Physics. — "*Further experiments with liquid helium. X. On the electric resistance of pure metals, etc. XIV. Influence of elastic deformation on the supraconductivity of tin and indium*". (Comm. N⁰. 174 from the Physical Laboratory at Leiden). By G. J. SIZOO and H. KAMERLINGH ONNES.

(Communicated at the meeting of June 27, 1925).

§ 1. *Introduction.*

As no satisfactory theoretical explanation of the supraconductive state of metals has been given yet, which might serve as a guide for further investigations, it seems desirable to try, by changing the external conditions, to discover the factors which play a roll in the appearing of the phenomenon. These considerations led to the institution of an inquiry into the influence which elastic deformation exerts on the appearing of the supraconductive state. The results of this investigation are published here.

In the first place the influence of the elastic extension on the "vanishing-point" was traced with tin, and then that of elastic compression with tin and indium.

A. Extension.

§ 2. *Method of the experiment.*

In the Heliumcryostate [1]) a tinwire (fig. 1. *A*) is placed, stretched vertically between two small tinblocks *B* and *C*. The lower one is kept in place by the glass tube *D*, which is fixed with sealing wax into the cap of the cryostate and the lower brim of which fits exactly in the circular incision in the tinblock. The upper block is carried by a small copper cylinder soldered to the glass tube *E*. This tube is suspended by means of a similar cylinder on the spiral *F*.

The length of the spiral, which is a measure of the applied tension, is read on a millimeter scale placed on the glass tube. In the tube *D* some holes are made so that the liquid may enclose the wire completely. The wire was made (drawn out) from "KAHLBAUM-tin".

The leads necessary for the resistance-measurements are soldered to the tinblocks. Two of them, isolated with glass tubes, pass through holes

[1]) Leiden Comm. N⁰. 124*c* (1911) fig. 4.

in the tinblocks (for clearness these tubes are not shown in the figure).

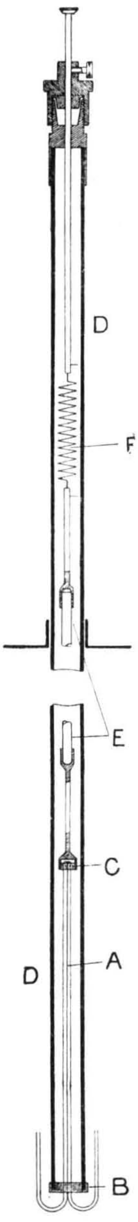

Fig. 1.

The method of resistance-measurements was always that of the balancing of the potential at the ends of the unknown and the known resistance, with the aid of a compensation apparatus of DIESSELHORST, free from thermo-effects. Even below the "vanishing-point" the found potentials were calculated to resistances as if OHM's law held.

The vapour pressures of the heliumbath were read with a cathetometer on a closed mercury manometer. The temperatures were calculated therefrom by aid of the formula of Leiden Comm. N^0. 147*b* (1915) p. 33 [1]).

For this purpose use was made of an accurately constructed curve which represents this formula in the temperature region required.

§ 3. *The measurements.*

The first measurements were made on March 28, 1924. As on the 4th of April following, it was possible to make a more complete series, the results of the first are not communicated here. They were however sufficient for it to be concluded that:

stretching of the tinwire was conducive to the appearing of the supraconductive state.

Namely, we repeatedly ascertained that at a temperature, below that at which the resistance begins to disappear, the resistance of the wire in the stretched was less than in the unstretched state.

On the 4th of April 1924 the measurement was repeated with a new wire of a length of 16.5 cm. and a diameter of 0.30 mm. The resistance of this wire at room-temperature was 0.30 Ω. The results of these measurements are given in table I, and represented by fig. 2.

The resistance-measurements were carried out in the order indicated by the Roman figures. Those indicated by II, III, IV, V, VI form a determination of the "vanishing point" of the unstretched wire; those by VI, VII, VIII, IX, X, XI, XII a similar determination of the stretched wire. The applied tension amounted to 197 grams, i.e. 2.52 k.g./mm^2. After this the wire was stretched and unstretched alternately, at different temperatures and every time the resistance determined (XIII^b and XIII^a, XIV^a and XIV$^{b \text{ and } c}$ XV^b and XV$^{a \text{ and } c}$).

In the measurement XV the current was maintained through the wire

[1]) See also Leiden Comm. N^0. 167*a* (1923) p. 4, note 1.

TABLE I. Measurements of April 4, 1924.

