Physics. — "Further experiments with liquid helium. R. On the electric resistance of pure metals etc. XI. Measurements concerning the electric resistance of ordinary lead and of uranium lead below 14° K." (Comm. N°. 160b from the Physical Laboratory at Leiden). By Prof. H. Kamerlingh Onnes and W. Tuyn.

(Communicated at the meeting of October 28, 1922.)

§ 1. Object of the research. Method of preparing the resistances.

In Comm. N°. 133d § 133 we reported that "Kahlbaum" lead became superconducting at the boiling point of liquid helium, and remained so at 4,3° K., the highest temperature attainable with the usual cryostat for liquid helium; in § 15 of the same Comm. from the threshold value of the current at 4,25° K. the vanishing point temperature was estimated at about 6° K. The object of the investigation described below was to establish the vanishing point temperature of lead more accurately, as well as to trace the difference in the vanishing point temperature of lead and uranium lead (Ra G) and to follow the course of the change in the resistance of lead with the temperature above the vanishing point, if possible up to 14°,0 K, the lowest liquid hydrogen temperature. Regarding a possible difference of vanishing point temperature for isotopes it seemed not impossible that the occurrence of the superconductivity might be influenced by the mass of the nucleus. 1).

For the preparation of the resistances we used "Kahlbaum" lead and uranium lead (Ra G), of which Prof. Hönigschmid of Vienna very kindly put 16,5 gr. at our disposal; the atomic weight of ordinary lead from non-radio-active sources is 207,20, that of Ra G from Bröggerit used is 206,06 1). Wires were drawn from both kinds of lead and resistances prepared from them in the manner described in § 1 of Comm. N°. 1604; the chemical properties of the metal

1) Concerning the properties of isotopes see the article by K. Fajans in the Elster-Geitel-Festschrift (Vieweg) and the Presidential Address to the American Association at Baltimore, Dec. 1918 by T. W. Richards.

2) According to a letter from the firm of May 17th, 1916, "Kahlbaum" lead contains a trace of Cu and Fe, the total impurity is less than 0,01%; in a letter of Dec. 8th, 1916 they give a more precise calculation of impurity: 0,002% Cu and Fe. For an account of the atomic weight of lead isotopes cf. F. W. Aston "Isotopes", London 1922.
made it possible to extend less care on them than on the preparation of the $Tl$-resistances, so that it is not necessary that the resistances should be shut off from the air in a glass tube with helium gas. We used the resistances $Pb$-1919-$B$, diameter 0,5 m.m. not enclosed in a helium atmosphere, $Pb$-1919-$I$, diameter 0,12 m.m. enclosed in a helium atmosphere and Isotope $Pb$-1919-$I$, in dimensions as much as possible the same as $Pb$-1919-$I$ and treated in the same way.

§ 2. Arrangement of the cryostat. The cryostat with which the experiments were made, is executed by and under the supervision of the chief of the Techn. Dep. of the Cryog. Lab., Mr. G. J. Fli.m. Roughly speaking, it is the same as that described in Comm. N°. 124$b$. A characteristic of the present cryostat is that objects to be measured are surrounded by helium vapour or gas (the latter at very low temperature); by using it, the temperature field between the boiling point of helium ($4°$,2 K.) and the lowest temp. obtainable with liquid hydrogen ($14°$,0 K.) is bridged over for the first time. For the arrangement see fig. 1. In the entirely silvered vacuum glass $A$, an also entirely silvered vacuum glass $B$ hangs in an inverted position, ending in a single silvered glass tube; the bell-shaped space inside this glass is the experimental chamber. In this space are found the resistances (in fig. 1 there is only one, marked $W$) and the heliumgas-thermometer $Th$. The upper end of $B$ opens out outside the cryostat and is connected with the gasholder; $B$ is there provided with a regulating tap $K$ for blowing off (not visible in the drawing). The liquid helium comes in through the entrance $D$; the floater $C$ shows the height of the helium level. If the tap $K$, leading to the gasholder, stands open, the helium will fill both $A$ and $B$; at the beginning of the experiment measurements can thus be made at the boiling point of liquid helium. If the
tap $K$ is closed, the helium vapour formed will quickly drive the liquid helium out of the bell-shaped cryostat space; by opening the tap $K$ and putting on the electric heating in the spiral $F$, a constant vapour stream may be sent through the cryostat; the stream may be brought to the temperature desired by electric heating of the spiral $G$; thus the liquid level of the evaporating helium remains between $F$ and $G$. The copper mantle $E$ inside the bell contributes to the acquiring of an even temperature over the whole space; further experiments must show in how far uniformity of temperature has been achieved with the arrangement as described. The first cooling uses a great deal of liquid helium.

