From the curves in fig. 4 we can further calculate that for the lower temperatures the thermal resistance in the supraconductive state is nearly proportional with $T^{-1.7}$, and in the non-supraconductive state with $T^{-1.2}$. As in the case of lead it increases more rapidly than T^{-1}. Proportionality with T^{-1} might be expected from the theory, at least for impure single-cristals. At the lowest temperatures the behaviour is probably entirely determined by chemical impurities and deformations of the lattice. According to the theory of PEIERLS [1]) if heat was transmitted by elastic waves exclusively, an impure single-cristal would have an additional thermal resistance proportional with T, which therefore cannot at all explain the strong increase at low temperatures.

As to the electronic waves, these are dispersed by the impurities and deformations without exchange of energy, as has been shown by NORDHEIM [2]). In case these waves formed the only mechanism of heat-transmission, the law of WIEDEMAN-FRANZ should be valid. As at low temperatures the electrical resistance in the non-supraconductive state is found to become constant, the thermal resistance had to become infinite as T^{-1}. Measurements of GRÜNEISEN and GOENS with impure metals at higher temperatures give a T^{-1} law.

We however find, that the thermal resistance increases more rapidly.

Further experiments only can throw light upon this question.

Finally we express our thanks to Mr. J. BIERMASZ for his valuable help during the measurements, and with the calculations.

[1]) R. PEIERLS, Ann. d. Phys. **5**, **3**, 1055, 1929.
[2]) L. NORDHEIM, Ann. d. Phys. **5**, **9**, 607, 1931.

Physics. — *Experiments to decrease the limit of the temperatures obtained.* By W. H. KEESOM. (Communication N⁰. 219a from the Physical Laboratory at Leiden.)

(Communicated at the meeting of February 27, 1932.)

§ 1. *Introduction.* In 1929 I described [1]) an arrangement which enabled to maintain temperatures below 1° K. in such a way that measurements can be made at those temperatures. Temperature measurements for determining the vapour pressure curve of helium were made [2]) with that apparatus down to a temperature of 0.90° K. Furthermore I could offer Messrs. DE HAAS and VOOGD an opportunity to observe gallium to be superconductive at 1.07° K. [3]).

[1]) These Proceedings **32**, 710, 1929. Comm. Leiden N⁰. 195c.
[2]) W. H. KEESOM, SOPHUS WEBER and G. SCHMIDT. These Proceedings **32**, 1167, 1929. Comm. Leiden N⁰. 202c.
[3]) W. J. DE HAAS and J. VOOGD. These Proceedings **32**, 733, 1929. Comm. Leiden N⁰. 199d.

The importance of research work in the temperature range from 1.1 down to 0.85° K. made possible by that apparatus, urged to proceed to measurements in this field. The progress of that work was seriously impeded, however, by the continuous severe demands put on the liquid helium installation for investigations in the range from 1.15 to about 10° K. So further measuring work in the region of temperatures mentioned above could not yet be carried out. Meanwhile it was possible to make the necessary preparations which enabled us to decrease the limit of the low temperatures obtained, set by KAMERLINGH ONNES [1]) at 0.82° K. in 1921, for something more than 0.1 degree.
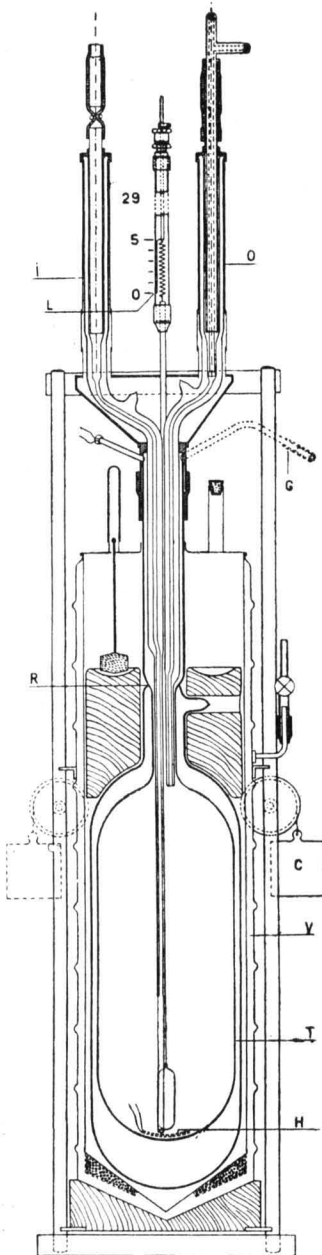
§ 2. *Transport vessel for liquid helium.* For these experiments we transported liquid helium in a separate vessel from the liquefactor to the apparatus [2]). A description of that vessel may be given here.

