Citation:

H. Kamerlingh Onnes & Beckman, B., On the Hall-effect and on the change in resistance in a magnetic field at low temperatures. VII. The HALL-effect for gold-silver alloys at low temperatures down to the melting point of hydrogen, in:
KNAW, Proceedings, 15 II, 1912-1913, Amsterdam, 1913, pp. 988-996

Physics. — "*On the* HALL *effect, and on the change in resistance in a magnetic field at low temperatures.* VII. *The* HALL *effect for gold-silver alloys at temperatures down to the melting point of hydrogen*". By BENGT BECKMAN. Communication No. 132*c* from the Physical Laboratory at Leiden. (Communicated by Prof. H. KAMERLINGH ONNES).

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

This communication is a continuation of Comm. N°. 130*b*.

IV. *Gold-silver alloys.*

§ 10. Measurements at temperatures of 290° K., 20°.3 K. and 14°.5 K. of the HALL effect for three *Au-Ag* alloys (I, II, III) containing a large percentage of gold were published by KAMERLINGH ONNES and myself in Comm. N°. 129*a*, § 12, and in Comm. N°. 130*c*, § 16. The results of my measurements made on one (I) of these alloys at 90° K. were given in § 9 of Comm. N°. 130*b*. I have since investigated three other alloys containing a greater percentage of silver. and in the present paper the results of these new measurements on the HALL effect for *Au-Ag* alloys are given and are discussed in connection with the former results.

The observational method was the same as was formerly used, viz. the form of the compensation method developed by LEBRET [1]) as used by VAN EVERDINGEN [2]). An iron-clad THOMSON galvanometer was used, with a period of about 4 secs, and a sensitivity of about 1 mm. deflection at 2.5 m. distance for 5×10^{-8} volts. In this method disturbances produced by the thermo-currents arising from the thermo-magnetic effect of VON ETTINGSHAUSEN are completely eliminated only in the case of instantaneous closing of the main current circuit. On account of the comparatively large period of the galvanometer this was not possible in the present experiments; but still, these disturbances were too small in the present case to be observed.

The main current was 0.5 to 1 amp. The plates were circular (11 mm. diam.) with point electrodes. The resistance of the plates was measured as well as the HALL effect.

The alloys were obtained by fusing pure gold and silver in a porcelain crucible, and then rolling them out. They were all submitted to analysis. I am greatly indebted for these analyses to

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[1]) LEBRET, Diss. Leiden 1895. Comm. Leiden N°. 19, 1895.

[2]) E. VAN EVERDINGEN, Comm. Leiden. Suppl. N°. 2. Cf. also H. KAMERLINGH ONNES and B. BECKMAN, Comm. N°. 129a, 1912.

Dr. C. Hoitsema, Master of the Royal Mint, Utrecht, and to Fil. Lic. G. Karl Almström, Upsala.

In the Tables, H represents the field strength in gauss, R the Hall coefficient in c. g. s. units, w_T the resistance in ohms at the absolute temperature T, and w_0 the resistance at 0° C.

Alloy II contained 10.7 atomic percentages of silver. The thickness of the plate was 0.049 mm.

TABLE XVI.

Hall effect for $(Au—Ag)_{II}$

H	$T = 290°$ K.		$T = 90°$ K.	
	RH	$-R \times 10^4$	RH	$-R \times 10^4$
8250	5.25	6.36	4.26	5.16
9360	—	—	4.96	5.31
9750	6.25	6.41	5.08	5.21
10270	6.51	6.34	5.45	5.31
0	$w = 8.06 \times 10^{-4}\ \Omega$ $\frac{w}{v'_0} = 1.03$		$w = 5.43 \times 10^{-4}\ \Omega$ $\frac{w}{w_0} = 0.69$	

Alloy III contained 30 atomic percentages of Ag. The plate was 0.078 mm. thick.

TABLE XVII.

Hall effect for $(Au—Ag)_{III}$.

$T = 290°$ K.			$T = 90°$ K.		
H	RH	$-R \times 10^4$	H	RH	$-R \times 10^4$
8250	5.03	6.10	9065	4.26	4.70
9360	5.70	6.09	9750	4.55	4.67
10270	6.18	6.02	10270	4.83	4.70
0	$w = 9.47 \times 10^{-4}\ \Omega$ $\frac{w}{w_0} = 1.015$		0	$w = 7.71 \times 10^{-4}\ \Omega$ $\frac{w}{w_0} = 0.825$	

Alloy IV contained 69.4 atomic percentages of *Ag*. The plate was 0.083 mm. thick.