No.	Tension in G.	Tension in kg./mm^2.	p_{helium} in mm. Hg.	T	$W_{Sn\text{-}1924\,sp}$
II	0	0	484.9	3.774 °K.	0.000181 Ω
III	0	0	473.4	3.753	0.000176
IV	0	0	463.6	3.735	0.000072
V	0	0	453.6	3.716	0.000000
VI	0	0	442.6	3.696	0.000000
VII	179	2.52	442.6	3.696	0.000000
VIII	179	2.52	453.5	3.716	0.000000
IX	179	2.52	463.7	3.735	0.000029
X	179	2.52	467.9	3.743	0.000072
XI	179	2.52	473.3	3.753	0.000165
XII	179	2.52	483.4	3.771	0.000187
XIII^a	179	2.52	477.6	3.760	0.000190
XIII^b	0	0	477.6	3.760	0.000176
XIV^a	0	0	473.7	3.753	0.000183
XIV^b	179	2.52	473.7	3.753	0.000172
XIV^c	207	2.92	473.7	3.753	0.000172
XV^a	207	2.92	468.4	3.744	0.000090
XV^b	0	0	468.4	3.744	0.000133
XV^c	214	3.02	468.4	3.744	0.000086

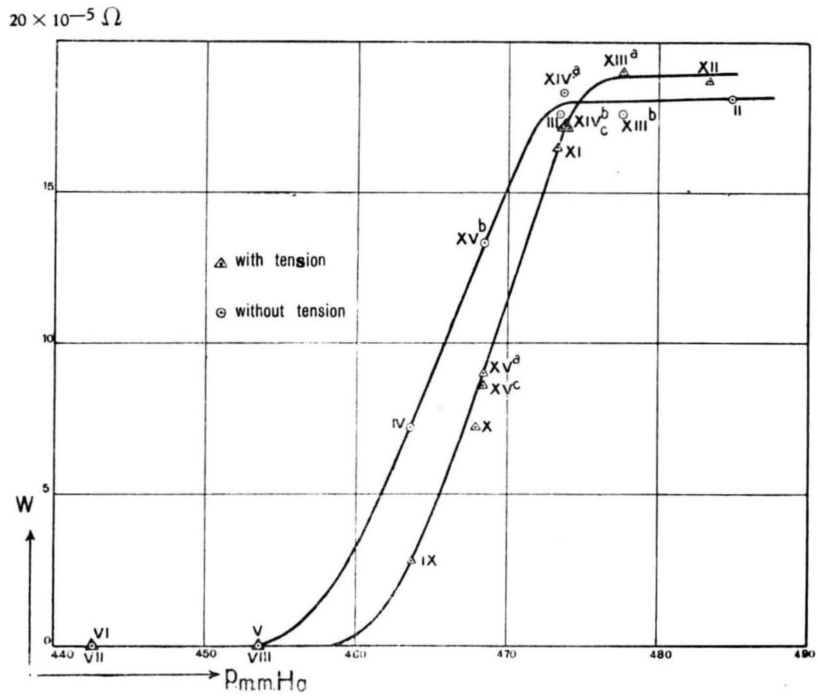

Fig. 2.

during the stretching and unstretching, and the galvanometer was read. It was observed that the latter was displaced about 8 mm., namely during the stretching in the direction corresponding to the diminishing of the resistance, during the unstretching in the opposite direction.

Fig. 2 shows clearly how the "vanishing-curve" is displaced by the stretching of the wire to the side, of the higher temperatures. At the place where the resistance has half disappeared, the displacement amounts to 3.5 mm. Hg., corresponding to 0.007 degrees Kelvin.

In the region of normal conductivity a small increase of the resistanee is to be observed. [1])

During these measurements the electrical current through the wire was always 13 mA. The highest tension with which was measured amounted to 3.02 k.g./mm^2. By trying to increase the tension still a little more, the wire broke. Thus the breaking load had been almost reached.

B. *Compression.*

§ 4. *Method of the experiment.*

The result, stated in § 3, gave rise to the supposition that compression of a tinwire would cause a displacement of the "vanishing-curve" to the side of the lower temperatures. To try this supposition an experiment was planned in which it would be possible to determine the "vanishing-point" of a tinwire, while this was subjected to a hydrostatic pressure. The amount of this pressure would, from the results found with the extension, have to be of the order of 200 kg/cm^2.

