Physics. — "On the Hall effect, and on the change in electrical resistance in a magnetic field at low temperatures. VIII. The Hall effect in Tellurium and Bismuth at low temperatures down to the melting point of hydrogen". By H. KAMERLINGH ONNES and BENGT BECKMAN. Communication N°. 132d from the Physical Laboratory at Leiden. Communicated by Prof. H. KAMERLINGH ONNES.

(Communicated in the meeting of December 28, 1912).

§ 20 [1]). *The HALLeffect in Tellurium*. The measurements were made with a short period WIEDEMANN galvanometer. The primary current was $J = 0.2$ amp. Two plates were investigated, both constructed from the purest MERCK tellurium. The first plate Te_{pI} was compressed in a steel mould, and the second plate Te_{pII} was cast in a steel mould. The first plate was very brittle. Both plates were circular with a diameter of 1 cm. The electrodes were platinum wires $^1/_2$ mm. in diameter, and were fused into the plates. To these platinum wires the leads were then soldered. The specific resistance and its temperature coefficient were different for the two plates; at $T = 289°K$. w_{sp} was twice as great for the first as for the second. The resistance temperature coefficient for Te_{pI} was always negative over the whole temperature region $289° > T > 20°.3$ K. Te_{pII} on the other hand exhibited a minimum in the resistance below $T = 70°K$.

The thickness of the plate Te_{pI} was 1.175 mm., its resistance

$$\text{at } T = 290°.\text{K} \quad \text{was} \quad w = 0.8 \ \Omega$$
$$20°.3 \quad w = 3.0$$

and again at $\quad\quad T = 290°. \quad\quad w = 1.0$;

at low temperatures therefore the resistance is considerably increased; cooling, moreover, caused an increase in the resistance at ordinary temperature, which is probably due to the production of small fissures.

At $T = 290°$ the specific resistance was 1.95×10^3 c. g. s. We obtained the following results (RH and R given in c. g. s. units): (see table XXV p. 998).

At $T = 290°$ the specific resistance of Te_{pII} was 1.01×10^3 c. g. s. The plate was 1.88 mm. thick. The change in the resistance with temperature is shown in Table XXVI and in fig. 5 [2]).

Hence, as has already been mentioned, the resistance of the plate Te_{pII} attains a minimum at about 40° to 60° K. This behaviour is somewhat similar to that found by DEWAR to be characteristic of

[1]) The sections of this Communication are numbered as continuations of Comm. No. 132a.

[2]) The diagrams are numbered as continuations of those in Comm. No. 132a.

TABLE XXV.				

HALLeffect for Te_{pI}				
H	$T = 290°$ K.		$T = 20°.3$ K.	
in gauss	RH	R	RH	R
3750	14.65×10^4	39.1	16.1×10^4	43.1
5640	22.4	39.7	—	—
7260	29.0	40.6	31.9	44.2
9065	35.4	39.1	41 4	44.5
10270	40.2	39.1	46 6	45.3

bismuth containing only a slight amount of impurity, and by J. KOENIGSBERGER, O. REICHENHEIM, K. SCHILLING [1]) for a kind of pyri-

TABLE XXVI.	

Variation of the resistance of Tellurium, Te_{pII}, with temperature.	
T	w
289° K	0.212 Ω
170.8	0.146
162.3	0.144
153.1	0.141
141.8	0.136
90	0.119
80	0.117
69.5	0.113
20.3	0.122
17.7	0.124
14.5	0.126

[1]) J. KOENIGSBERGER. Jahrb. d. Rad. u. Elektr. 4, p. 158, 1907.
   O. REICHENHEIM. Inaug.-Diss. Freiburg i. Br. 1906.
   J. KOENIGSBERGER und K. SCHILLING. Ann. d. Phys. 32, p. 179, 1910.

tes, 'for magnetite, metallic titanium and metallic zirconium, a phenomenon explained by J. KOENIGSBERGER by the dissociation of electrons from the atoms.
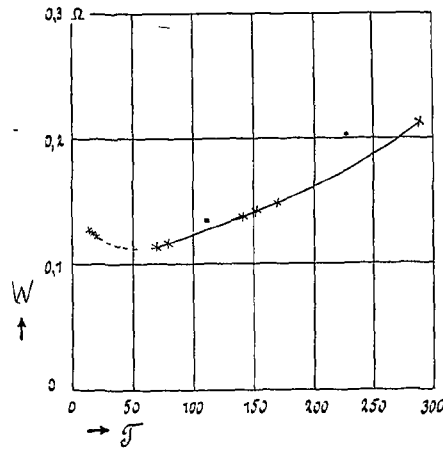

Fig. 5

With this plate, too, an increase of the resistance was observed on returning to ordinary temperature $T = 290°$ K after having cooled it to hydrogen temperatures. In this case, however, it was much smaller than with Te_{pl}, and was, at the most, $5°/_0$. We obtained the following results:

	TABLE XXVII.							
	HALLeffect for Te_{pII}							
H in gauss	$T = 291°$ K		$T = 89°$ K		$T = 20.°3$ K		$T = 14.°5$ K	
	RH	R	RH	R	RH	R	RH	R
3720	6.90×10⁵	185.5	7.85×10⁵	210.5	7.98×10⁵	214.5	7.85×10⁵	211
5680	10.55	186	11.95	210	12.1	213	11.85	208.5
7260	13.6	187	—		15.4	212	15.0	206.5
9065	16.75	185	18.75	207	19.05	210	18.65	205.5
10270	18.85	183.5	21.25	207	21.4	208.5	21.0	204.5

At any definite temperature R is practically constant for various fields; at lower temperatures there is an indication that R diminishes somewhat in the stronger fields; this is most marked at hydro-

65*

gen temperatures at which R_0 (R for $H = 0$) is about $5°/_0$ greater than R for $H = 10000$.

For both plates the HALLeffect increases at lower temperatures, while the ratio $\dfrac{R_{20°K}}{R_{290°K}}$ is the same. This is very remarkable, for the plates are completely different with regard to their specific resistance, resistance temperature coefficient and absolute magnitude of the HALLeffect. For both plates the value of the HALLeffect is small compared with that obtained by A. v. ETTINGHAUSEN and W. NERNST[1]), 530, and also by H. ZAHN [2]), and the electrical conductivity is also small. According to the researches of A. MATTHIESEN[3]), F. EXNER[4]), W. HAKEN[5]), J. F. KRÖNER[6]) and others, various modifications of tellurium occur; according to KRÖNER it exhibits dynamical allotropy. The two modifications have very different conductivities. The specific gravity of the plate $Te_{\mu II}$ was 6.138; this is perhaps connected with the circumstance that it cooled slowly after casting, and that it was subjected to local heating when fusing in the electrodes. For a preparation very quickly cooled KRÖNER gives a specific gravity as low as 5.8. The modification with the lowest specific gravity seems to have the smallest electrical conductivity.

§ 21. *The HALLeffect in Bismuth crystals.* In Table XIII, Comm. N°. 129a, we gave results of measurements of the HALLeffect in bismuth crystals for the case in which the crystalline axis is perpendicular to the field, and the main current runs in the direction of the axis. To these we are now in a position to add results for the case in which the field is parallel, and the main current perpendicular, to the axis. For these measurements we used one of the crystal prisms which had been used by VAN EVERDINGEN (Suppl. No. 2) in his measurements, choosing the most regular of the three (2, 3 and 5 1. c.) which had been found suitable for this purpose (cf. p. 82 1. c.).

In the following Table are given R, H and RH in c.g.s.

At ordinary temperature and in weak fields RH is negative, as was first discovered by VAN EVERDINGEN and subsequently confirmed by J. BECQUEREL [7]).

1) A. VON ETTINGHAUSEN und W. NERNST. Sitz. Ber. Akad. d. Wiss. Wien. 94, p. 560, 1886.

2) H. ZAHN. Ann. d. Phys. 23, p. 146, 1907.

3) A. MATTHIESEN und M. VON BOSE. Pogg. Ann. 115, 385, 1862.

4) F. EXNER. Sitz. Ber. Akad. d. Wiss. Wien. 73, 285, 1876.

5) W. HAKEN. Inaug. diss. Berlin 1910.

6) J. F. KRÖNER. Inaug. diss. Utrecht 1912.

7) J. BECQUEREL, C. R. 154, p. 1795. June 24, 1912.

In stronger fiields RH becomes positive, as was also found to be the case by VAN EVERDINGEN and BECQUEREL. We, may, however, incidentally remark that the initial negative values found by BECQUEREL are much greater than ours, and that with him zero is reached in much stronger fields than with us. This leads us to suspect that the initial negative values we have obtained are to be ascribed to some cause which occasioned their occurrence to a much higher degree in BECQUEREL's experiments; this would be the case, for instance, if our bismuth were purer than his, but still not yet quite free from impurity. If that were the case, then with absolutely pure bismuth we should, perhaps, at ordinary temperature, obtain nothing but increase of RH with the field, the rate of increase being slower in the initial stages.

TABLE XXVIII.

Hall-effect for a Bismuth crystal with its axis parallel to the field.

