

polating the steep part of the mobility curve to the point where it strikes the voltage axis.

¹ H. B. Wahlin, *Physik. Rev.*, **20**, No. 3, Sept., 1922, p. 267.

² H. A. Erikson, *Ibid.*, **20**, No. 2, Aug., 1922, p. 117.

³ H. B. Wahlin, *Phil. Mag.*, March, 1925, p. 566.

⁴ H. A. Erikson, *Physik. Rev.*, **24**, No. 5, Nov., 1924, p. 502.

THERMAL CONDUCTIVITY AND THERMO-ELECTROMOTIVE FORCE OF SINGLE METAL CRYSTALS

BY P. W. BRIDGMAN

JEFFERSON PHYSICAL LABORATORY, HARVARD UNIVERSITY

Communicated August 18, 1925

This note summarizes results which will be given in much greater detail elsewhere. The thermal conductivity at room temperature and the thermal e.m.f. in the range between room temperature and 100°C. is measured as a function of direction for single crystal rods of Bi, Zn, Cd and Sn. A few very incomplete results have also been obtained for Sb and Te, which will be found in the detailed paper.

Thermal Conductivity.—In figure 1 are plotted for Bi, Zn, Cd and Sn the reciprocals of the experimentally determined thermal conductivities against the specific electrical resistance in the same direction in which the thermal conductivity was measured. The experimental error is considerable, but nevertheless certain conclusions may be definitely drawn. In the first place there is the question whether the symmetry relations deduced by Voigt¹ for thermal conductivity are satisfied. Voigt's relations demand that the thermal conductivity have rotational symmetry about the axis for these four metals, and that the relation be such that the reciprocal of thermal conductivity be a linear function of electrical resistance. The heavy lines in figure 1 indicate what seem to me to be the best straight lines through the experimental points. It would seem that within the somewhat large experimental error the relation of Voigt is satisfied.

We have further to consider whether the Wiedemann-Franz relation between electrical resistance and thermal conductivity holds in detail for all directions in a crystal. In this case, the relation between electrical resistance and reciprocal thermal conductivity is not only linear, but the straight line must pass through the origin. In the figure the dotted line indicates what seems to me the best line through the points and the origin. It would seem that in the case of Cd and certainly in the case of Zn the experimental error is not large enough to allow a line through the

origin, and that the conclusion may be drawn that the generalized Wiedemann-Franz law cannot hold for all directions in a crystal.

Thermo-electromotive Force.—The thermal e.m.f. between crystal rods of different orientations and copper was measured. For any single orientation the e.m.f. of the couple could be expressed in a two-power series in the temperature:

