From the relation (9) ensues moreover $\sigma = 6$. In all the (P^3) occur therefore *six* groups, of which the three points P have coincided into *one*; in the (p^3) belonging to them *six* groups with united lines p.

Physics. *Further Experiments with Liquid Helium. I. The* HALL-*effect, and the magnetic change in resistance at low temperatures.* IX *The appearance of galvanic resistance in supra-conductors, which are brought into a magnetic field, at a threshold value of the field*". By H. KAMERLINGH ONNES. Communication No. 139*f* from the Physical Laboratory at Leiden.

(Communicated in the meeting of February 28, 1914).

§ 1. *Introduction, first experiments*. In my last paper upon the properties of supra-conductors, and in the summary of my experiments in that direction which I wrote for the Third International Congress of Refrigeration in Chicago (Sept. 1913, Leiden Comm. Suppl. N°. 34*b*), I frequently referred to the possibility of resistance being generated in supra-conductors by the magnetic field. There were, however, reasons to suppose that its amount would be small. The question as to whether the threshold value of the current might be connected with the magnetic resistance by the field of the current itself becoming perceptible could be answered in the negative, as we had then no reason to think of a law of increase of the resistance with the field other than proportional to it, or to the square of it, and the law of increase of the potential differences at currents above the threshold value could not be reconciled with either supposition. A direct proof that in supra-conductors only an insignificant resistance was originated by the magnetic field was found in the fact that a coil with 1000 turns of lead wire wound within a section of a square centimetre at right angles to the turns round a space of 1 c.m. in diameter remained supra-conducting, even when a current of 0.8 ampère was sent through it. The field of the coil itself amounted in that case to several hundred gauss, and a great part of the turns were in a field of this order of magnitude, without any resistance being observed. The inference was natural, that, even if we should assume an increase with the square of the field, the resistance would probably still remain of no importance even in fields of 100 kilogauss. In my publication (see Report, Chicago, Suppl. N°. 34*b*) I restricted my conclusion about the resistance in the magnetic field to a limit of 1000 gauss, and I also remarked that when it came to making use of the supra-conductors for the construction of strong magnets without iron, it would be necessary in the first place to investigate what resistance the magnetic field would

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generate in a supra-conductor, and I immediately prepared experiments in connection with this. That I was firmly convinced that the action would be only small, is shown by the fact that I arranged the apparatus for these experiments as if for a phenomenon that could only be studied with profit in fields of 10 kilo-gauss, but it now appears that even then without further preparation, I might have made the observations described below quite easily with the field of 2 kilo-gauss that I then had at my disposal.

For our experiments a coil was prepared as described above, but wound non-inductively. When (17 January 1914) it was brought into a field of 10 kilo-gauss, it showed a considerable resistance. We had not been so successful in the construction of this coil as in the previous one, as it did not become supra-conducting. It was therefore possible that not much value could be attached to this experiment. A coil with tin wire prepared in the same way as the above described non-inductive lead coil also showed a considerable resistance in a field of 10 kilo-gauss when cooled to 2° K., which decreased more slowly than proportionally, when the field was reduced to 5 kilo-gauss. In this case again we had not succeeded in making the coil so that it would become supra-conducting, but (always assuming a regular decrease with the field, and supposing that the fact that the coil did not become supra-conducting only gives a non-essential disturbance) the results of both experiments did not seem to be reconcilable with the above mentioned observations, in which the magnetic field generated no resistance in supra-conductors.

The first thing to do was therefore to repeat the experiments with the coils of tin and lead, which had become supra-conducting in the former experiments, notwithstanding that the windings were in a magnetic field. That these coils were not wound induction-free, was of no consequence, now that it was a question of such comparatively large resistances.

§ 2. *Further experiments with lead and tin which show a sudden change in the resistance at a threshold value of the magnetic field.*

The lead coil of Table XII Comm. N°. 133, as it was not wound induction-free, was placed in the cryostat of the apparatus to be described in a future paper for magnetic measurements in liquid helium, so that the plane of the windings coïncided with the lines of force of the magnetic field which is to be applied. This last acts therefore partly transversely upon the conductor (lines of force at right angles to the current), partly longitudinally (lines of force in the direction of the current).

It was first ascertained that the coil was supra-conducting at the boiling-point of helium. Further that it remained supra-conducting when a current of 0.4 ampère was sent through it; even then the windings were in a not inconsiderable field of their own current.

For further confirmation it was ascertained that the current actually passed through the windings by bringing a small cardanically suspended magnet (pole seeker) near the cryostat; it showed the movements which were to be expected.