The experiment was arranged in the following way:

The resistance to be measured is wound round a small glass tube. The windings are separated from each other by silk thread. Round the resistance coil a second glass tube is slipped. The whole is placed in a copper cylinder (fig. 3. A) [2]), with an inside diameter of 7 mm. and an outside one of 11 mm., closed at the bottom and at the top by a heavy head (screwed and soldered). Two german-silver capillaries pass through the upper. The first one serves for the admission of the helium gas and is connected with the compression apparatus. Through the second the copper wires, necessary for the resistance measurements are led. These wires leave the capillary outside the cryostate by a connecting-piece *D*, in which the packing has been replaced by a little ebonite block. The four little holes, through which the wires are led outside, are afterwards filled up with piceine.

In order to produce the required pressure on the resistance, the cylinder *A*, whilst under the liquid helium, and the leads are first filled from a cylinder with compressed helium to a pressure of about 60 atmospheres.

---

1) See however § 5.

2) Compare also Leiden Comm. N^0. 132*b* (1912) fig. 1.

In the cylinder A and in a part of the capillaries liquid helium is formed then. After this, with the aid of a hydraulic press, the pressure is increased to the desired amount. This press is 8 filled with glycerine, which, in two communicating pressureboxes, is separated by mercury from the heliumgas.

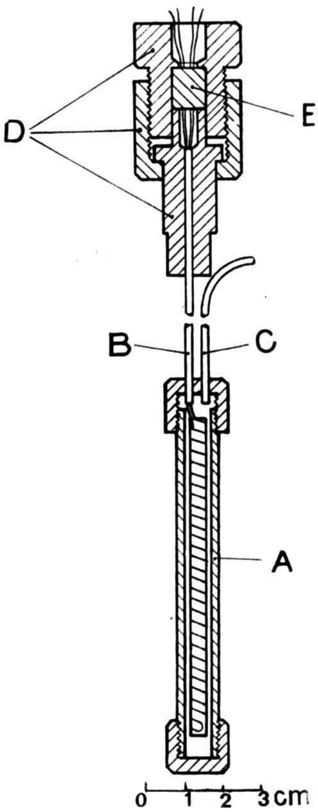

Fig. 3.

For the determination of the pressure two metal-manometers were used with ranges of measurement from 0—150 k.g/cm^2 and from 0—1500 atmospheres. Both were, after the measurements, calibrated with the small pressure-balance of the Physical Laboratory of Amsterdam. We wish to express our gratitude to Dr. A. MICHELS for his valuable help in this connection.

The resistance-measurements were made in the same way as set out in § 2. Also for the measurements of the vapour pressures and the determination of the temperatures reference may be made to § 2.

§ 5. *The measurements with tin.*

The measurements were made with the resistance Sn-1924-A, wound from a drawn tinwire of diameter 0.24 mm. The material used was "KAHLBAUM-tin". They were carried out on Oct. 24, Oct. 30, and Nov. 14, 1924. On the first two dates they had to be stopped, because of the appearing of a leak in the joint-piece D (fig. 3). A pressure of 300 atmospheres seemed scarcely admissable for the pressure installation, especially for this joint-piece. The last time, however, the measurement could be carried out undisturbed. The current through the wire always amounted to 4 mA.

The results of the measurements are contained in the Tables II, III, IV. They contain determinations of the "vanishing-point" at 4, 95, 193 and 300 kg./cm^2 hydrostatic pressure. As it was not possible to give all the points in one figure, fig. 4 represents, as an example, the vanishing-curve" at a pressure of 95 kg., whilst in fig. 5 the four curves are given, omitting the measured points. [1])

[1]) In constructing the graphs we always started from the idea that the line representing the disappearance of the resistance ("vanishing-curve") should be a continuous curve. Sometimes, however, by the position of the measured points the suspicion was raised that this supposition was wrong, and that the curve should show one or more discontinuities. To definitely settle down this question, however, a great number of measurements would have to be made and an exceedingly high constancy of the temperature of the heliumbath would be required.

TABLE II. Measurements of October 21, 1924.

Pressure in kg./cm^2.	p_{helium} in mm. Hg.	T	$W_{Sn.\ 1924\ A}$
4	483.5	3.771 °K.	0.00131 Ω
	474.3	3.754	0.00123
	468.4	3.744	0.00077
	464.4	3.736	0.00018
	466.6	3.740	0.00047
	458.5	3.725	0.00000
95	458.6	3.725	0.00000
	464.2	3.736	0.00039
	466.6	3.740	0.00078
	468.5	3.744	0.00097
	474.5	3.754	0.00126
	483.0	3.770	0.00131
	494.0	3.790	0.00131
	466.4	3.740	0.00068
193	474.6	3.754	0.00128
	468.6	3.744	0.00105
	466.5	3.740	0.00092
	464.0	3.735	0.00052

TABLE III. Measurements of October 30, 1924.