TABLE XVIII.

HALL effect for $(Au-Ag)_{IV}$.

H	$T=287^\circ K$		$T=90^\circ K$		$T=20^\circ.3\,K$		$T=14^\circ.5\,K$	
	RH	$-R\times10^4$	RH	$-R\times10^4$	RH	$-R\times10^4$	RH	$-R\times10^4$
9220	5.55	6.02	4.77	5.17	4.12	4.47	4.08	4.43
9760	5.76	5.90	5.12	5.25	4.40	4.51	4.26	4.37
10270	6.20	6.04	5.41	5.27	4.66	4.54	4.55	4.43
0	$w=9.8\times10^{-4}\Omega$ $\frac{w}{w_0}=1.01$		$w=8.43\times10^{-4}\Omega$ $\frac{w}{w_0}=0.875$		$w=7.92\times10^{-4}\Omega$ $\frac{w}{w_0}=0.82$		$w=7.90\times10^{-4}\Omega$ $\frac{w}{w_0}=0.82$	

Alloy V contained 90.9 atomic percentages of *Ag*. The plate was 0,082 mm. thick.

TABLE XIX.

HALL effect for $(Au-Ag)_{V}$

H	$T=290^\circ$ K.		$T=90^\circ$ K.		$T=20.^\circ3$ K.		$T=14.^\circ5$ K.	
	RH	$-R\times10^4$	RH	$-R\times10^4$	RH	$-R\times10^4$	RH	$-R\times10^4$
9065	6.62	7.31	5.88	6.49	5.22	5.76	5.16	5.69
9760	7.23	7.42	6.30	6 45	5.59	5.73	5.66	5.80
10270	7.52	7.32	6 58	6.40	5.98	5.82	5.86	5.71
0	$w=5.29\times10^{-4}\Omega$ $\frac{w}{w_0}=1.025$		$w=3.81\times10^{-4}\Omega$ $\frac{w}{w_0}=0.735$		$w=3.40\times10^{-4}\Omega$ $\frac{w}{w_0}=0.66$		$w=3.40\times10^{-4}\Omega$ $\frac{w}{w_0}=0.66$	

Alloy VI contained 97.8 atomic percentages of *Ag*. The plate was 0.093 mm. thick.

TABLE XX.

Hall effect for $(Au-Ag)_{VI}$

H	$T = 290°$ K.		$T = 90°$ K.		$T = 20.^{\circ}3$ K.		$T = 14.^{\circ}5$ K.	
	RH	$-R \times 10^4$	RH	$-R \times 10^4$	RH	$-R \times 10^4$	RH	$-R \times 10^4$
9220	7.10	7.70	6.79	7 37	6.41	6 95	6.38	6.92
9500	—	—	—	—	—	—	6.59	6.94
9760	7.56	7 75	7.22	7.41	6.82	6.99	6.73	6.90
10270	7.95	7.74	7.71	7.51	7.13	6.94	7.09	6.90
0	$w = 25.2 \times 10^{-5} \Omega$ $\frac{w}{w_0} = 1.04$		$w = 12.7 \times 10^{-5} \Omega$ $\frac{w}{w_0} = 0.525$		$w = 8.7 \times 10^{-5} \Omega$ $\frac{w}{w_0} = 0.36$		$w = 8.7 \times 10^{-5} \Omega$ $\frac{w}{w_0} = 0.36$	

In Table XXI are collected my results for alloys of gold and silver. In it are given results for the Hall coefficient R_T, and its temperature coefficient $\frac{R_T}{R_{290}}$, for the Leduc constant $D_L = \frac{R}{w}$, and for the temperature coefficient of the resistance without a magnetic field. All are expressed in c. g. s. units.

Fig. 1 is a diagram of the electrical conductivity (σ) at $T = 290°$ K. and at $T = 90°$ K. as a function of the atomic percentage of *Ag*. The unit in which the conductivity is expressed is the reciprocal of the resistance in ohms of a 1 cm. edged cube. The conductivity was calculated from the analyses. (See a previous paper [1])).

