\nu/1} - 1}$$

This representation agrees with the facts for the frequencies ν which do not deviate too much from those calculated by the elasticity data and which are suitable for the calculation of specific heats, and this fact increases the probability that the theory of quanta is applicable here.

Fig. 13.



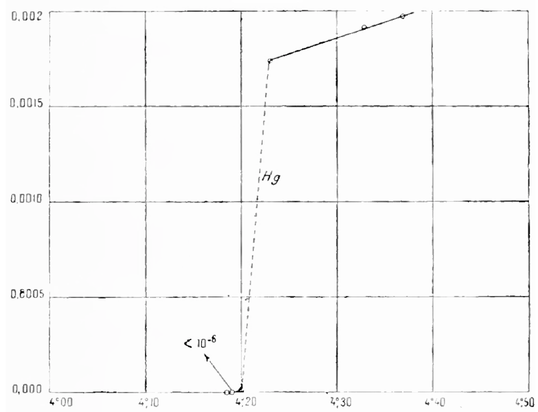
It was thus possible to predict how the mercury resistance should behave.

According to calculations at $4^o.25$ absolute, the boiling point of helium, the resistance of pure mercury must still be appreciable and must be practically zero at 3^o absolute. It could also be expected that mercury could be obtained pure enough to allow verification. The result confirmed this prediction.

The mercury has been purified as perfectly as possible by distillation in liquid air. After freezing in a capillary glass tube, the mercury wire thus obtained was placed in communication at each end with two mercury wires obtained by the same process and which served, one to send current into the resistor, and the other to measure the drop in potential. The results are shown in Fig. 13. It can be seen that the resistance at 3^o absolute is smaller than $1/1,000,000$ of its value at 0^o C. New research suggests that this limit can be lowered further. For a lowering of the temperature down to 2^o absolute the resistance remains below this limit. Despite this confirmation, I consider the formula above as only a crude attempt to apply quantum theory. It can therefore not be stated that the oscillators considered here are the same as the ones corresponding to extremely long wavelengths observed by Rubens in the radiation of the mercury arc. One can only notice that they are not very different.

According to the most recent research on the way in which resistance disappears, certain characteristics have been shown which do not fit into the proposed explanation and whose origin I have not yet fully analyzed.

Fig. 14.



I cannot yet fully explain myself on this point. However, it seems certain that, as shown in figure 14 displayed on a scale 200 times larger than in figure 11, the resistivity of mercury undergoes, a little below the boiling bridge of helium, a very rapid decrease and almost a discontinuity which produces the disappearance of the resistance above the temperature predicted by the formula stated above.

I would like to make a few more observations :

1^{o} The interesting formula which M. Lindemann gave at the same time as I published mine only yields quantitative conclusions, as its author indicates, if the theoretical calculation of constants is replaced by an empirical determination. Again a residual resistance is introduced. If we take into account the fact that the limit resistance of pure metals is practically zero, Mr. Lindemann's formula is transformed into the empirical law proposed by Nernst when, to make it applicable to pure metals, we canceled in it the residual resistance. The limit resistances which can remain in the case of pure metals are probably an order of magnitude smaller than the limit resistances which appear in the empirical formula of Nernst and which must be attributed to impurities.

2^{o} One can notice that the way, not yet explained, it is true, in which alloys behave could predict the invariability at very low temperatures of the residual resistance attributable to impurities.

DISCUSSION OF THE REPORT OF M. KAMERLINGH ONNES.

M. Langevin. – I would like to ask Mr. Kamerling Onnes if the very rapid variation which occurs in the neighborhood of 4^o absolute in the conductivity of mercury does not correspond to a change of state accompanied, for example, by a sudden variation of volume. It is a common fact that the changes in volume which occur during fusion, for example, are accompanied by an enormous change in conductivity, probably as a result of a change in the number of free electrons. Any contraction corresponds to an increase in this number, and there is reason to wonder whether the enormous increase in conductivity observed by M. Onnes is not the consequence of such a contraction. The discontinuity in the variation of resistance may result from a discontinuity in the variation of the number of free electrons, or, as M. Onnes supposes, from a rapid variation, determined by the formula of M. Planck, in the agitation of these electrons.

M. Kamerling Onnes. – I would have liked to have already been able to measure at these low temperatures the calorific conductivity, the specific heat, the density, the expansion and the elasticity of mercury. These measurements were called for first of all by the theory which I had used (see Communication n^o 119 from the Leyden Physics Laboratory), a theory which, moreover, I consider only a sketch of the way in which we can include Planck's vibrators in the deduction of conductivity in the theory of electrons. But I haven't gotten that far yet. I therefore cannot answer Mr Langevin's question yet.

It is possible that this is a change in volume, appreciable, which would give as a secondary result an increase in conductivity. This increase should then be much greater than in analogous cases. It is also possible that the modification consists mainly in the change of the period of the vibrators which I have just mentioned. When their frequency would change, for example, from single to double, the conductivity would already be greatly increased according to the accepted formula.

In any case, the new state of mercury is distinguished from that above $4^o.2$ K by a quite extraordinary conductivity.