Then the magnetic field was applied. With a field of 10 Kilogauss there was a considerable resistance, at 5 Kilo-gauss it was somewhat less. This made it fairly certain that the magnetic field created resistance in supra-conductors at larger intensities, and not at smaller ones. The apparent contradiction that so far had existed between the different experiments, was hereby solved. Later it appeared that 500 gauss was below the threshold value, and 700 above it. Further investigation gave for the resistance (expressed in parts of the resistance at 0° C) as function of the field, the curve that is given diagrammatically completed in fig. 1. The numerical values, in so far as they are necessary for the description of the phenomenon, can be read from the figure, so that they need not be separately detailed here.

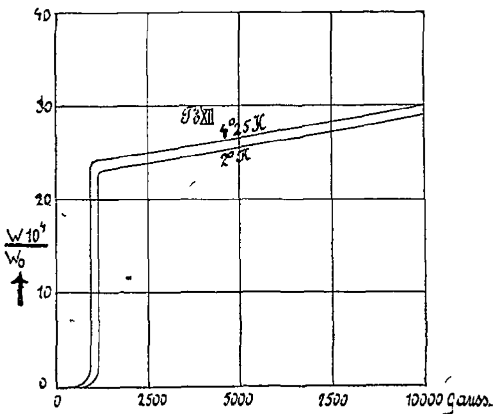

Fig. 1.

It will be seen that the transition from the supra-conducting condition to the ordinary conducting condition through the magnetic field takes place fairly suddenly. The curve, which represents the change of the resistance with the field is closely analogous to that which represents the change of the resistance with the temperature (comp. $I = 0{,}004$ amp. in fig. 7 in Comm. N°. 133). The resistance measurements were made with a current of 0,006 ampère. Of the two curves in fig. 1, one refers to 4°.25 K, and the other to 2° K. The sudden change in the resistance moves at low temperatures towards higher fields; beyond this point the resistance increases at lower temperatures (2° K.) almost in the same way as at higher ones, it seems as if *the introduction of the magnetic field has the same effect as heating the conductor.*

The tin coil of Comm. N° 133 Table IX was examined in the same way. With this too we have a result in which longitudinal

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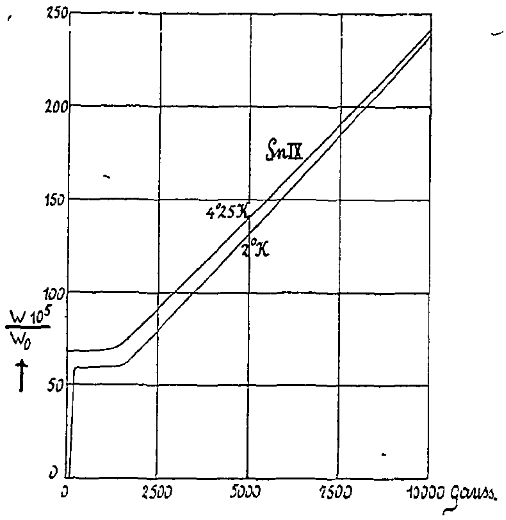
and transverse effects are combined. At 4°,25 K the tin is still in a state of ordinary conductivity, the curve, which represents the resistance as a function of the field decreases in steepness (see fig. 2) with a diminishing field and meets the axis of ordinates pretty nearly parallel to the axis of abcissae. The only thing, therefore, that is remarkable here as compared to what is observed at higher temperatures, is the decrease of the slope to zero. There is no indication of a sudden change.



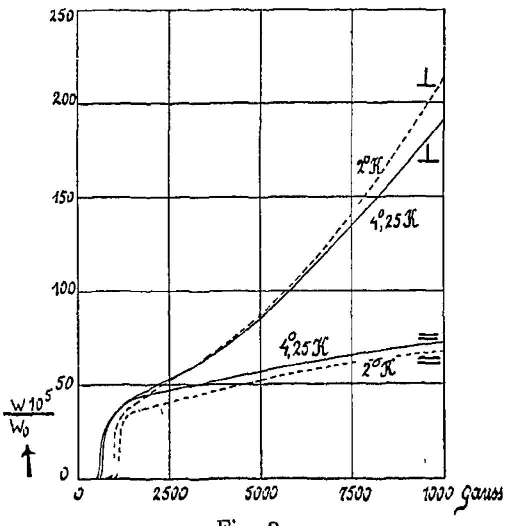
Eig 2.

With the supra-conducting tin at 2° K we find, as with lead a sudden change, in this case at the threshold value of 200 gauss. In fact with tin at 2° K we are much nearer to the temperature of sudden change for the resistance (3°,8 K) than in the case of lead (sudden change for the resistance 6° K (?) (comp. Comm. N°. 133).

§ 3. *Separate observations of the longitudinal and of the transverse effect with lead.*

Pressed lead wire was wound on a plate, so as to cover it with a few flat layers of insulated windings. The windings could be so directed that the effect was entirely transverse, or almost entirely longitudinal. The results for the temperatures of 2° K and 4°.25 K are given in the four curves in fig. 3.