At lower temperatures the characteristic curves become steeper. This is strongly marked at hydrogen temperatures as is shown by the measurements of Kamerlingh Onnes and Clay [2]) on a gold-silver alloy containing about 0.4 % *Ag*, and by Clay's [3]) measurements on *Au-Ag* alloys with various compositions. The latter measurements have been confirmed by mine, and have been further extended to embrace cases of average and of small content of *Au*. For these cases, somewhat similar results were obtained as with small content of *Ag*: the addition of a small quantity of gold to pure silver causes such an enormous decrease in the conductivity that, for

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[1]) Bengt Beckman. Upsala Univ. Årsskrift 1911.

[2]) H. Kamerlingh Onnes and J. Clay. Comm. n⁰. 99. 1907.

[3]) J. Clay. Comm. n⁰. 107*d*, 1908.

TABLE XXI.

Substance	Atomic percent. *Ag*	R_{290°	R_{90°	$R_{20^\circ.3}$	$R_{14^\circ.5}$	$\frac{R_{90^\circ}}{R_{290^\circ}}$	$\frac{R_{20^\circ.3}}{R_{290^\circ}}$	$\frac{w_{90^\circ}}{w_1}$	$\frac{w_{20^\circ.3}}{w_0}$	$[D_L]_{T=290^\circ}$	$[D_L]_{T=90^\circ}$	$[D_L]_{T=20^\circ.3}$
Au	0	7.2×10^{-4}	7.6×10^{-4}	9.8×10^{-4}	9.8×10^{-4}	1.05	1.36	0.285	0.135	3.2×10^{-7}	12.6×10^{-7}	133×10^{-7}
$(Au—Ag)_I$	2.0	6.8	6.6	6.7	6.5	0.97	0.98	0.49	0.30	2.3	4.8	8.03
$(Au—Ag)_{II}$	10.7	5.6	5.25	3.7	3.7	0.82	0.66	0.69	0.585	1.05	1.12	1.23
$(Au—Ag)_{III}$	30.0	5.6	4.7	3.6	3.7	0.77	0.64	0.825	0.755	0.61	0.57	0.52
$(Au—Ag)_{IV}$	69.7	6.0	5.2	4.5	4.4	0.87	0.75	0.875	0.82	0.64	0.64	0.60
$(Au-Ag)_V$	90.9	7.35	6.45	5.75	5.75	0.88	0.79	0.735	0.66	1.45	1.79	1.80
$(Au—Ag)_{VI}$	97.8	7.7	7.4	6.95	6.9	0.96	0.91	0.525	0.36	3.2	6.1	8.5
Ag	100	8.0	8.2	10.15	9.9	1.02	1.27	0.23	0.0091	4.95	23.1	720

instance, an admixture of 2 atomic percentages of gold reduces the conductivity (expressed in the above measure) from 71.10×10^6 to

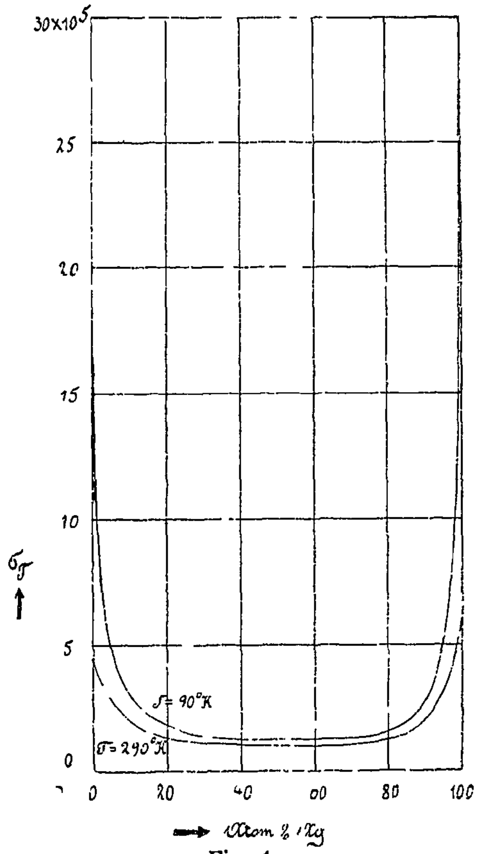

Fig. 1.