§ 3. Resistance and temperature determinations.

The resistances are measured by comparison of the deflections of the galvanometer, when connected with the extremities of an unknown and a known resistance (0,001 or 0,01 $\Omega$ O. WOLFF); the resistances are proportional to the means of the deflections for both directions of the current, as follows from the comparison of the deflections for 0,001 and 0,01 $\Omega$.

The temperatures are determined with a helium-gas thermometer of constant volume and with open manometer, the height of the barometer is read from an aneroid. In the measurements of May 18th 1920 the zero pressure of the thermometer was calculated to be about 1140 c.m.; as it was not easy to determine this pressure accurately, the pressure at the temperature of liquid helium was taken as calibration point (this temperature followed from the vapour pressure of the bath).

For the measurements of May 28th 1920 the zero-pressure of the thermometer was decreased to 290 cm., in order to have less difficulty with the corrections on the provisional international Kelvin scale, these corrections in and below the field of liquid hydrogen being insufficiently known. As two calibration points the tensions of the thermometer served, placed in liquid helium (May 28th 1920) and in liquid hydrogen (May 29th 1920); the temperatures of these points again follow from the vapour pressure of the bath, using the data from Comm. N°. 147b and N°. 156b.

For the correction of the indications of the thermometer on the provisional international Kelvin scale, we had at our disposal the data of Comm. Suppl. N°. 34a, p. 17, note 4 (obtained from the data of Comm. N°. 102c), in which $B_{-254^\circ C}$ has been taken zero,
Further we have made use of the newly calculated $\Delta t$'s, and from this we deduce Table II.

TABLE II.

<table>
<thead>
<tr>
<th>Filling I. $p_0 = 1140$ c.m. May 18, 1920.</th>
<th>Filling II. $p_0 = 290$ c.m. May 28 and 29, 1920.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{vapour tension}}$</td>
<td>$\Delta t$</td>
</tr>
<tr>
<td>-----------------------------------------</td>
<td>------------------------------------------</td>
</tr>
<tr>
<td>4.20 K.</td>
<td>0.60</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>4.22 K.</td>
<td>0.15</td>
</tr>
</tbody>
</table>

* $\Delta t = (T - T_0) - \left( \frac{T_{\text{He}} - T_0}{100 v} \right)$, in which $v$ is the volume, $T$ the temperature, $T_0$ the reference temperature, $T_{\text{He}}$ the temperature of the helium thermometer, and $P$ the pressure of the gas in the tube. The reference volume $v_0$, according to calculation, may be neglected even with a large density.
and also from Comm. N°. 119 § 5b $B_{4,29K} = -0.000047$\(^1\); Table V of Comm. N°. 156a gives a resumé of the corrections, calculated with the above data. In accordance with note 1 and 3, p. 27, Comm. N°. 156a here $B_s = 0.000489$, $B_{100} = 0.000476$, $\alpha_{45} = 0.0036614$ are taken, and the influence of the $C$'s is neglected\(^3\).

New determinations, to be published shortly, of helium isotherms at $T = 20°, 3°, 3°, 7$ and $3°, 4$ K. gave provisional new values for $B$, which therefore infer the introduction of different corrections in the provisional intern. Kelvin-scale; they are larger than those in Table V, Comm. N°. 156a and they do not come into line so well with those for higher temperatures. For the sake of completeness we give a comparison of these in Table I. (cf. p. 387).

§ 4. **Temperature of the vanishing point.** On May 18th and 28th 1920 all three resistances proved superconducting in liquid helium and behaved, therefore, in the usual way. After this the cryostat was gradually brought to a higher temperature by electric heating of the vaporised helium. At a certain moment the galvanometer moved quickly over 35 c.m. on the scale and the vanishing point was apparently reached; the suddenness of the deflection speaks well for the usefulness of the cryostat if not too high demands are put upon it. A repetition of the heating (very gradually) confirmed the first result. While the temperature was kept constant the thermometer was read at the vanishing point. The results are given in Table III.

