Physics. "*Further experiments with liquid helium. L. The persistence of currents without electro-motive force in supra-conducting circuits.*" (Continuation of J). By Prof. H. KAMERLINGH ONNES. Communication N°. 141*b* from the Physical Laboratory at Leiden.

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§ 9. *The preservation of an electro-kinetic momentum.* All the phenomena that were dealt with in the preceding sections (J) [1]) showing the persistence of the magnetic moment of the coil, without the action of an electro-motive force, agree with what was deduced on the supposition that a current flows through the coil of the value calculated, and which diminishes according to the time of relaxation calculated. At the same time, it was desirable to have a conclusive proof that the magnetic moment of the coil is really caused by a current. We should then be able to prove conversely by the continuation of the moment, that the time of relaxation of the current is very long, and a value, or otherwise an upper limit could be given for the micro-residual-resistance of the conductor in which this current flows.

I got this proof in the following manner.

On either side of the place, where the ends of the windings of the coil are sealed together and close to it, two wires *b*, *b* (see fig. 2 and 1) were fixed which lead to a ballistic galvanometer. Between these points of attachment the current can be cut through under helium, by pulling up by a thread a bronze loop provided on the inside with a knife edge at *m* (see figs 3 and 1. Figs 1 and 2 give

[1]) Disregarding the existence of threshold-values of current and field and considering that, below these, supra-conductors add up algebraically without appreciable loss the inductional impulses which act on them in the course of time, two points of view may be very simply contrasted in connection with the experiments so far described on the production of currents persisting for a long time.

The first is analogous to that taken up in WEBER's explanation of diamagnetism. In this case we deal with supra-conducting circuits which are currentless outside the magnetic field. By bringing these into a field currents may be obtained which persist as long as the field remains unchanged. But when the field disappears the circuits become again free of current. In this manner a good imitation is obtained of diagmagnetic polarisation. The other point of view may be called the antilogon of that of WEBER. We provide in a magnetic field supra-conducting circuits which are free of current. When these circuits are brought outside the field, they show a current persisting for a long time. Outside the field they imitate permanent magnets. It must, however, not be lost sight of, that this imitation is in so far incomplete, as when the circuits are brought back into the field, they return to the currentless condition.

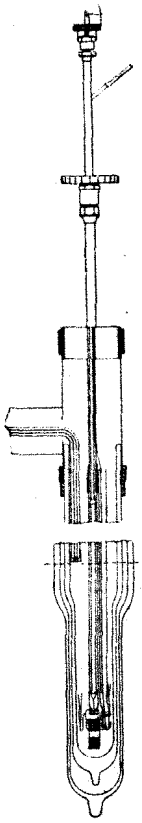

Fig. 1.

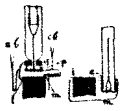

Fig. 2.

Fig. 3.

a combined view of the experiments of sections 9 and 11). The thread runs through a tube, the lower part of which is of glass and can be moved by means of a rubber-tubing attachment at the top of the apparatus (fig. 1). The coil was cooled to 2°.4 K. in a field of 200 gauss by helium evaporating under reduced pressure. The current was again produced through induction by removing the field. When the compass needle with the compensation-coils was arranged, as before, beside the cryostat, a moment corresponding to a current of 0.36 amp. was registered. The observation was continued for an hour, in which the diminution of the current in 45 minutes was within the limits of probable error of the measurement (2%); after this the circuit of the coil was cut through. The needle of the compass fell back to a deviation that corresponded to a current of 0.05 amp. in the coil. The ballistic galvanometer (with a negligible self-induction and with 2000 Ω in the circuit) showed an electro-kinetic momentum Li of 300000, from which follows with $L=10^7$, that a current of about 0.3 amp. flowed in the coil. The remaining moment is again the same fraction of the principal effect as was observed previously, it was extinguished as soon as the coil was pulled up above the liquid helium. The experiment proves conclusively, that a current does really flow through the coil.

§ 10. *Further consideration of the momentum produced in the coil, when the circuit is not closed. Persisting* FOUCAULT-*currents.* In the previous experiments the question arose in how far magnetic properties of the frame of the coil, which developed at the lowest temperatures had an influence, and whether a part of the moment that remained, when the coil, without the ends being connected, was cooled and exposed to the field, was due to windings which were short-circuited. For this purpose first of all a tube of brass, exactly like that used as the frame of the coil, was cooled in the field. It showed no residual magnetism.