Pressure in kg./cm^2.	p_{helium} in mm. Hg.	T	$W_{Sn.\ 1924\ A}$
4	760	4.2 °K.	0.00132 Ω
	493.5	3.788	0.00131
	483.4	3.770	0.00131
	479.4	3.763	0.00130
	479.1	3.763	0.00129
	478.2	3.761	0.00129
	475.8	3.756	0.00126
	473.5	3.753	0.00116
	466.6	3.740	0.00045
	463.4	3.734	0.00008
	460.5	3.729	0.00000
95	494.4	3.790	0.00131
	484.4	3.772	0.00131
	473.7	3.753	0.00126
	468.2	3.743	0.00100
	464.8	3.737	0.00054
	461.0	3.730	0.00008
	458.4	3.724	0.00000

TABLE IV. Measurements of November 14, 1924.

Pressure in kg./cm².	p_{helium} in mm. Hg.	T	$W_{Sn.\ 1924\ A}$
4	483.9	3°.772 K.	0.00131 Ω
	473.7	3.753	0.00122
	467.8	3.742	0.00071
	463.3	3.734	0.00011
	462.0	3.732	0.00000
300	483.3	3.770	0.00131
	473.2	3.752	0.00127
	469.4	3.745	0.00110
	464.0	3.736	0.00056
	457.1	3.722	0.00000
193	484.5	3.773	0.00131
	473.8	3.753	0.00126
	469.7	3.746	0.00112
	466.4	3.740	0.00089
	463.1	3.734	0.00041
	460.1	3.728	0.00007
95	483.7	3.772	0.00130
	473.7	3.753	0.00126
	469.0	3.744	0.00108
	464.9	3.736	0.00050
	460.6	3.729	0.00007
4	473.9	3.753	0.00122
	468.8	3.740	0.00076
	464.3	3.736	0.00014

The measurements show the correctness of the supposition mentioned in § 4. *The "vanishing-curve" is shifted by the application of the pressure to the side of the lower temperatures.*

The displacement at the place where the resistance has half disappeared, for 300 kg./cm², amounts to 2.4 mm. Hg., corresponding to 0.005 degrees KELVIN. It is noteworthy that the displacement with increasing pressure soon seems to have reached a maximum value. The displacement, corresponding to an increase of the pressure from 193 to 300 kg. is scarcely outside the experimental error.

That the elastic limit is not exceeded by the application of the pressure, is clear from the return of the normal "vanishing-point" when the pressure is released. Also the resistance of the wire at 0° C., which was determined several times before, between, and after the measurements had not changed. It amounted to 2.0199 Ω.

It is noteworthy that in the region of normal conductivity no change due to the pressure could be observed within the experimental accuracy. This is in agreement with what might be expected from the measurements of KAMERLINGH ONNES en BENGT BECKMANN [1]), who found only a small pressure effect at hydrogen temperatures, which, besides, diminished with temperature. It is understandable that this result has caused some doubts about the reality of the increase of the resistance in the region of normal conductivity found with stretching.

Perhaps this increase, which, besides, is only just outside the experimental error in this region, is to be ascribed to very small fractures in the wire, produced by the stretching.

