ART. VI. — *The Thermo-magnetic and Galvano-magnetic Effects in Tellurium*; by MORTON GITHENS LLOYD, Ph.D.

THE investigations here described were begun with the idea of measuring all of the thermo-magnetic and galvano-magnetic effects in the same specimen of a non-metal, tellurium being the substance chosen. It has heretofore been investigated for only two of the transversal effects. Satisfactory numerical values of the magnitude of most of these effects have not yet been obtained, owing to the difficulties involved in their measurement, but as the work must be interrupted for some time, it is thought best to publish the qualitative results at once.

If a conducting plate carrying an electric current be placed in a magnetic field perpendicular to the lines of force, the following galvano-magnetic effects have been observed.

1. A difference of electric potential is produced between the edges of the plate, perpendicular to the direction of the current and of the magnetic field. (Hall effect.)

2. A difference of temperature is produced between the same points.

3. A change of resistance occurs. (Longitudinal Hall effect.)

4. A difference of temperature is produced in the direction of the current.*

If a flow of heat replace the primary electric current, four analogous thermo-magnetic effects are observed.

1. A difference of electric potential between the edges of the plate.

2. Rotation of the isothermal lines or a difference of temperature between the same points.

3. A change of conductivity for heat.

4. A difference of potential in the direction of the heat-flow. (Longitudinal thermo-magnetic effect.)

The transversal effects are reversed in direction when either the magnetic field, or the primary current of heat or electricity, is reversed in direction; but the longitudinal effects are independent of the direction of the field.

It has already been proposed† to call the galvano-magnetic temperature-difference, the thermo-magnetic temperature-difference, and the thermo-magnetic potential-difference by the respective names, Ettingshausen effect, Leduc effect and Nernst effect. Most of these effects were first observed in bismuth, and some of them only in bismuth. The change of conduc-

* Nernst, Wied. Ann., xxxi, p. 784, 1887.

† Thesis: The Transversal Thermo-magnetic Effect in Bismuth, M. G. Lloyd, Philadelphia, 1900; Beiblätter, 24, p. 1014.

tivity for heat was first announced by Righi* and shortly afterward by Leduc.† The Leduc effect has been observed by Leduc,† Righi,‡ and van Everdingen.§ The Nernst effect, discovered by von Ettingshausen and Nernst,|| has been observed by van Everdingen, Yamaguchi,¶ Moreau** and the writer, these observations covering a number of metals. The Ettingshausen effect was observed by its discoverer†† in bismuth, antimony and tellurium, and was included in van Everdingen's observations on bismuth. The longitudinal thermo-magnetic effect has been observed in bismuth by von Ettingshausen and Nernst, van Everdingen,‡‡ and Lownds.§§

Chemically pure tellurium was obtained from Eimer and Amend, and cast into the form of a plate, 6.7^{cm} long, 2.5^{cm} wide and 0.1^{cm} thick, with two lugs projecting from the middle of the lateral edges. Six thermo-electric couples of copper and German silver wire made electric connection with the plate; one to each of the lugs, the other four along the center line of the plate, separated by distances of 15, 13, 18^{mm}. These couples served to determine the temperature at the six points and thus the temperature-gradient, and in addition could be used to determine the difference of potential between any two points. The ends of the tellurium plate were pressed by springs against projections from two brass tubes, through which steam and cold water, respectively, could be passed. The whole was mounted on a wooden frame, and suspended between the poles of a powerful electro-magnet. The pole-faces were 6.3^{cm} square and 1.3^{cm} apart, and the magnetic field between them practically uniform. The strength of field was determined from the resistance of a calibrated bismuth spiral which was also attached to the wooden frame. When sending an electric current through the plate, cold water flowed through both brass tubes, to which the lead-wires were attached. Differences of potential were measured by comparison with a standard Clark cell, using the potentiometer. A very sensitive astatic reflecting Thomson galvanometer was used as a current-indicator.