$$E_{\text{Cu-Crys.}} = at + \frac{b}{2} t^2.$$

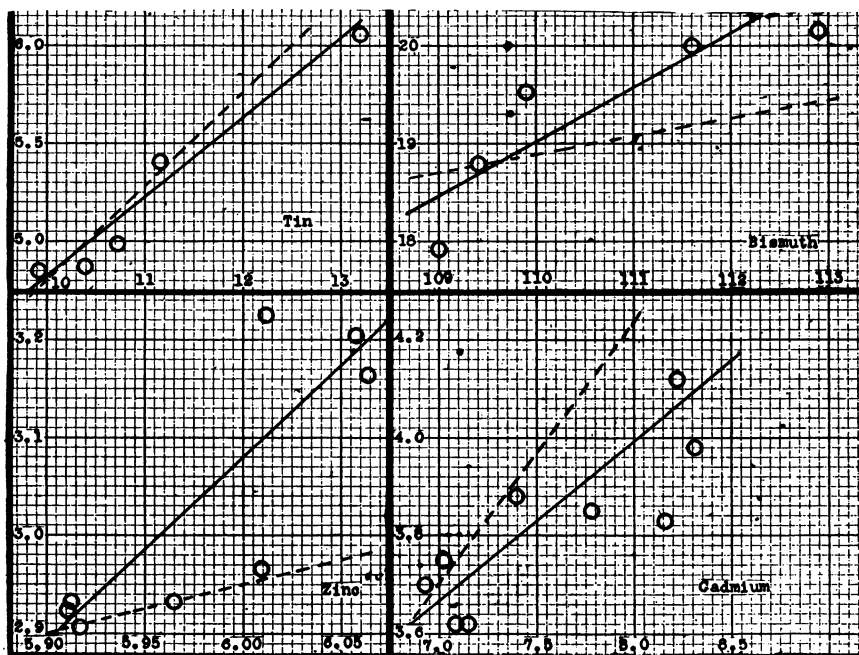


FIGURE 1

Reciprocal of the thermal conductivity (in gm. cal./cm. sec. °C.) as ordinates against specific electrical resistance in ohms per cm. cube $\times 10^6$. The full lines show the best lines through the observed points, and the dotted lines the best lines through the origin. Voigt's symmetry relations demand that the points lie on the full lines, the generalized Wiedemann-Franz law demands that they lie on the dotted lines. The maximum possible range of resistances for directions ranging from perpendicular to parallel to the crystallographic axis is, respectively: Sn, 9.9 to 14.3; Bi, 109 to 138; Zn, 5.91 to 6.13; Cd, 6.80 to 8.30.

From this the Peltier heat when current passes from Cu to a crystal rod of the orientation in question is found by the conventional thermodynamic analysis to be

$$P_{\text{Cu-Crys.}} = (a + bt) \tau,$$

and the Thomson heat in the crystal when current is flowing in this particular direction is:

$$\sigma_{\text{Crys.}} - \sigma_{\text{Cu}} = b\tau.$$

Here t is ordinary Centigrade temperature and τ is absolute Centigrade temperature.

The experiments gave the coefficients a and b as a function of the direction in the crystal. The experimental accuracy is much greater here than for thermal conductivity, so that the experimental points need not

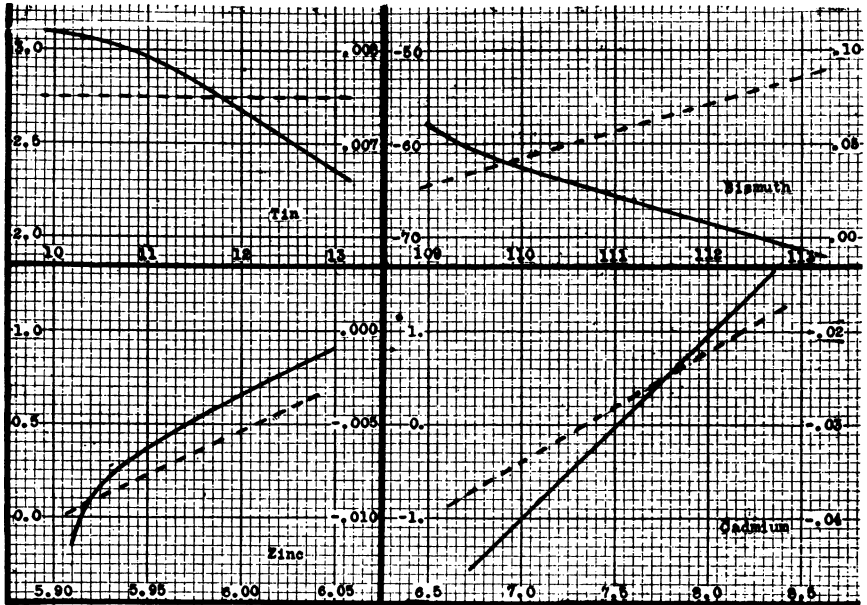


FIGURE 2

Plotted against specific electrical resistance $\times 10^4$ as abscissae are the coefficient a (Peltier heat against Cu at $0^\circ\text{C.}/273$) shown as full lines with the scale at the left in microvolts, and the coefficient b (Thomson heat against copper $/273$) shown as the dotted line with the scale at the right in microvolts.

be given in detail. In figure 2 are plotted the coefficients a and b in microvolts as a function of the specific resistance in the direction in question. It appears from the diagram that the Thomson heat, which except for a constant is equal to b , is a linear function of the resistance, but that except in the case of Cd, a (or Peltier heat) is certainly not a linear function.

The sort of results to be expected theoretically appear to have been discussed only by Thomson² and Voigt.³ Thomson's results are not given

in detail, but only certain general conclusions are stated which Voigt states are in agreement with his own results. Voigt's analysis is given in complete detail. It appears on examination that Voigt's analysis applies only to the Thomson heat and not at all to the Peltier heat, which is by far the most important effect experimentally; it would appear by implication that Thomson did not consider this part of the phenomenon either. From Voigt's analysis we may conclude that the Thomson heat has the same sort of rotational symmetry as electrical resistance or reciprocal thermal conductivity. The linear relation between b and electrical resistance shown in figure 2 verifies this analysis.