The construction is so as to reduce to the utmost the helium loss in connecting and disconnecting the vessel with liquefactor or apparatus to be filled, and also to keep the evaporation of the liquid helium sufficiently small.

The silvered vacuum glass T, Fig. 1, with narrow neck is surrounded by a metal vacuum vessel V which is kept filled with liquid air till above the rim R. O is a double-walled tube for filling in, I for siphoning out. The apparatus is drawn connected to the liquefactor. L is the index for indicating the level of the liquid helium. During the transport a small rubber balloon is connected to G for collecting the helium evaporated. H is a heating wire to evaporate the residu of the helium, C are counterweights to facilitate moving up and down when connecting or disconnecting the vessel with liquefactor or apparatus.

Fig. 1.

[1]) H. KAMERLINGH ONNES. Comm. Leiden N⁰. 159 1922.
[2]) W. MEISSNER. Zs. f. Phys. **66**, 483, 1930, already used and described a similar transport vessel for the same purpose.

§ 3. *The apparatus.* In constructing it we have benefited from the experiences gained by KAMERLINGH ONNES in his experiments of 1921. The method we followed was entirely the same.

The two leading ideas that secured the progress now obtained were: First, the exhaust capacity of the pump aggregate which has to remove the helium vapours is largely increased. It was now 675 liter per second, whereas KAMERLINGH ONNES could dispose of a capacity of 40 liter. Second the viscosity resistance in the cryostat was considerably diminished by chosing larger diameters.

On the other hand we did not aim at diminishing the evaporation to the utmost. As a matter of fact the dimensions of the vessel in which the helium was to be cooled to the lowest temperature were not chosen too small, so that after the first experiments it might be possible to proceed to measurements during which some supplementary heat would enter through supply wires or connecting tubes of the measuring apparatus to be introduced into the space to be cooled.

The apparatus is represented in Fig. 2. C is the helium cryostat glass, into which liquid helium from the transport vessel is siphoned over through S. R leads to the pump, with which the pressure above the cryostat helium was reduced, P to the manometer on which that pressure was read. The glass C was suspended by rubber tubing from a connecting piece, in which holes for the tubes just mentioned were spared. This piece again was suspended by rubber tubing from a connecting piece of special form to avoid 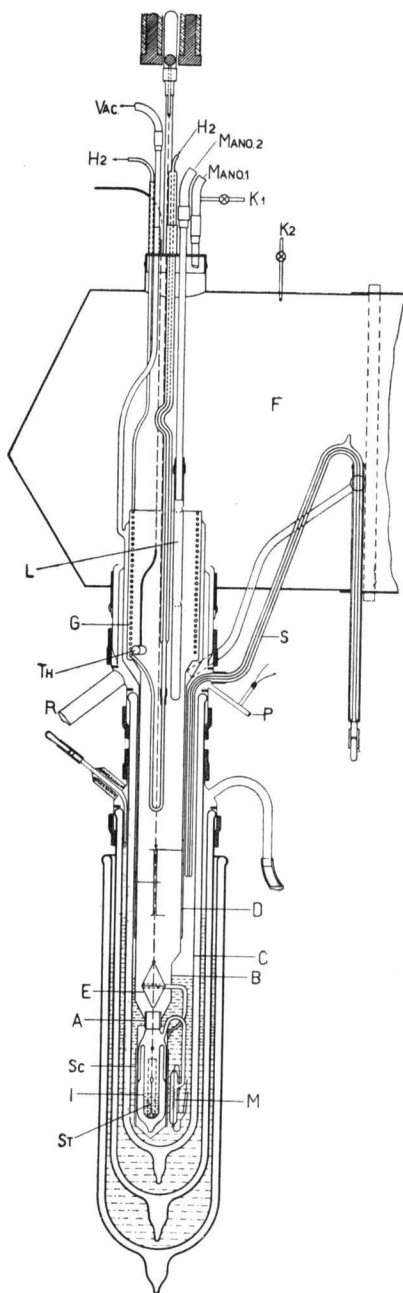as far as possible heat conduction to the parts cooled to liquid hydrogen temperatures. This piece is connected with an iron cap F, which has taken the place of the funnel F of Fig. 1 of

Fig. 2.