The electromotive force, E , in microvolts, of a thermo-electric circuit of copper and German silver, one junction of

* Rend. Acc. Lincei, iii, p. 481, 1887; Beiblätter, 11, p. 670.

† Comptes Rendus, civ, p. 1783, 1887.

‡ Rend. Acc. Lincei, iii, p. 6, 1887.

§ Proc. Royal Acad. Sci. of Amsterdam, i, p. 72, 1898; Comm. from Leiden, No. 42.

|| Anz. d. kais. Akad. Wien, xiii, p. 114, 1886; Wied. Ann., xxix, p. 343.

¶ Ann. d. Physik, i, p. 214, 1900.

** Journal de Physique ix, p. 497, 1900.

†† Wied. Ann., xxxi, p. 737, 1887.

‡‡ Ann. d. Physik, iv, p. 776, 1901.

§§ Leiden Comm., No. 48; Proc. R. A. S. A., Mar. 25, 1899.

which is at 25° C. and the other at T°, has been found by Dr. H. C. Richards to be

$$E = 15.20 (T - 25) + 0.0272 (T - 25)^2.$$

One of the couples used in this work was tested between 0° and 100° and found to agree with the formula, which has been used in determining temperatures.

The plate was insulated and protected from air-currents as well as possible by the use of mica, asbestos, cotton, etc.

Ettingshausen effect.—If the primary current flow from right to left, and the lines of magnetic force are directed away from the observer, the upper edge of the plate is cooled and the lower warmed. This is in the same direction as in bismuth. The effect was measured by passing current through the plate between the two tubes, and observing the temperatures at the edges of the plate for both directions of the field, giving time in each case for temperatures to become constant. A series of readings was taken, reversing field each time, in order to eliminate any error due to the gradual change in temperature of the whole plate. Readings in zero field were not used in the calculations. They showed, however, that the effect was not symmetrical, i. e., the change for one direction of the field was not the same as for the opposite direction of the field: starting with zero field in both cases. The coefficient of the Ettingshausen effect, P, is defined by the equation

$$T = PH \frac{C}{t}$$

where T is the difference in temperature produced, by a change of field H, between the edges of a plate of thickness t when traversed by a current C. Temperatures are measured in Centigrade degrees; other quantities in C.G.S. electromagnetic units. The values of P observed ranged between 0.00014 and 0.00029 for fields up to 5500 gaussés, at a temperature of about 65°. The high resistance of tellurium causes a correspondingly large generation of heat and the temperature of the interior is considerably higher than that of the surroundings. The flow of heat from the center of the plate to the edges (cooled by water flowing through the tubes) will produce a Leduc effect which may interfere with the measurements of the Ettingshausen effect. In this case the measurements were made at the center of the plate, where the temperature-gradient may be assumed zero.

Hall effect.—If the primary current flow from right to left, and the lines of force are directed away from the observer, the upper edge is at the lower potential. This direction coincides with the results of other observers and is usually considered as

positive. It is in the opposite direction in bismuth. To determine the Hall effect, the difference of potential was measured between the copper wires connected to opposite edges of the plate. This P.D. includes the thermo-effect due to the two points of contact not being at the same temperature. If the temperature remained constant, the thermo-effect could be eliminated by taking readings for both directions of the field. But the temperatures are not constant, the Ettingshausen effect producing a change whenever the field is reversed, and this must be allowed for. It was found in this case to affect the second significant figure by one unit only and hence is neglected. The coefficient of the Hall effect, R , is defined by the equation

$$E = RH \frac{C}{t}.$$

In a field of strength 4,000 gaussess, the value of R found was 430 C.G.S. at a temperature of 65° .

Change of resistance.—The resistance was determined by the difference of potential of two points between which a current was flowing. The current and P.D. were measured with Weston ammeter and voltmeter. The accuracy of the observations would serve to determine a change in resistance of one-half of one per cent. No change was found in fields up to 5,500 gaussess. Other observations* on tellurium show an increase in resistance less than this.