We have now to consider the significance of the most important term, the Peltier heat absorbed reversibly when current passes across the surface of a crystal into an isotropic conductor. By means of very simple considerations to be given fully in the detailed paper, it may be shown that the heat absorbed at the surface of discontinuity does not depend at all on the orientation of the surface with respect to the crystal, but only on the direction of flow within the crystal before emergence. It is an immediate simple deduction that when the direction of current flow changes inside the crystal there is a reversible absorption or evolution of heat equal exactly to the difference of ordinary surface heat corresponding to the two directions of flow. This internal heat may be called the internal Peltier heat. I cannot find that it has been previously mentioned, although experimentally it may evidently be very large.

There is no simple connection between the sign of the internal Peltier heat and direction. In the case of Bi and Sn, heat is absorbed when the direction of current flow changes from parallel to the axis to perpendicular to the axis, whereas for Zn and Cd the sign is opposite.

There do not seem to be any such conditions of symmetry on the Peltier heat, either external or internal, as there are on the Thomson heat. Experimentally this conclusion is justified by the various shapes found for the curves of a against resistance. It does not even seem necessary that P have rotational symmetry. Experimentally the results have not sufficient accuracy to justify a final conclusion on this point, but the conclusion is at least justified that any departure from rotational symmetry is slight for these particular metals.

The mere existence of an internal Peltier heat would seem to have important bearings on our views of the nature of electrical conduction. I cannot see that any of our ordinary pictures of electrical conduction would lead us to expect a reversible absorption of heat on changing the direction of current flow. The dimensions of P are significant. We have here a definite absorption of heat *per electron* when the direction of flow is altered, independent of the magnitude of the current or the velocity of flow. This rules out any attempted explanation in terms of kinetic energy or mo-

mentum effects. It may be that we shall be driven to assume that the electron here functions as a dipole (magnetic), evidence for which has already been given by Compton, and that when moving in different directions in the non-isotropic force field of a crystal it assumes different orientations.

¹ W. Voigt, *Lehrbuch der Krystallophysik*, Teubner, Leipzig, 1910, p. 369.

² W. Thomson, *Edin. Proc.*, 3, 255, 1854; *Edin. Trans.*, 21, 153, 1857; *Phil. Mag.* (4) 11, 379 and 433, 1856.

³ W. Voigt, *l. c.*, p. 534.

ON THE QUANTUM THEORY OF THE POLARIZATION OF RESONANCE RADIATION IN MAGNETIC FIELDS

By J. H. VAN VLECK

DEPARTMENT OF PHYSICS, UNIVERSITY OF MINNESOTA

Communicated August 20, 1925

Introduction.—The theory of the polarization of resonance radiation in magnetic fields strong enough for spacial quantization was developed independently and simultaneously by Pringsheim,¹ Breit,² Joos³ and Gaviola and Pringsheim,⁴ following to some extent previous suggestions of Hanle⁵ and of Foote, Ruark and Mohler.⁶ It is a direct consequence of the quantum theory of the Zeeman effect, which may be either normal or anomalous. The polarization of an individual Zeeman component^{*} is linear or circular according as the change in the magnetic quantum number is zero or unity in the quantum transition with which the component is associated. In the experiments of Wood,⁷ Ellett⁸ and others the Zeeman components are unresolved and so the observed polarization is the resultant polarization resulting from the superposition of the linear and circular components. This resultant polarization is the quantity in which we are here interested and can be computed when we know the relative intensities of the Zeeman components; i.e., the relative probabilities of the various transitions.

The present paper aims to call attention to two interesting consequences of this quantum theory of polarization: (1) the quantum theory gives the same angle 54.7° of no polarization as does the classical theory provided the hypothesis of spectroscopic stability (explained below) is valid; (2) the recent experiments of Ellett and others on the amount of polarization of sodium *D* resonance radiation are in reasonably good accord with the theory for determining transition probabilities developed by Ornstein and Burger,⁹ and extended independently by Hönl,¹⁰ Goudsmit and Kronig,¹¹ Heisenberg (unpublished) and H. N. Russell.¹² Only the original rules