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Physics. — "*On the* HALL *effect and the change in the resistance in a magnetic field at low temperatures.* II. *The* HALL-*effect and the resistance increase for bismuth in a magnetic field at, and below, the boiling point of hydrogen*". By H. KAMERLINGH ONNES and BENGT BECKMAN. Communication N°. 129^c from the Physical Laboratory at Leiden.

V. *Linear variation in strong fields.*

§ 14[1]. *Linear variation of the* HALL *effect for bismuth in strong fields.*

a. As was suggested by J. BECQUEREL[2], the fact that the HALL effect for bismuth in strong fields can be represented by a linear function of the field strength may be regarded as resulting from the composition of the effect from two separate components. One of these is proportional to the field, and was found by us (see Comm. N°. 129*a* § 4) to be always negative for plates of compressed electrolytic bismuth. The second approaches a limiting value, and, with our plates, was found to be constant at hydrogen temperatures, in fields greater than 3 kilogauss.

That is to say, the law of linear dependence upon the field is rigidly obeyed by the first component of BECQUEREL, within the limits of experimental error in fields greater than 3 kilogauss. As an example we give in Table XIV values calculated from

$$RH = a'H + b' \quad . \; . \; . \; . \; . \; . \; . \; . \quad (3)$$

in which $a' = 54.3$ and $b' = 42.10^3$

(with both a' and b' in absolute units), and alongside these we put values for $T = 20°.3$ K. taken from Table III.

The linear form is found to be just as rigidly obeyed in the experiments made by BENGT BECKMAN upon the same experimental material at the temperature of liquid air; for an account of these experiments we may refer to § 3 of the Communication N°. 130*a*.

It is noteworthy that, in the case of the second component, saturation is most easily attained at low temperatures. In this respect this component is analogous to the magnetization of a ferromagnetic substance. The linear dependence of the first component upon the field strength recalls the behaviour of diamagnetic polarisation. In the region of very low temperatures the very rapid variation of a' with the temperature can be represented by a simple empirical formula which was obtained by compounding the data given by BECKMAN for liquid air temperature (see Communication N°. 130*a*). From this it was found that

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[1] The sections of this paper are numbered in continuation of those of Comm. No. 129*a*.

[2] C. R. **154**, 1795, 1912.

TABLE XIV.

Linear variation of the **Hall** effect for Bi_{pII} in strong fields $T = 20^\circ.3$ K.

H	RH Obs.	RH Calc.
3450	230×10^3	229×10^3
5660	350	352
7160	431	434
8520	503	507
9880	583	582
11090	647.5	647
12090	700	702

$$a' = a'_0 e^{-\beta' T} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad (4)$$

within the temperature region 90° K. $\geq T \geq 14^\circ$ K. A much more complicated formula would be required to embrace the observations at higher temperatures as well.

On going down to liquid hydrogen temperatures the constant b', the maximum value of the second **Becquerel** component, which is negative at ordinary temperature becomes positive in the case of Bi_{pI} and Bi_{pIII}. **Beckman**'s investigations upon the same plates at the temperature of liquid air show that the reversal of the sign must take place below 72° K.

b. With regard to crystals we have already stated in § 13 that, when the crystalline axis is perpendicular to the field, the **Hall** effect is negative at ordinary temperature, and approaches a limiting value. To this we may now add that with another rod also with its axis perpendicular to the field we found, at ordinary temperature, a maximum at $H = 9500$, and then a decrease (10^{-3} RH fell from 37 to 35,4); this leads us to suspect that proceeding to stronger fields than those we employed would have brought to light the same behaviour in the case of the rod quoted in § 13. At hydrogen temperatures the sign of the **Hall** effect reverses and becomes positive, increasing linearly with the field for fields above 3 kilogauss [1]. From this it appears that in

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[1] J. **Becquerel** draws attention to the fact that at low temperatures RH becomes very large. The values we here give for hydrogen temperatures make this all the more striking. For Bi_{pII} we obtained $RH = 500 \,.\, 10^3$ for $H = 8500$. With this plate, indeed, at the temperature $T = 90^\circ$ K. we get a higher value ($RH = 214 \,.\, 10^3$ for $H = 8500$) than that given by **Becquerel** for his plates. From his data (loc. cit.) we calculate for the temperature of liquid air $RH = 168 \,.\, 10^3$ (or $R = +19.8$) for $H = 8500$.

the case of the axis perpendicular to the field, the positive effect must be much weaker at ordinary temperature than the negative, and begins to be appreciable only at very low temperatures. What we have found for the case of the axis perpendicular to the field is analogous to what BECQUEREL obtained with the axis parallel to the field.

With our crystalline rod placed in a definite position the value of the field at which the second component attains saturation at hydrogen temperatures is the same as that at which a plate consisting of crystals of various orientations (for instance, a plate of compressed electrolytic bismuth) reaches saturation. That is to say, on going down to hydrogen temperatures, the saturation field appears to be independent of the orientation.

§ 15. *Linear variation of the increase of resistance of bismuth in strong fields.*

In § 2 we remarked that in strong fields the resistance varied directly as the field. For fields of 12000 gauss upwards we find

$$\frac{w'}{w} = aH + b \quad . \; . \; . \; . \; . \; . \; , \; . \; . \quad (1)$$

(cf. fig. 1 of the Communication N°. 130*a* by BENGT BECKMAN) where the values of a and b vary greatly with peculiarities of the bismuth employed (wire or various plates made from compressed electrolytic bismuth).

It is worth noting that the coefficient a of the linear variation of resistance, and the coefficient a' of the linear variation of the HALL effect can, for temperatures below that of liquid air, be represented by the same functions of the temperature, so that we may write

$$a = a_0 e^{-\beta T} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (2)$$

This is found to be the case when we use the values given by BENGT BECKMAN for the temperature of liquid air (see sections 2 and 3 of the Communication N°. 130*a*) in conjunction with those contained in Tables I, II, and III. If we remember that the values of β and β' can differ greatly for the different plates,

(for Bi_{pI} $\beta = 0{,}023$ and $\beta' = 0{,}023$
,, Bi_{pII} $\beta = 0{,}014$,, $\beta' = 0{,}006$
,, Bi_{dI} $\beta = 0.027$)

it is evident that we can as yet give no answer to the question as to whether the values of β and β' are the same or not for pure bismuth, and the agreement in the case of $Bi_{,I}$ can quite well be accidental.

The constant b, which is very small at ordinary temperature, becomes large and negative at hydrogen temperatures.