Physics. — *"Further experiments with liquid helium. J. The imitation of an* AMPÈRE *molecular current or a permanent magnet by means of a supra-conductor.* (*Cont.*). By Prof. H. KAMERLINGH ONNES. Communication N°. 140*c* from the Physical Laboratory at Leiden.

(Communicated in the meeting of May 30, 1914).

§ 5. *The main experiment repeated.* Although the original experiments on the persistence of a current which is started in a closed supra-conductor have established the fact that the diminution of the current with the time is very small (at least if it is assumed that in the phenomena hitherto unknown magnetic properties do not play an important part), still for the magnitude of the change only an upper limit could be fixed. As no change of the current was observed, this upper limit was determined by the uncertainty in the measurement of the current. The only fact established so far was that, if the change had been greater than 10 %, it would have been observed.

In repeating the experiment it was attempted to determine the change itself or otherwise to reduce its upper limit, in so far as the conditions under which the experiment had to be made allowed this. The same supra-conducting lead-coil was used. As before the current was produced in the closed conductor by induction in order that the circuit might be kept free from connections other than of lead fused together [1]). The current was again measured by compensating the action of the coil on a compass-needle by means of a current in a subsidiary coil. The arrangement was however improved by this coil (of insulated copper wire) being placed in a small vessel with liquid air in a fixed position with respect to the needle. When the compensation was obtained, the experimental coil was turned 180° about a vertical axis and again compensated with the current in the second coil reversed, the magnetic moment of the experimental coil being deduced from the mean of the two observations.

If the diminution of the current can actually be calculated from the residual micro-resistance given in Comm. No. 133, viz. $\frac{r_{1^0.8\,\mathrm{K.}}}{r_{290^0\,\mathrm{K.}}} = 0.5 \times 10^{-10}$, or with $r_{290^0\,\mathrm{K.}} = 734\ \Omega$ [2]): $r_{1^0.8\,\mathrm{K}} = 37$, the time

[1]) An attempt is at present being made to manufacture a supra-conducting current-key.

[2]) This value given already in Comm. N° 140*b* is a more accurate value than the one given in Comm. N°. 133.

of relaxation, with $L = 10^7$, would come to about 270000 seconds or 75 hours. In that case the current would fall by 4 % in three hours. It was hoped that it would be possible with the improved arrangement to establish a diminution of that amount.

The experiment was made with a field of 189 gauss at a temperature of 1.°7 K. The current amounted to about 0.4 amp. (as before no account was taken of the possibility of magnetisation or of induced circulating currents inside the supraconducting material) and during about $2^1/_2$ hours no diminution of the current was observed; it was then necessary to admit a fresh supply of helium into the cryostat: during this operation the temperature rose temporarily to 4.°25 K. During the next hour the current was found to undergo a gradual diminution and to approach asymptotically a new value of about 0.36 amp. which did not show any further change for $1^1/_2$ hours. The observations during the two periods mentioned render it probable, that the change does not attain the value of 4 % in 3 hours as calculated above.

It was considered possible, that the changes of shape of the helium-liquefier and the cryostat during the process of condensation and transfer of the liquid helium, as well as a possible change of zero of the compass-needle which after the magnet has been removed is still near various iron parts of the apparatus, might have had an influence on the values of the current as measured at different moments. Judging by the correspondence of the various readings the accuracy was smaller than had been expected. In again repeating the experiment therefore two compensating coils were used by which compensations on the east and on the west could be effected. They were mounted each in a small vessel with liquid air on a fork-shaped stand and could be rotated about vertical axes in such a manner that the distance of the axes could not change. The same needle served for the compensation on both sides. Guiding pins guaranteed the same position each time of the needle relatively to the compensating coil which was being used. The common support of the two coils was moveable parallel to itself in a horizontal direction on a slide and by means of marks it was possible to place it each time in the same direction and the same position relatively to the vertical axis of the experimental coil. The axes of the three coils were provided with horizontal divided circles moving along fixed pointers. Each measurement consisted of 8 readings in the obvious combinations of 4 positions both with compensation on the left and on the right.