1.35×10^6. The curves expressing the temperature quotient $\frac{\sigma_T}{\sigma_0} = \frac{w_0}{w_T}$ as a function of the atomic percentage follow a similar course. The researches of KAMERLINGH ONNES and CLAY [1] on various gold wires have shown that the degree of purity of a metal can be very

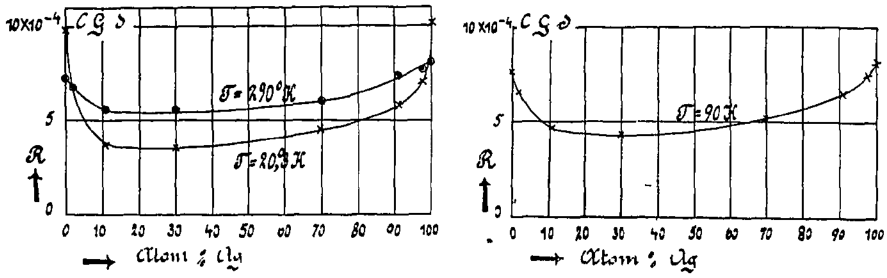

Fig. 2 and 3.

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[1] See note 3 p. 991.

accurately gauged from a determination of the temperature coefficient of its resistances at hydrogen temperatures.

Figs. 2 and 3 show the HALLcoefficient R_T at temperatures of 290° K., 90° K. and 20°.3 K. as a function of the atomic percentage of *Ag*. The curves resemble those which give the electrical conductivity and the temperature quotient of the resistance as functions of the atomic percentage. (Cf. KAMERLINGH ONNES and BENGT BECKMAN, Comm. N°. 130*c*). When silver is gradually added to pure gold, the HALLcoefficient at low temperatures diminishes, at first rapidly, and then more slowly, until with a mixture of about equal quantities of *Au* and *Ag*, a large change in the composition occasions only a very small change in the HALLeffect. The lower the temperature the steeper is the descent of the curve. For instance, when a 2 °/₀ admixture of silver is added to pure gold the HALLcoefficient diminishes

at $T = 20°.3$ K from 9.8×10^{-4} to 6.7×10^{-4},
at $T =$ 90° K from 7.6×10^{-4} to 6.6×10^{-4},
at $T =$ 290° K from 7.2×10^{-4} to 6.8×10^{-4}.

Hence a small *Ag* impurity in gold occasions only a small variation of the HALLeffect at $T = 290°$ K. which, however, becomes more appreciable at lower temperatures. On the other hand, as is evident from the measurements of A. VON ETTINGSHAUSEN and W. NERNST[1]), E. VAN AUBEL[2]) and A. W. SMITH[3]), the addition of a small quantity of *Sn* or *Sb* to *Bi*, which exhibits an unusually large HALL-effect, occasions even at ordinary room temperature a great change in the HALL-effect.

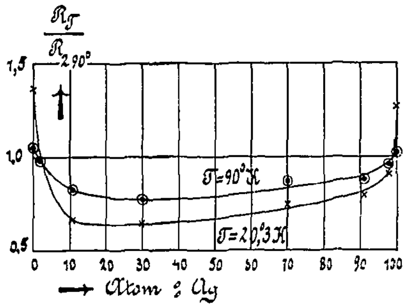

Fig. 4.

In Fig. 4 are shown the curves of the temperature quotients $\frac{R_{90°}}{R_{290°}}$ and $\frac{R_{20.3°}}{R_{290°}}$ as functions of the atomic percentage of *Ag*. These curves have the same general features as those of Figs. 1, 2, and 3.

In Fig 5 is shown the relation between *R* and *T* for some *Au*-*Ag* alloys. The course of the curves between 20°K. and 90°K. is not quite certain, as no observations could

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[1]) A. v. ETTINGSHAUSEN und W. NERNST: Wied. Ann. **33**, p. 474, 1888.
[2]) E. VAN AUBEL: C. R. **135**, p. 786, 1902.
[3]) A. W. SMITH: Phys. Rev. **32**, p. 178, 1911.