Comm. N⁰. 195c. The pump aggregate drawn there was further used without modification.

I is the inner helium glass. It is surrounded by a metal screen *Sc*, in which two small windows have been spared. These can be shut by means of a screen which can be moved from outside. *M* is a hot wire manometer.

The inner helium vessel is soldered to a chrome-iron connecting-piece *A*, which again is soldered to the single-walled tube *B*. This is connected to a vacuum tube *D*. *St* is a stirring rod, which is continuously moved up and down by a motor. *E* is a double cone, which by conduction is maintained at the temperature of the surrounding helium bath. It serves to shield off radiation from above. Its form is chosen so that the helium vapours will suffer only little resistance. *G* is a spiral through which liquid hydrogen is led to cool this part of the apparatus and in this way to diminish the viscosity in the upper part of the apparatus. The temperature there is read with the helium thermometer *Th*. *L* is a tube which could be moved up and down from outside and had an opening sideways near the lower end. This tube served to measure the pressure at some different heights in the apparatus, to get an idea about the distribution of the viscosity resistance [1]).

§ 4. *The experiments.* Experiments to decrease the limit of the temperatures obtained were performed at December 15 and 22, 1931, and on February 10 and 18 of this year. On the three days mentioned first the apparatus did not appear to give fully what could be expected. So we restrict ourselves to a brief description of the experiment on the day last-mentioned.

At 13ʰ15 the transport vessel is filled with 2.35 liter liquid helium. The vessel is disconnected from the liquefactor and transported to the cryostat. This has been cooled preliminarily with liquid hydrogen.

The transport vessel is connected to the cryostat and liquid helium siphoned over. The pressure above the liquid helium in *C* (Fig. 2) is somewhat reduced and by the small overpressure obtained by this helium is condensed within *B*. When the inner vessel *I* is sufficiently filled condensing is stopped. Now liquid helium is again siphoned over into *C* to replace the quantity evaporated, the transport vessel is disconnected. Then 0.6 liter is left in the transport vessel. The pressure in *C* is then further reduced.

In the meantime the cooling of the spiral *G* by liquid hydrogen is started, and the high vacuum pump aggregate is set working. The helium in *I* is continuously stirred. At 14.20 the pressure in the exhaust cap *F* is 2.0 μ of mercury, the sound tube *L* shows 5.1 μ, the level of the inner helium is at 4.1 cm. above the bottom of *I*. Pressure above the liquid helium in the cryostat is kept at 8 mm.

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[1]) It appeared that the viscosity resistance was distributed rather uniformly. We conclude that dimensions and temperatures of the apparatus have been properly chosen.

At 14.25 the hot wire manometer is read : 5.3 μ ; pressure in the exhaust cap 1.78 μ, in the sound tube (lowest position, cf. Fig. 2) 3.8 μ.

The pressure decreases regularly, at 14.40 the hot wire manometer shows 4.0 μ, it then still slowly decreases to 3.8 μ at 15.02 (temperature 0.71° K.). Cf. the course of the pressure in Fig. 3. The thermometer Th shows —236° C. Volume of the liquid helium in I 5.0 cm³.

In the meantime the level of the helium in the cryostat vessel has descended so far that we decide to refill. This is made between 15.30 and 16.00.

At 16.15 the pressure in the hot wire manometer is 3.67 μ. The windows in Sc are now closed. The pressure in the exhaust cap is 0.84 μ, in the sound tube 2.3 μ. Th shows —243° C. The sound tube is moved 10 cm. higher.

At 16.20 the hot wire manometer shows 3.60 μ. This is the lowest pressure obtained (cf. Fig. 3). The pressure in the exhaust cap is 0.75 μ. Level of the liquid helium in I 1.1 cm. above the bottom (volume 1.4 cm³).
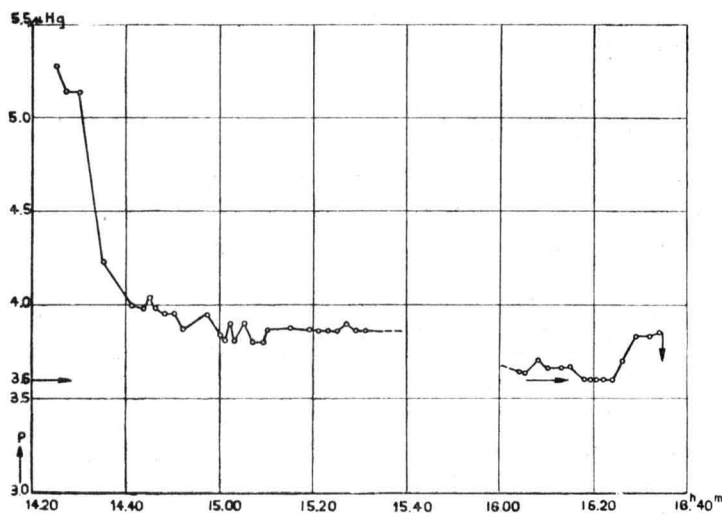