In the experiment with this improved method of reading care was

also taken, that the current did not rise above the value at which no further change had been observed at 4°.25 K. The current was therefore raised to only 0.22 amp. (approximate value calculated as before from the observed magnetic moment of the coil), so that the supply of a fresh quantity of helium would probably not have the disturbing effect which had been noticed in the previous experiment. The temperature used was 2° K. In the beginning again a fall of current was noticed which must however be considered as uncertain, inter alia owing to the possibility of the changes of shape of the apparatus and the change of zerò of the needle not having been sufficiently eliminated yet in these observations. In the three hours subsequent to the initial period no further diminution was observed, the last observation even giving a small increase. Still in this experiment the accuracy could not be considered greater than about 2% of the measured moment and, as it was found impossible to continue the experiment beyond three hours, again only an upper limit for the change could be established, to be put at about $^2/_3$ % for current and induced magnetisation combined. Taking all the experiments together it may be considered as probable, that the change of the current is less than 1 % per hour which raises the time of relaxation to above 4 days.

§ 6. *Upper limit of the residual micro-resistance according to these experiments.* So far no contradiction has arisen in reasoning on the assumption of the existence of a residual micro-resistance which below the threshold-value of the current again obeys OHM's law. On this view the upper limit of this micro-resistance for lead, which in Comm. N°. 133 was placed at $0{,}5\ 10^{-10}$ of the ordinary resistance at 0°, can now on the basis of the above observations be moved further back to about $0.3\ 10^{-10}$ or $0.2\ 10^{-10}$ of the resistance at the ordinary temperature.

§ 7. *Some of the control-experiments repeated.* In the previous paper a few other experiments beside the main experiment were described: some of these have now also been repeated.

Again we did not succeed in conducting the experiment in which the windings are placed parallel to the field, the coil cooled below the vanishing-point while in the field and then the field removed in such a manner, that the compass-needle, when brought near the cryostat after removal of the electro-magnet, did not show any deflection. After the action of a field of 400 gauss at 4°.25 K. a current of 0.1 amp. was found in the coil. This would give 0.045

amp. with a field of 189 gauss, the same as used with the other experiments, whereas the main experiment at the same temperature and inducing field had given 0.4 amp.

More satisfactory was the experiment in which first a current is produced in the coil — analogous to the currents in resistance-free paths as imagined by WEBER for the explanation of diamagnetism — and then destroyed by the removal of the field: an almost complete compensation was obtained in this case. The experiment was made with a field of 189 gauss. This result is of special importance as it practically disposes of the supposition mentioned in the previous paper as possible, although very improbable, that magnetic properties of the material of the coil might play an important part in the phenomena.

The current in the coil changes with any new magnetic field applied and with any further change in it, or with any change of position relatively to the field. In this respect the influence of the earth-field may be noted. The current in the coil, when placed with its windings at right angles to the meridian, will assume a slightly smaller value in the one position North-South and a somewhat larger value in the opposite position Sout-North than in the position East-West, which is practically the position in which the experiments were made. In our experiments this action was however too small to be taken into account considering the accuracy which could be attained at the most.

It may be observed that our conductor carrying its current in the absence of an electromotive force, when undergoing the relatively small action of the field of the earth, is analogous to the AMPÈRE molecular currents (in the form of circulating electrons) which play a part in LANGEVIN's theory of magnetism, when they experience a diamagnetic action on being brought into a field, in accordance with LORENTZ's theory of the ZEEMAN-effect.

§ 8. *The experiments repeated with the circuit open.*

So far it has been constantly assumed, that the magnetic properties of the material of the coil play but a secondary part in the phenomena observed, when the experiments were arranged so as to produce a permanent current. This view was based firstly on the difference in the results with the windings parallel and perpendicular to the field during the cooling in the field and secondly on the compensation found on applying and removing the field after the conductor had already been cooled to helium-temperature. Furthermore that the part of the effect which is independent of the circu-

lating current must be ascribed to the lead itself, was to be inferred from the fact, that the current is quenched, as soon as the temperature of the coil rises somewhat above the boiling point of helium and passes the point which, as being the vanishing point for lead, has a special physical meaning for this substance.