be made between hydrogen and oxygen temperatures. These portions of the curves are therefore indicated by dotted lines. With *Ag* and *Au* the HALLcoefficient increases as the temperature falls. This increase takes place chiefly in the temperature region $20° < T < 77°$ K. In the hydrogen region, $20°.3 > T > 14°.5$, R is constant within the limits of accuracy. A very small diminution of the HALLcoefficient is exhibited by the alloy $(Au\text{-}Ag)_I$ with $2\,^0/_0$ *Ag* at low temperatures. At low temperatures alloys with more than $2\,^0/_0$ of *Ag* show a distinct diminution in the HALL effect, which is greatest for alloys of medium concentrations. Thus alloy III with $30\,^0/_0$ *Ag* gives $\frac{R_{20^0}}{R_{290^0}} = 0.64$. With *Au* and *Ag* the ratio $\frac{R_{90^0}}{R_{290^0}}$ differs but very little from 1, while with alloys of medium concentration it differs considerably from 1. Of the alloys with a large percentage of *Au*, a distinct diminution of the HALLeffect at low temperatures is already exhibited by alloy VI, with $2\,^0/_0$ of *Au*.

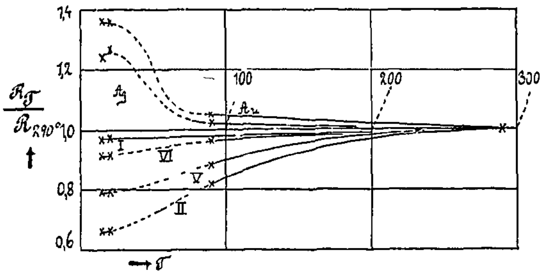

Fig. 5.

In fig. 6 is shown the relation between the LEDUC constant $D_L = \frac{R}{w}$ and the atomic percentage of *Ag* at $T = 290°$ K. and $T = 90°$ K. This constant is the tangent of the angle of rotation of the equipotential lines in unit field. The curves are of the same nature as the conductivity-silver percentage diagrams; at lower temperatures they become steeper. When two per cent of *Au* is dissolved in *Ag*, D_L at $T = 20°\ 3$ K. sinks from 720×10^{-7} to $8\ 5 \times 10^{-7}$. It is worth noting that with alloys of medium concentration D_L is approximately constant throughout the whole temperature region $290° > T > 14°.5$; this holds for $10.7 \leq x \leq 90.9$ that is to say, for alloys in which the percentage of neither component is less than 10.

With alloys which may be regarded as dilute solutions, hence for $0 \leq x \leq 11$ and $90 \leq x \leq 100$, as a rule R is, to a first approximation, a linear function of the temperature quotient $\frac{w_T}{w_0}$ ($T = 290°$ K, $90°$ K., 20° 3 K.). Only the alloys with a large percentage of *Ag* at $T = 20°,3$ K. are an exception to this rule.

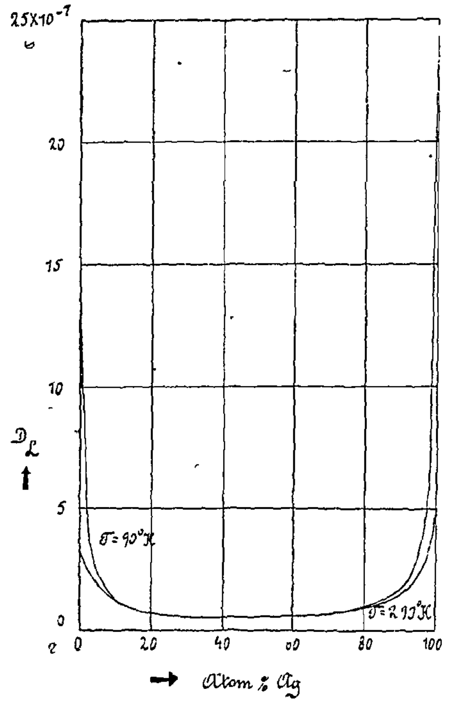

Fig. 6.

At $T = 290°$ K. the HALL coefficient for dilute solutions is proportional to the conductivity $\sigma_{290°}$.

It would undoubtedly be of the greatest importance to systematically extend these investigations of the HALLeffect in alloys at low temperatures, which I have, to my regret been obliged to confine to a single series of alloys, and to further investigate alloys of different types. I hope to continue this research as soon as I can find a suitable opportunity.

I gratefully acknowledge my indebtedness to Prof. KAMERLINGH ONNES who invited me to undertake these investigations of the HALL effect at low temperatures.