Fig. 3

The helium is still an easily mobile liquid. To the stirring rod every time a small quantity of liquid adheres which then falls down in a couple of drops. Capillarity and refractive index have apparently increased.

Some pressure measurements are made, with the sound tube being moved up another 10 cms. at 16.22. At 16.34 the pressure in the hot wire manometer suddenly drops. The inner vessel I is empty.

Then the zero current of the hot wire manometer is measured, and some calibrations at adjusted values of the pressure are made (cf. § 5).

At 17.50 the experiment is finished.

§ 5. *Measurement of the pressure.* The pressure above the liquid

helium was measured with a hot wire manometer immersed in the cryostat helium bath. For the manometer a phosphorbronze wire was used, diameter 51 μ, length about 15 cm., wound to a spiral with length about 2 cm., diameter about 2 mm. The resistance was 10.41 Ω at room temperature, 6.36 Ω at 1.65° K. The wire was heated to 7.4 Ω (temperature 4.2° K.).

The manometer was calibrated by comparison with the pressure read in the exhaust cap F (Fig. 2), when in the inner vessel I no liquid helium was left, but otherwise the temperatures in the whole apparatus still were the same as with the pressure measurements. A correction was applied for the thermomolecular pressure difference. This correction amounted to 1.6 μ at the calibration points 4.6 μ. This correction is not quite certain, as it depends on an extrapolation to higher values of the ratio diameter of the tube: mean free path at the temperatures in the apparatus. If the value assumed should not be exact, it is rather more probable that it is taken too large then too small. If the correction ought to be smaller, the pressures above the evaporating helium would be to a corresponding amount smaller than the values we give.

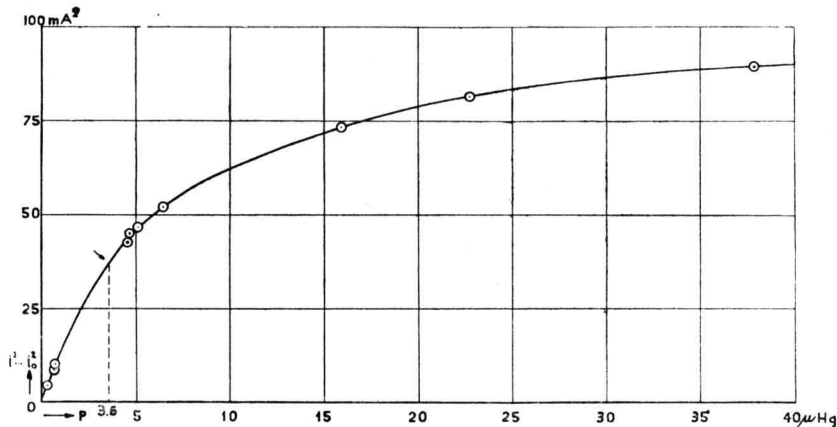Fig. 4 shows the results of the calibrations. i is the current necessary to

Fig. 4

heat the manometer wire to the adopted resistance, i_0 the same for $p = 0$. The lowest pressure measured above liquid helium is indicated by an arrow.

§ 6. *The lowest temperature reached.* KEESOM, WEBER and SCHMIDT [1]) deduced from their measurements on the vapourpressure curve of helium two formulae for the connection between saturated vapour pressure and temperature, one for temperatures above 2.19° K., another for temperatures below 2.19° K. These formulae are to be considered as a purely empirical representation of the results of those measurements. The authors remark [2])

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[1]) Cf. p. 136, footnote 2.
[2]) Cf. Comm. N⁰. 202c § 5.

that in deriving those formulae, they did not consider the values of the heat of vaporisation, nor the question whether the latter formula is the best for extrapolation to lower temperatures.