<table>
<thead>
<tr>
<th>Data.</th>
<th>Filling</th>
<th>$\rho_{gas}$ thermom. in local m.m. Hg.</th>
<th>$T_{He}$, uncorrected</th>
<th>$\angle t.$</th>
<th>$T.$</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 18, 1920.</td>
<td>I</td>
<td>263.6</td>
<td>6.2(_s)</td>
<td>0.58</td>
<td>6.8 K.</td>
</tr>
<tr>
<td>May 28, 1920.</td>
<td>II</td>
<td>73.9</td>
<td>a. 7.0(_s)</td>
<td>0.15</td>
<td>a. 7.2(_s)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>b. 7.1(_s)</td>
<td>0.15</td>
<td>b. 7.2(_s)</td>
</tr>
</tbody>
</table>

\(^1\) The $B = -0.000047$ is that derived according to $pv = RT + \frac{B}{v}$; the $B$'s further mentioned in this number are those according to $pv = RT\left(1 + \frac{B}{v}\right)$, in agreement with the change of notation mentioned in note 360 of Comm. Suppl. N°. 23.

\(^2\) These values for $B_0$, $B_{100}$ and $\alpha_{45}$ were retained to get the corrections on the provisional internat. Kelvin-scale. Measurements have shown that it would have been more correct to use $B_0 = 0.000513$, $B_{100} = 0.000492$ and $\alpha_{45} = 0.0036613$ (Comm. N°. 103b, Table I and Com. N°. 156a, p. 22, note 1); this would lead to a second provisional internat. Kelvin-scale (helium-Avogadro-scale) for which reason we retain the first $B$'s.
In filling II $a$ is calculated by interpolation between calibration points 20°,24 and 4°,07 K., $b$ by using only the calibration point 20°,24 K. in the same way as in filling I only calibration point 3°,60 K. needed to be used.

The agreement between the measurements with filling I and II is bad. If in filling II we calculate, with the pressure increase of 10,3 m. per degree, the temperature of the helium on May 28th, 1920, the calculation yields 4°,27 K, while the vapour pressure gave 4°,22 K (table II); this is in favour of the measurements on May 28th. If we further take the large $\Delta t$'s in filling I into consideration, a determination with filling I deserves less confidence than one with filling II. We take $T$ vanishing point lead $= 7°,2 K$, although it is still desirable to make a more accurate determination.

§ 5. Comparison of the vanishing point temperatures of lead and uranium lead ($Ra G$).

On May 18th, 1920 the cross-thread of the kathetometer was adjusted to the mercury meniscus in the open tube of the thermometer at the pressure belonging to the vanishing point temperature of $Pb-1919-I$ (the meniscus in the closed tube must of course always be kept on the same mark).

After a decrease of temperature $Isotope Pb-1919-I$ was inserted in the resistance circuit and the temperature again raised. If the galvanometer moved, because the resistance passed through the vanishing point, the meniscus in the tube of the thermometer passed the cross thread; this phenomenon was certain up to 1 m. Hg: "Kahlbaum" lead, atomic weight 207,20 and uranium lead ($Ra G$), atomic weight 206,06 have the same vanishing point temperature within the accuracy of $1/_{4}$ degree. The same result was yielded by $Pb-1919-B$; an influence of the smaller current density in consequence of the larger diameter could not be detected (the strength of the measuring current was always 7,8 m.A.).

§ 6. Resistances above the temperature of the vanishing point.

The results of these measurements are given in fig. 2; the point most to the right, placed within a square, is the result of a measurement in liquid hydrogen. As vanishing point 7°,2 K was taken. To make the curve join properly to the one in the field of liquid hydrogen it must be traced as in the diagram; that is why correspondence with the points marked is defective. The broken crosses have the following meaning; if the difference between the vanishing
point temperatures found on May 18th and May 28th may be attributed entirely to $\Delta t$ having been taken too large on May 18th, all the other temperatures must be recalculated, this recalculation yields the crosses. Although this approximation is theoretically not quite correct, as $T - \Delta t$ and not $T$ ought to rise at every temperature in the same ratio, yet the results are in favour of the suggested assumption.

![Graph](image)

Fig. 2.

- $Pb-1919-I$, 18 May 1920.
- $Pb-1919-B$, 28 May 1920.
- $Pb-1919-B$, 28 May 1920.
- Reduced observations: § 6.