To get further light on possible short-circuits in the coil Pb_{XII}, after it had been shown that cooling in liquid air did not alter

its moment, a new coil of 650 turns was wound, in which the possibility of short-circuiting was excluded by insulation of the windings by picein and paper. It is true that the magnetic properties of these materials are not known, but from the extinction immediately above the boiling-point of helium of persisting current which was found in the course of the experiments it is almost certain, that the phenomena are entirely due to the lead. It was ascertained that this coil was superconductive, which was a welcome result also for the reason that the wire had been manufactured by compression, and this process gives a much better guarantee of getting the same product again by using the same method, and therefore of obtaining beforehand the certainty of the wires prepared in this way being supra-conducting. In making the experiment with 200 gauss at 2°.4 K. a residual effect of the same order as with Pb_{XII} was found, but smaller. The principal current was 0.5 and the residual current 0.020 Amp. It becomes probable, when these figures are compared with those found with Pb_{XII}, that in the latter there really is some short-circuiting, but there is also apart from the effect due to the short-circuited windings a moment caused by the lead.

It seems as if in the mean time this may be attributed to circular currents in the lead of the wire, which are possible owing to the wire having a certain thickness. We must distinguish in the wire between an inside which is turned towards the axis of the coil, and an outside. In the wire, even when the circuit is opened, a current arises, in which the electricity passes along the whole length of the windings on the outside of the wire (that is not closed in itself), in order to turn round at the one end of the wire and go back along the internal side. With induction in the closed circuit this current is superposed upon the mean electric movement in the circulating current, so that in the wire there is say a stronger current on the outside, and a weaker on the inside. If by means of a galvanic cell a current is sent through the wire, the same phenomenon arises through the action of the field of the current itself. We are here evidently dealing with persisting FOUCAULT-currents [1]).

§ 11. *A supraconducting key.* In the experiments so far described the supra-conducting closing of the conductor tested for supra-conductivity was obtained by melting the two ends together. Now

[1]) Several of the well known experiments by ELIHU THOMSON with alternating currents could also be made with parallel currents and supra-conducting experimental objects.

that these experiments had proved that a current generated in a circuit which is supra-conducting over its whole length, continues without electro-motive force, we could investigate in how far an electric contact interposed in an otherwise supra-conducting circuit, measured by the amount of conductivity of supra-conductors, might be considered as having no resistance. The immediate cause of this investigation was a suggestion made by my colleague KUENEN, whether the current the relaxation period of which was to be studied, might not be obtained in the coil by short-circuiting.

I thought then, that the transitional resistance in a contact to be manipulated under liquid helium could hardly be made small enough for this purpose. The transitional resistance of a stop-contact treated with all due care at ordinary temperature is not likely to be less than 0,0001 Ω, which is still 100,000 C.G.S. while the micro-resistance of the coil itself is only 37. It has now been found, however, that transitional resistances such as we are considering can become very small at low temperatures. A quite moderate pressure, between two pieces of lead appeared to be sufficient for the purpose. The arrangement is shown in Fig. 2. The small lead plate *p*, provided with three small cones directed upwards and connected with the coil through a spirally-wound part of the lead wire which acted as a spring, is attached to a thin rod (partly formed of wood) and was pressed against the block soldered to the glass tube by screwing up the rod, the force being accurately regulated by means of a spring (see top of fig. 1). The tube is provided with a number of side-openings to prevent the very much intensified heat convection (caused by resonance phenomena) which occurs in tubes closed at the top when the bottom is at a very low temperature, and which would lead to excessive evaporation of the helium.

By means of this simple key we were enabled to arrange the following experiment. To each extremity of the windings of the coil two wires were attached (fig. 1 and 2). By means of the one pair *ac* a current can be sent through the coil. The other pair *bb* can be connected to a ballistic galvanometer. Moreover the two ends are connected to the two parts of the supra-conducting key. With the key and the galvanometer open, a current is sent through the cooled coil, in the neighbourhood of which the compass-needle has been mounted. The coil is then closed in itself, which gives no change in the deviation of the needle. One can then convince oneself as long as one likes, that the side-current, which in ordinary cases is immediately extinguished, remains unaltered in the supra-conductor; the galvanometer connection is then closed, which also brings no change

in the current, and if thereupon the current connection is opened this is accompanied by a throw of the ballistic galvanometer in the circuit of which the current is instantly extinguished and by a return of the needle of the compass into the position which it would also take up, if the current in the closed coil had been generated by a magnetic field equal to that of the current itself. The continuation of the movements in MAXWELL's mechanism, when it has a supra-conductor as carrier, is demonstrated by this experiment with equal clearness and simplicity.