$T = 290°$ K.			$T = 90°$ K.			$T = 20°.3$ K.			$T = 14°.5$ K.		
H	RH	R	H	RH	R	H	RH	R	H	RH	R
1000	-0.05×10^3	-0.05	1005	$+3.4 \times 10^3$	$+3.4$	1670	$+5.2 \times 10^3$	$+3.11$	2970	$+8.55 \times 10^3$	$+2.88$
1660	$+0.09$	$+0.06$	2490	$+7.8$	3.13	2740	7.95	2.90	5680	15.5	2.73
2970	$+0.86$	$+0.29$	4220	12.2	2.89	3720	10.45	2.81	8260	22.1	2.69
3720	$+1.57$	$+0.42$	5710	15.9	2.78	5680	15.4	2.71	10270	27.4	2.67
5680	$+4.12$	$+0.72$	7300	20.0	2.75	7260	19.3	2.66			
7260	$+6.60$	$+0.91$	9110	24.7	2.71	9065	24.0	2.65			
9065	$+9.8$	$+1.08$	10320	27.7	2.69	10270	27.2	2.65			
10270	$+11.9$	$+1.19$									

But one can still quite well imagine, however, that at higher temperatures negative values can be obtained in weaker fields in the course of the change which RH as a function of H undergoes with the temperature. The part played by admixture would then be restricted to a displacement of the temperature at which a negative value could still just appear, and this temperature would be higher for bismuth of greater purity than for impure bismuth. This would be analogous to the diminution of the negative effect at lower temperatures in the case discussed in § 14 of Comm. No. 129c in which the axis stands perpendicular to the field.

At lower temperatures we found the HALLeffect positive in all fields, which is not what BECQUEREL found to be still the case at liquid air temperatures. It is further worth noting that RH shows no further change with temperature below the temperature of liquid air. This makes it important to amplify the measurements given in Table XIII for the axis perpendicular to the field by others at the temperature of liquid air.

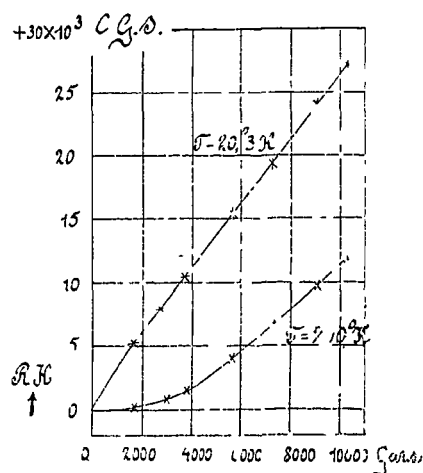It is seen from Fig. 6 that for fields greater than 2000 gauss at

Fig. 6.

low temperature, and in fields greater than 6000 gauss at ordinary temperature, RH is clearly a strictly linear function of the field. If we write

$$RH = a'H + b',$$

in this region, we obtain

$T = 290\ °K$	$T = 90\ °K$	$T = 20.3\ °K$
$a' = +1.7$	$a' = +2.56$	$a' = +2.56$
$b' = -5600$	$b' = +1300$	$b' = +1100$

§ 22. *Remark upon the increase in the resistance of bismuth in a magnetic field.* A friendly remark by Prof. H. DU BOIS leads us to a further development of our ideas concerning the occurrence of a maximum in the isopedals for the increase in the resistance of bismuth.

Our measurements make it probable that the maximum found by BLAKE at the temperature of liquid air must be ascribed to the presence of impurity or to some modification occasioned, for instance, by mechanical treatment, and that this maximum is not obtained with pure normal bismuth at these temperatures. The values which we obtained at the boiling point of hydrogen make it also certain that neither is a maximum to be found between the temperatures of liquid air and of liquid hydrogen. In the region of hydrogen temperatures a falling off in the rate of increase of the resistance of the bismuth wires is clearly apparent. The existence of this diminution has been proved twice, and on each occasion for different currents (and, as is evident from the table, for various fields). But a maximum, that is, to say, a return to smaller values, we have not obtained. From the course of the curves given by BENGT BECKMAN in Comm. N°. 130a, it still remains possible that the phenomenon reaches a limiting value. From various analogous phenomena we might quite well expect something of this kind to happen at extremely low temperatures. In Comm. N°. 129a we commented under I, § 2, upon the uncertainty as to whether a maximum is reached at these temperatures, or rather an asymptotic approach would be found to be made to a limiting value, stating that "Perhaps as the purity increases the maximum in the isopedals is displaced towards lower temperatures". The measurements we have made with the plates *Bi* lay further emphasis upon the "perhaps." As the temperature falls to 20° K the plates $Bi_{p}I$, $Bi_{p}II$, which were not so pure as the wire, exhibit no diminution in the rate of increase. And yet, on account of the greater impurity suspected in these plates, they should be expected to exhibit a maximum between 14.°5 and 73°.K, if there were a maximum for pure bismuth at temperatures lower than 14°.5 K and if this maximum were displaced towards lower temperatures only by an increase in the purity of the material. In contrast with this we here find that only the diminution in the rate of increase remains between 20° K and 14°5 K. Further experiments upon different bismuth preparations are of course highly desirable.