In order to obtain further information as to the part of the phenomenon which depends upon the material itself, the experiments were repeated after the lead-wire connecting the ends of the coil had been cut, so that the circuit was no longer closed (apart from possible short-circuits in the coil).

This time the experiments with the exception of one could only be performed at 4.°25 K: still there does not seem to be any objection to applying the results for the explanation of the irregularities which had been left unexplained in the main experiments, although these had been mostly carried out at a lower temperature.

In all the experiments a certain residual effect remained, which was reduced to about one tenth when the windings were parallel instead of at right angles to the field and in the latter case was fairly well independent of the field. The amount of this effect corresponded to a moment which was equivalent to a current of 0,05 or 0,06 amp. in the closed circuit. In one of the experiments, the only one in which the temperature was lower than 4.°25 K., viz. about 3° K., the moment was estimated to be equivalent to as much as 0,07 amp. The effect with the circuit open is thus very much smaller than in the main experiments. The share born in the effect by the frame of the coil and the lead independently of closing the circuit may therefore be put at less than $^1/_4$ of the total effect in the main experiment.

As a check on former experiments the following additional experiments were made with the coil with the lead wire cut.

In the first place at the ordinary temperature after joining up to a ballistic galvanometer the induction was measured arising from putting on or taking off the field with the windings in the position in which they were supposed in the previous experiments to be parallel to the field. The induction was found to be $^1/_{20}$ of the effect in the position at right angles to the field. This observation may contribute to the explanation of the residual effect observed in the experiments in helium in the position with the windings parallel to the field.

In the second place a known current was sent through the coil and its strength measured by the same method as used in determining the moment of the experimental coil in the experiments with the

lead circuit closed. Although the matter requires further elucidation, it would seem to follow from this measurement, that a few of the layers of the coil are short-circuited. After opening the circuit a residual moment remained in the coil as before which was destroyed on raising the temperature slightly above that of the helium-bath.

Physics. — *"Further experiments with liquid helium. K. Appearance of beginning paramagnetic saturation."* By Prof. H. KAMERLINGH ONNES. Communication N°. 140*d* from the Physical Laboratory at Leyden.

(Communicated in the meeting of May 30, 1914).

The question, whether paramagnetic substances would show a saturation-effect at high field-strengths, has always been considered a very important one. Although it could hardly be assumed, that the susceptibility would remain independent of the field at higher strengths than were attainable, still so far at the highest fields available it appeared to be the case. LANGEVIN's theory brought the explanation, why so far all attempts to find paramagnetic saturation-effects had remained unsuccessful. According to this theory the magnetisation appears to be determined by the expression $a = \frac{\sigma_m H}{RT}$, where σ_m is the magnetic moment of the molecules per gramme-molecule, R the gas-constant, T the absolute temperature and H the field. As long as a remains below 0,75, the changes of the susceptibility with the field escape the ordinary method of observation and at the ordinary temperature even a substance as strongly paramagnetic as oxygen gives for a with a field of 100000 not more than about 0,05. As I pointed out at the 2nd International Congress of Refrigeration at Vienna (1910) this theory shows that lowering the temperature is the means by which the observation of paramagnetic saturation might be attained and that helium-temperatures are the most suitable for the purpose. In fact as the absolute temperatures to which one may descend by means of helium are 70 and even 150 times lower than the normal temperature, the result will be equivalent to raising the magnetic field at which the observation is made 70 or 150 fold.

I have lately at last been able [1]) to fulfil my desire to attack by

[1]) Viz. by the acquisition a short time ago of an electromagnet (built according to WEISS's principle and utilising his friendly advice) the interferrum of which leaves sufficient room at fields of 20000 for experiments with liquid helium.