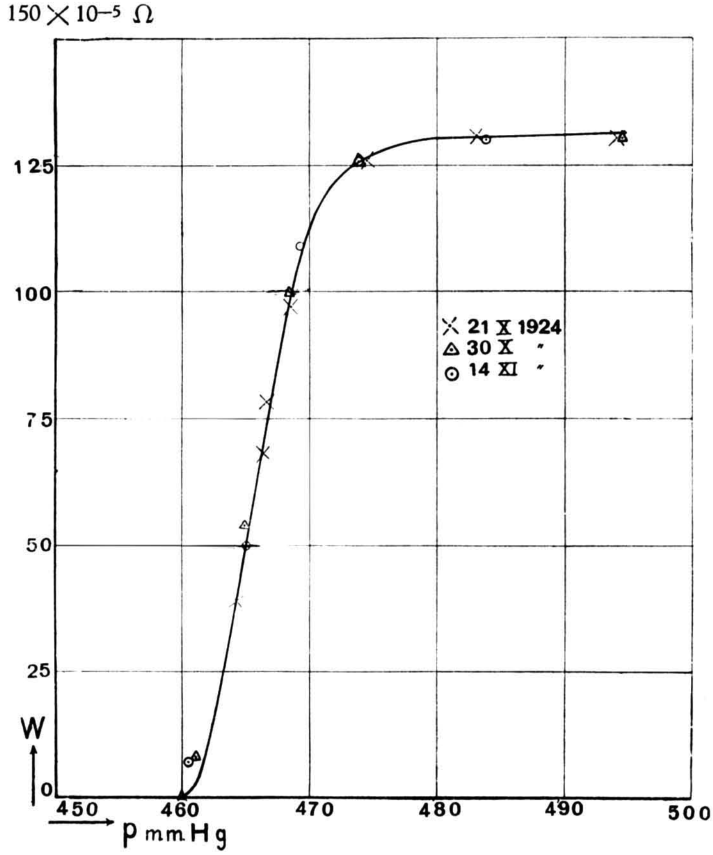

Fig. 4.

§ 6. *The measurements with indium.*

In order to decide the question whether the phenomenon mentioned above is to be regarded as a special property of tin rather than as a general property of the supraconductors, it was considered desirable to repeat the experiment with at least one of the other supraconductive metals. The most suitable for this purpose was indium, as it may be

[1]) Leiden Comm. N⁰. 132*b* (1912).

drawn into wire (in opposition to mercury), as it does not oxidise too fast in the air (in opposition to thallium), whilst besides the situation of the "vanishing-point" is suitable (in opposition to lead).

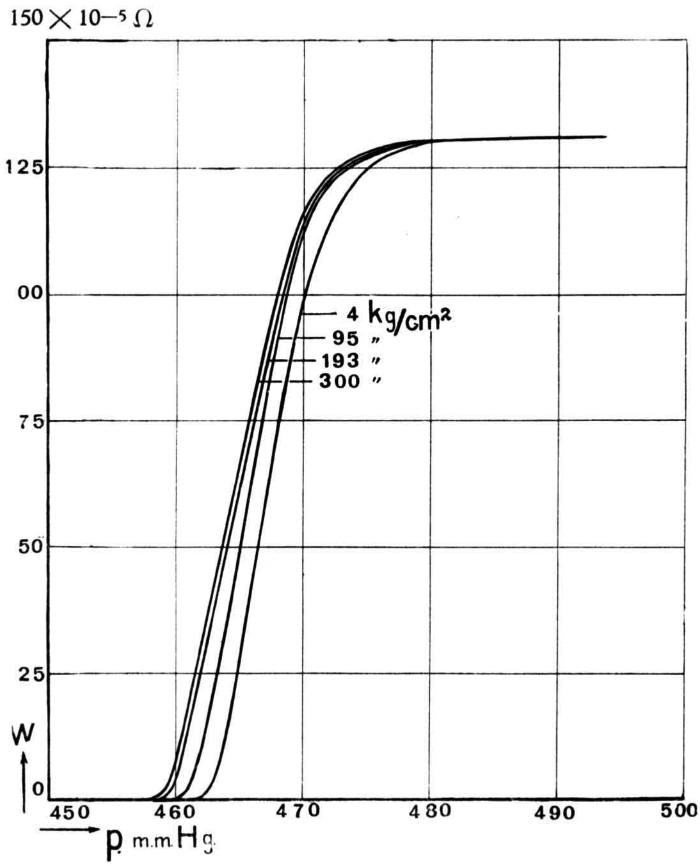

Fig. 5.

The resistance Ind.-1924-A, with which the measurements were carried out, was made of the same wire as that of the resistance Ind.-1922-A, used by W. TUYN [1]). The resistance at 0° C. was 2.2862 Ω.

The measurements were performed in the same way as those with tin. Although the great value of the resistance at the temperatures of liquid helium favoured accurate measurements above the "vanishing-point", it hindered the measurements in the region of the great decrease of resistance; namely, very small temperature changes in the heliumbath cause then very considerable changes in the resistance to be measured. Therefore in this region the measurements were made with a current of only 0.4 mA; above the "vanishing-point" a current of 4 mA. was used. The results follow in the tables V and VI and are represented by fig. 6. The applied tensions were 4,100 and 200 k.g./cm.². respectively.

[1]) Diss. Leiden (1924) p. 29.

TABLE V. Measurements of December 12, 1924.