The sudden change in both effects takes place almost at the same threshold value of the field. The longitudinal effect is weaker than the transverse effect. The value of the effect at hydrogen temperatures was examined by Dr. K. Hof and myself, and I take this opportunity to thank him



Eig. 3.

for his help. A paper on the subject will be published shortly. It appears from this that the effect which (see fig. 3, and in detail fig. 4) changes little with the fall from 4°.25 K to 2° K, increases considerably with the fall from .14° K to 4°,25 K.

It is worthy of notice that the sudden change *differs considerably in magnitude* with Pb_{XII} and Pb_{f1}. Possibly there is a difference in the nature of the lead in the two coils. In fact at 20° K

$$\frac{W_{PbXII}}{W_0} = 0{,}0284 \text{ and } \frac{W_{Pbf1}}{W_0} = 0{,}0274.$$

Amongst the different questions that arise, one is whether a lead wire might be constructed in which the magnetic resistance, remaining zero as far as the threshold value of the field, will further gradually increase with the field from the value 0 upwards.

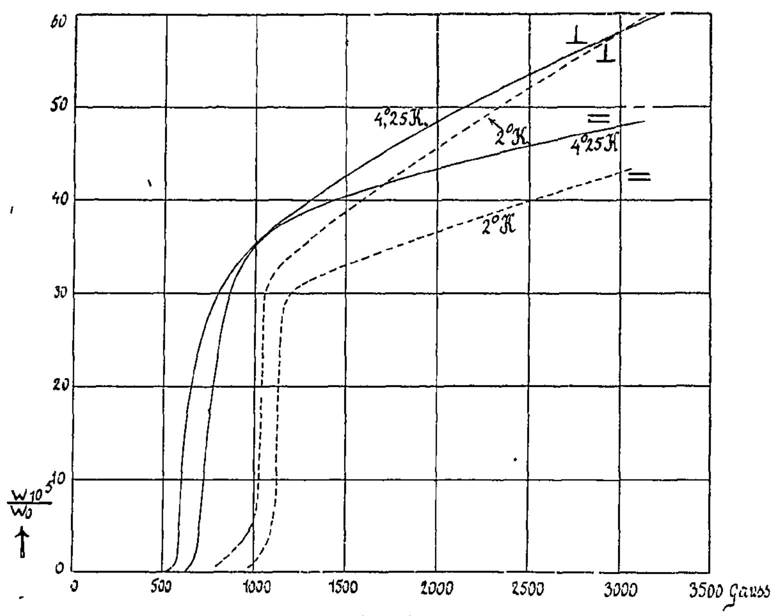


Fig. 4.

There is no doubt that the phenomenon discovered here is connected with the sudden appearence of ordinary resistance in the supra-conductors at a certain temperature. The analogy between the influence of heating upon the resistance and that of the introduction of the magnetic field, is so far complete.

One would be inclined to assume that an energy of rotation determined by the magnetic field might be simply added to the energy of the irregular molecular motion. If, in the production of the obstructions which determine the resistance we have to do with dissociations in the sense, that movements of electrons in certain paths become unstable at a definite temperature, the magnetic centrifugal force might make there motions one-sidedly unstable at another temperature.

If the creation of ordinary resistance in supra-conductors with currents above a certain threshold value, which is fully described in Comm. N°. 133, really is a peculiarity of the supra-conducting metal, and not due to disturbances, then the new phenomenon might also be connected with this property. In fact if it were once proved — to use an image already introduced into my paper for the Congress in Chicago — that the vibrators which cause the resistance can only be set in motion when the stream of electrons passes them with sufficient rapidity, then it would not be surprising that the magnetic resistance does not arise until the rapidity of the circulating motions of the electrons is great enough to carry the atoms with it and set them in rotation, by which they can then disturb the regular motion of the electrons.

Finally, it is certain that the phenomenon described is connected with the laws of magnetisation of supra-conductors which are as yet unknown.

Before however drawing definite conclusions from the new phenomenon, it is desirable to gather more experimental information on the subject.

Physiology. — *"Electrocardiograms of surviving human Embryos"*. By Prof. J. K. A. Wertheim Salomonson.

(Communicated in the meeting of February 28, 1914).

By the kindness of Dr. H. Treub, Professor of Obstetrics and Gynaecology I was enabled to record the electrocardiograms of 3 human embryos, born after operation for extrauterine pregnancy etc. The age of the embryos was given as about 6 weeks, 5 months and 8 weeks and agreed with the length measurements.

As the operations were performed in the University Institute for Obstetrics and Gynaecology, the embryo had to be sent to my laboratory in the University hospital about one mile distant, there being no telecardiographic connection between the two.

The embryo was put into a bottle containing a warm solution of Ringer. In the laboratory it was immediately placed in the hot moist chamber, which I had formerly used for my experiments with chicken embryos. The leads to the Einthoven galvanometer were placed on the upper part of the thorax and on the abdomen.