Leduc effect.—If the heat flow be from right to left and the lines of force are directed away from the observer, the upper edge of the plate is cooled. The direction in bismuth is the reverse of this. The coefficient of the Leduc effect, S , is defined by the equation

$$T = SbH \frac{d\tau}{d\lambda}$$

where b is the breadth of the plate and $\frac{d\tau}{d\lambda}$ the longitudinal temperature-gradient. Values of S between 0.000002 and 0.000005 were obtained at temperatures between 30° and 38° in fields of strengths from 2,500 to 5,200 gaussess. The coefficient appears to increase with the temperature.

Nernst effect.—If the heat flow be from right to left, and the lines of magnetic force are directed away from the observer, the upper edge is at lower potential. In bismuth the direction is the same. The coefficient of Nernst effect, Q , is defined by the equation

$$E = QbH \frac{d\tau}{d\lambda}.$$

* Goldhammer, Wied. Ann., xxxi, p. 360, 1887.

The difference of potential between the copper leads connected to opposite edges of the plate is the resultant of the Nernst effect and the thermo-electric effect at the two junctions. Since the two junctions are in general at slightly different temperatures, they do not balance one another. If their temperatures were constant, the thermo-electric effect could be eliminated by taking readings for both directions of the magnetic field; for in one case the Nernst effect would be added to it and in the other case subtracted. Owing to the Leduc effect, the temperatures do not remain constant, but are altered by reversing the field.

Let E =Nernst effect; V and V' =the observed P.D.'s for two directions of the field; ϵ =thermo-electric power for copper and tellurium; t_1 and t_2 =the temperatures of the two junctions for one direction of the field, t_1' and t_2' for the other;

T =Leduc effect= $\frac{1}{2} (t_1 - t_1' + t_2' - t_2)$. Then

$$\begin{aligned} V &= \epsilon(t_1 - t_2) + E \\ V' &= \epsilon(t_1' - t_2') - E \end{aligned}$$

whence

$$E = \frac{V - V'}{2} - \epsilon T.$$

It is thus seen that the observed values of V must be corrected for the Leduc effect. In bismuth this correction was found negligible; in tellurium it is not so, owing to the enormous thermo-electric power of copper and tellurium, but assumes a magnitude of the same order as the Nernst effect. An accurate determination of the Nernst effect requires an accurate knowledge not only of one value of this thermo-electric power, but also of its variation with temperature and with strength of field. The values of ϵ observed are slightly over 600 microvolts, whereas the value usually given is about 500.

Observations of the Nernst effect give a value of $Q=0.36$ at 33° in a field of about 3,000 gauss. As in the case of the Hall effect the constant is larger than has been observed in any metal.

Change of heat-conductivity.—The conductivity is lessened in the magnetic field. The relative conductivities were calculated from observations of temperature at four points along the center line of the plate, assuming the thickness to be uniform and the surface-conductivity to be constant. Neither of these conditions is fulfilled, and hence the results are only approximate. The ratio of conductivity in a field of strength 4700 gauss to that in zero field was found to be 0.9.

Longitudinal thermo-magnetic effect.—The warm end of the

plate is at the higher potential. This direction is the same as Lownds* has found in bismuth at ordinary temperatures.

Two suggestions have been made† which might explain the origin of the longitudinal effects. One is, that the thermo-electric-power is altered in a magnetic field. Lownds has demonstrated that the effect observed by him cannot be so explained. The other suggestion is, that owing to a change in heat-conductivity, the temperatures at the junctions are changed, thus changing the E.M.F. in circuit. This explanation is plausible where the effect was measured by compensating the E.M.F. in zero field, and observing the change produced by the field. Lownds does not mention whether he made any test of this possibility, but in one of his experiments at least (p. 779) it is evident that the E.M.F. could not have had this origin.

The longitudinal effect has been observed in bismuth also by van Everdingen,‡ and found to vary with the strength of field according to the same law as the variation of resistance.