§ 12. *Combination of parallel currents into one of greater strength.* In trying to make the same experiments with mercury that we have made with lead, it will be necessary in so far to change the experiment, that one winding will be sufficient. This might be got by freezing mercury in a capillary tube returning in itself with an expansion head (like our other U-shaped mercury resistances). The chief questions then are 1) if with a conductor of as large a section (keeping for the present to the circular form) as would be necessary, with a view to the threshold value of current density, in order to get an action comparable to that with the lead coil, the threshold value of current density — of which as in N°. 133 it is assumed that it is determined principally by the current density — does not undergo a considerable diminution in consequence of the larger section, as some considerations in N°. 133 would make us fear, and 2) if we can reckon with the microresidual resistance as an ordinary resistance even for such a completely different section as that for which it has been determined. An inducement to try the experiment immediately with a lead ring [1]) was a remark by my colleague EHRENFEST,

[1]) I am glad to mention here that Mr. J. J. TAUDIN CHABOT of Degerloch (Württemberg) shortly after my paper on the disappearance of resistance in mercury and, as I found afterwards, only acquainted with my result, that the resistance of gold and platinum in an absolutely pure condition would probably disappear altogether at extremely low temperatures, communicated to me a number of suggestions regarding the condition into which meta's pass below this temperature and which he would like to be considered as a distinct "fifth" state of aggregation.

Amongst these suggestions was the following: "if a ring (of gold) is brought to the condition of absolutely no resistance (in helium), an impulse (viz. by induction) will be sufficient to produce a permanent current, which will make the ring into a magnetic shell, as long as the temperature of the metal remains below a certain critical value". By critical value was meant — not the vanishing point as discovered afterwards — but the temperature characteristic of each metal at which, according to my earlier views, the resistance of the pure metal would become zero independently of the current-strength. The idea, however, underlying this speculation — which was further developed by supposing the cooled ring to

that the experiment could be made equally well with the windings "parallel" as it had been made with the windings in "series". A calculation (by estimation and further proceeding in the same way as with the coil) about the experiment with a lead ring of an internal radius of 1.2 cm. of a thickness of 0.3 cm. and of a width of 0.35 cm. and assuming that the threshold value found for the thin lead wire would also hold for the thick ring, showed me, that it might succeed very well.

This proved to be the case. The current of 320 amp. that was registered in the ring remained constant for half-an-hour to 1%, hence the current density of 30 was in this experiment not much smaller than it had been in one of the experiments with the coil of lead wire, viz. 49. This may for the present be regarded as a confirmation of the supposition that the threshold value of current strength of a conductor is mainly a threshold value of current density for the material of the conductor.

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be subjected to a magnetic field which was to be removed afterwards — was also applied in my experiments for the purpose of obtaining persisting currents in supra-conductors, and in the above last experiment actually with a ring as the conducting circuit.

At the time I was so much occupied with the investigation of the peculiar laws of electric conduction in mercury below the vanishing-point and of the degree to which currents might be realised in resistanceless circuits without electromotive force, that I had not yet attacked or was able to fully go into the problems relating to currents to be generated in closed supra-conductors by induction (amongst which problems that of the imitation of diamagnetic polarisation was an obvious one). Still Mr. TAUDIN CHABOT'S letter was the cause of my coming even then to the conclusion, that in order to be able to obtain persisting currents outside the magnetic field by induction, an artifice based on the peculiarity of supra conductors was required. As such I then found, that the cooling which is to make the conductor supra-conducting is not applied, until the conductor is in the field which is to be used for the induction. Afterwards it was found, that by utilizing the knowledge of the threshold values of current and field circumstances may be realized, in which a permanent current may be obtained outside the field by induction on a circuit which has been made supraconducting by cooling before the field is applied.