The latter question is of special importance now that with the aid of the vapour pressure formula we have to extrapolate from 0.90° K., being the lowest temperature measured with the helium thermometer, downwards.

Meanwhile measurements of the specific heat of liquid helium, made in collaboration with Dr. K. CLUSIUS, have given new data which can render service in deducing a new vapour pressure formula. By taking account of these results the following formula was derived:

$$log_{10} \ p_{cm} = -\frac{3{,}018}{T} + 2{,}484 \ log_{10} \ T - 0{,}00297 \ T^4 + 1{,}197,$$

valid for $T < 2.19°$ K.

It has the following advantages above the formula given in Comm. N⁰. 202c. The coefficient of $log \ T$ and the constant term have the values expected by theory. The formula concurs with the results of the specific heats of the liquid, and also accounts better (though not completely) for the values of the vaporisation heat [1]). It is made to agree with the formula of Comm. N⁰. 202c at 1° K. Between 1.7 and 2° K. it represents the measurements of the vapour pressure as well as the previous formula, from 2 to 2.19° K. rather better. On the other hand the temperatures according to this new formula are at 1.4° K. about 0.01 degree higher than those given by the previous formula and about 0.015 degree higher than the experimental values. This amount is rather the limit of accuracy of the temperature measurements in this territory. For the rest further measurements on the thermomolecular pressure difference will have to show whether a small correction has still to be applied to the results of the temperature measurements of Comm. N⁰. 202c or not.

We now prefer to choose the temperature scale fixed by the equation given above. On that scale a pressure of 3.60 μ corresponds to a temperature of 0.707° K. Rounding off we put the lowest temperature obtained at 0.71° K.

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[1]) L. I. DANA and H. KAMERLINGH ONNES. These Proceedings 29, 1051, 1926. Comm. Leiden N⁰. 179c.

Summary.

A temperature of 0.71° K. is reached in a volume of 5 cm³. by exhausting the vapours from liquid helium. The lowest pressure obtained above the liquid helium which was stirred continuously was measured to be 3.6 μ of mercury.

A vessel is described in which liquid helium can be transported from the liquefier to an apparatus.

Physics. — *The specific heat of solids at temperatures obtainable with liquid helium.* IV. *Measurements of the atomic heats of tin and zinc.* By W. H. KEESOM and J. N. VAN DEN ENDE. (Comm. N⁰. 219*b* from the Physical Laboratory at Leiden).

(Communicated at the meeting of February 27, 1932.)

§ 1. *Introduction.* These measurements are a continuation of our investigations on the specific heats of lead and bismuth [1]). They concern the atomic heats of tin and zinc between 1.3 and 21° K.

We chose the metals tin and zinc, because we could expect that the heat capacity of a not too large block of these materials, even at the lowest temperatures, would be still large enough to make measurements possible with the desired accuracy. Besides we should be able to compare the atomic heat of tin, which becomes supraconductive at 3.70° K. [2]) with that of zinc, which does not become supraconductive.

§ 2. *Method.* We followed the method described in Comm. N⁰. 203*d*, with the following improvements:

1. Besides constantin we used as thermometer wire also phosphor-bronze. This made measurements below 7° K. much more accurate [3]). The thermometers consist of a spiral of constantin wire 0.1 mm. thick (annealed as usual) and a spiral of phosphorbronze wire 0.05 mm. thick (not annealed). These spirals are attached to a mica cross (see Fig. 1) fixed to a copper cap C_3, which closes the inner cylinder C_2 of the core.

To avoid too many supply wires, the thermometer wires are connected as is drawn in Fig. 2. The platinum wires *A, B* and *C* are fixed together in a small glass cross *D,* they are mutually isolated by means of very thin glass capillaries. This glass cross is fixed in a copper tube *E,* which is soldered to the cap C_3. For the rest this core is almost the same as at previous measurements.

[1]) These Proceedings **33**, 243, 1930. Comm. Leiden N⁰. 203*d*, see also these Proc. **34**, 210, 1931. Comm. Leiden N⁰. 213*c*.

[2]) H. KAMERLINGH ONNES, Comm. Leiden N⁰. 133*d*. Compare J. VOOGD, Thesis, Leiden, 1931.

[3]) Cf. these Proceedings **32**, 1171, 1929. Leiden Comm. N⁰. 203*c*.