In my own experiments the temperatures at the junctions were observed in the given field as well as in zero-field, and allowance made for the change. Theory§ indicates that longitudinal effects should be proportional to the square of the strength of field, and independent of its direction. I have noticed that in every case the effect was greater for one direction than for the other. The mean value for a field strength of 2750 gauss, mean temp. = 39°, difference of temp. = 19°, was 1050 microvolts.

If we regard the transversal differences of temperature and potential as due to the transfer of heat and electricity respectively across the plate, we notice that in tellurium the transfer of electricity is always in the same direction as the transfer of heat. That is, the edge which is raised in potential is also raised in temperature. Moreover, to produce the same effects with a current of electricity as with a current of heat, the direction of flow must be the same for both. For example, the edge which is warmed by the Leduc effect has its potential increased by the simultaneous Nernst effect. And to warm the same edge by the Ettingshausen effect as by the Leduc effect, the primary currents of electricity and heat must have the same direction.

In bismuth, the reverse is the case, the heat and electricity being transferred in opposite directions. Thus the edge which is warmed by the Leduc effect has its potential lowered by the simultaneous Nernst effect. And to warm that same edge by

* Ann. d. Phys., iv, p. 776, 1901.

† Grimaldi, Nuov. Cim. (3), xxii, p. 5, 1887; Goldhammer, *l. c.*

‡ Leiden Comm., No. 48, 1899.

§ Drude, Ann. d. Physik, iii, p. 377, 1900.

the Ettingshausen effect would require a primary electric current in the direction opposite to the heat flow producing the Leduc effect. These facts are of especial interest in connection with Liebenow's* theory of thermo-electric currents, in which he arrives at the conclusion that in metals heat always flows with the *negative* electricity, whereas in non-metals it accompanies the *positive* electricity. If this relation between the directions be a general one, a knowledge of the direction of any one of the four transversal effects would be sufficient to determine the direction of the other three. Of the eleven elements examined by Nernst† for the Nernst effect, six (Bi, Sb, Ni, Fe, Zn, Pb) bear out this relation with the Hall effect, if we regard antimony as a non-metal. Of the other five, three (Cu, Ag, Sn) showed such a small effect that they may be regarded as doubtful. The two notable exceptions are carbon and cobalt. It has been already noted by several writers‡ that cobalt occupies an anomalous position as regards its Hall-constant, and it may be that the Ettingshausen effect is large enough in this metal to entirely vitiate the measurements which have been made of its Hall-effect, even to changing the sign. In this regard it is to be noted that the thermo-electric-power is large between cobalt and copper, the metal usually used for lead-wires. Or the measurement of Nernst effect may have been equally influenced by Leduc effect. Moreau (l. c.) however, found an opposite direction for the Nernst effect in cobalt, which would make it agree with the general rule. The direction of the Ettingshausen effect in antimony is in harmony with the other effects.

This idea comes in conflict, however, with the "Electronentheorie" of Drude,§ which requires that the Ettingshausen effect be in the same direction in all metals. For the above relation to hold, the Hall-effect must also be in the same direction in all metals, which we know is not the fact. In the only three substances yet examined, bismuth, tellurium and antimony, the direction of the Ettingshausen effect has been found the same.

I summarize the constants for the four transversal effects.

		$H_{\max}$	t
Ettingshausen.....	$P = 0.0002$	5500	65.
Nernst	$Q = 0.36$	3000	33.
Hall	$R = 430.$	4000	65.
Leduc.....	$S = 0.000004$	5200	30-38

* Wied. Ann., lxxviii, p. 316, 1899.

† Wied. Ann., xxxi, p. 760, 1887.

‡ Von Ettingshausen u. Nernst, Wiener Berichte, xciv, p. 560, 1886; J. C., Beattie, Proc. Royal Soc. Edinburgh, xx, p. 481, 1895; Drude, Ann. d. Phys., iii, p. 392, 1900.

§ Ann. d. Physik, iii, p. 369, 1900.