Pressure in kg./cm².	p_{helium} in mm. Hg.	T	$W_{Ind.\ 1924\ A}$
4	760	4°.2 K.	0.07668 Ω
	319.1	3.438	0.07647
	313.5	3.424	0.07647
	308.4	3.412	0.07584
	305.4	3.405	0.0042
	306.6	3.408	0.0338
	306.6	3.408	0.0375
	304.8	3.404	0.0000
100	319.5	3.439	0.07646
	313.2	3.423	0.07646
	308.0	3.411	0.07636
	307.5	3.410	0.07614
	307.8	3.411	0.0757
	305.9	3.406	0.0515
	305.0	3.404	0.022
	305.5	3.405	0.0520
	303.2	3.400	0.0000

TABLE VI. Measurements of December 19, 1924.

Presssure in kg./cm².	p_{helium} in mm. Hg.	T	$W_{Ind.\ 1924\ A}$
200	317.9	3°.434 K.	0.07648 Ω
	313.0	3.423	0.07627
	308.1	3.411	0.07608
	306.8	3.409	0.07592
	305.2	3.405	0.0732
	304.8	3.404	0.0643
	304.0	3.402	0.0050
	304.2	3.403	0.0206
	304.5	3.403	0.0284
	304.4	3.403	0.0248
	304.9	3.404	0.0543
	305.5	3.405	0.0704
	305.2	3.405	0.0637
	304.0	3.402	0.0034
	303.2	3.400	0.0000

The results show that the behaviour of indium is the same as that of tin. The displacement of the "vanishing-curve" at the point where the resistance has half disappeared, for a pressure of 200 kg./cm² amounts to 2.1 mm. Hg., corresponding to 0.006 degrees KELVIN, thus only slightly different from that with tin.

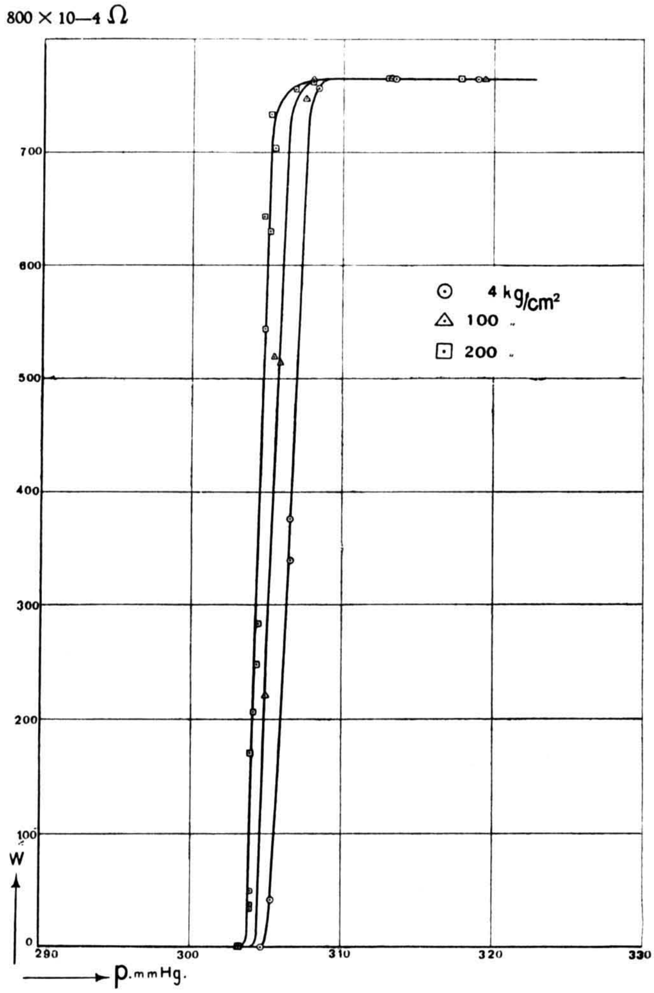

Fig. 6.

§ 7. *Discussion.*

If the extension and the compression of the supraconductive metal may be considered as equivalent to an increase and decrease respectively, of the distances between the atoms, then the results communicated above may be considered as supporting the hypothesis which has been stated in the report of KAMERLINGH ONNES to the IVth Conseil-Solvay, based on the drawings of Dr. H. A. KRAMERS contained therein; namely, that a relatively large space between the atoms is favourable for the appearing of the supraconductive state, when the further special conditions, shown only by the class of supraconductors, are present.