THE LONGITUDINAL THERMOMAGNETIC POTENTIAL DIFFERENCE IN A BISMUTH CRYSTAL

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Abstract

The longitudinal thermomagnetic potential difference in a bismuth crystal has been measured at room temperature for various orientations of heat current, magnetic field, and crystal axis. The results are plotted to show the change of thermoelectromotive force as a function of magnetic field strength. When the heat current is parallel to the crystal axis the field produces an apparent increase of thermoelectromotive force, the maximum being about 7 percent in a field of 7000 gauss. When the heat current is perpendicular to the crystal axis the field produces a decrease of thermoelectromotive force, the maximum being 23 percent in a field of 7000. Some of the data are in poor agreement with previous work by Lownds and Defregger. The results may be explained qualitatively by assuming that a magnetic field produces a structural change of some sort in the atomic system of bismuth. This change, in the direction normal to the field, is essentially different from the change parallel to the field.

IF A copper-bismuth thermocouple is arranged so that the bismuth is in a magnetic field it is found that the thermoelectromotive force of the couple is changed by the field. At room temperatures most observers have found an increase of electromotive force. When the bismuth is placed so that the heat current in it is transverse to a uniform magnetic field the phenomenon is frequently called the longitudinal thermomagnetic potential difference, and may be represented[1] by the equation $e=LH(T_2-T_1)$. Here e is the difference of potential of the junctions produced by the field H, the junctions being at temperature T_1 and T_2 respectively. The coefficient L is positive when e is in the same direction as the heat flow in the specimen.

The profound influence of crystal structure on galvano- and thermomagnetic phenomena suggests that an accurate knowledge of these effects can only be obtained by making measurements with single crystal specimens. Defregger[2] and Lownds[3] have used single crystals but they were limited by the form of their specimen to certain restricted orientations of the crystalline axis with respect to field and heat flow. The writer has made a series of measurements on specimens cut from a single crystal,—the same crystal for which the Hall effect has been investigated[4]—and quite different results have been obtained for different orientations of the crystal axis.

[1] Hall and Campbell, Proc. Am. Acad. **46**, 625 (1911); A. W. Smith, Phys. Rev. **2**, 383 (1913). Nernst, Ann. d. Physik **31**, 760 (1887), proposed the equation $e=LH^2(T_2-T_1)$, and Lownds, Ann. d. Physik **4**, 776 (1901), uses the expression $e=n(T_2-T_1)$, where n depends on H. Campbell, Galvanomagnetic and Thermomagnetic Effects, defines L by Nernst's method but gives numerical values not calculated by Nernst's formula.

[2] Defregger, Ann. d. Physik **63**, 97 (1897).

[3] Lownds, Ann. d. Physik **6**, 146 (1901).

Apparatus and Method

The specimen, in the form of a plate or bar, had its ends soldered with Wood's metal to copper tubes. Cold water was passed through one tube, hot through the other, constancy of flow being maintained by large storage vessels in each line. The elevation of these storage vessels determined the water pressure. Since the water was cooled (by a refrigerating plant) or heated (by an electrical heater) before entering the tanks these vessels also served to smooth out irregularities of temperature of the inflowing water streams.

Two separate copper-manganin thermojunctions of fine wire were fixed to the bismuth crystal with a tiny particle of Wood's metal. They were a short distance apart and on a line parallel to the length of the specimen. The specimen was wrapped in cotton and supported between the poles of a Weiss electromagnet. The pole-pieces were 10 cm in diameter and 3.15 cm apart.

When heat was flowing through the bismuth the temperatures of two points on the line of flow could be determined by means of the thermocouples. When the thermomagnetic potential difference was to be measured, a galvanometer, in series with a potentiometer, was connected to the two copper wires of the thermojunctions soldered to the bismuth. The manganin wires from these junctions were left with their ends electrically insulated. The potentiometer was then adjusted to balance the thermoelectromotive force of the copper-bismuth couple formed by this arrangement. When the magnet was excited the change of setting of the potentiometer for balance gave the value of e.

In practice certain precautions were necessary. If the copper wires soldered to the specimen are not exactly on a thermal line of flow a component of the transverse thermomagnetic electromotive force will act. This effect was eliminated by measuring e for opposing directions of H and taking the mean. The potentiometer setting for zero field was always observed immediately before and after each observation with the field.

A magnetic field changes the thermal conductivity of bismuth, hence the temperatures of the two copper junctions may be changed by the field. This temperature change, however, will not be instantaneous,—an appreciable time will be required for the attainment of thermal equilibrium after the field is applied, so if observations are made rapidly enough the error due to this effect will be negligible. In the present experiments it is believed that changes of thermal conductivity have produced no appreciable error. It was possible to secure a new balance of the potentiometer about four seconds after the magnetic field was removed, and this potentiometer setting did not change gradually as would be expected in case the junctions were coming to new temperature differences in the absence of the field. In other words, there was no observable time lag between e and H.

The sensitivity of the apparatus was such that a value of e of about 1 microvolt could be measured.

Results

In Fig. 1 the results are exhibited graphically. Here e is the change produced by the magnetic field H in the original electromotive force E. The relative directions of heat current h, magnetic field H, and crystal axis a, are indicated for each curve by the sets of arrows on the diagram. The curves marked A were obtained with a bar of dimensions $1.0\times0.216\times0.414$ cm,

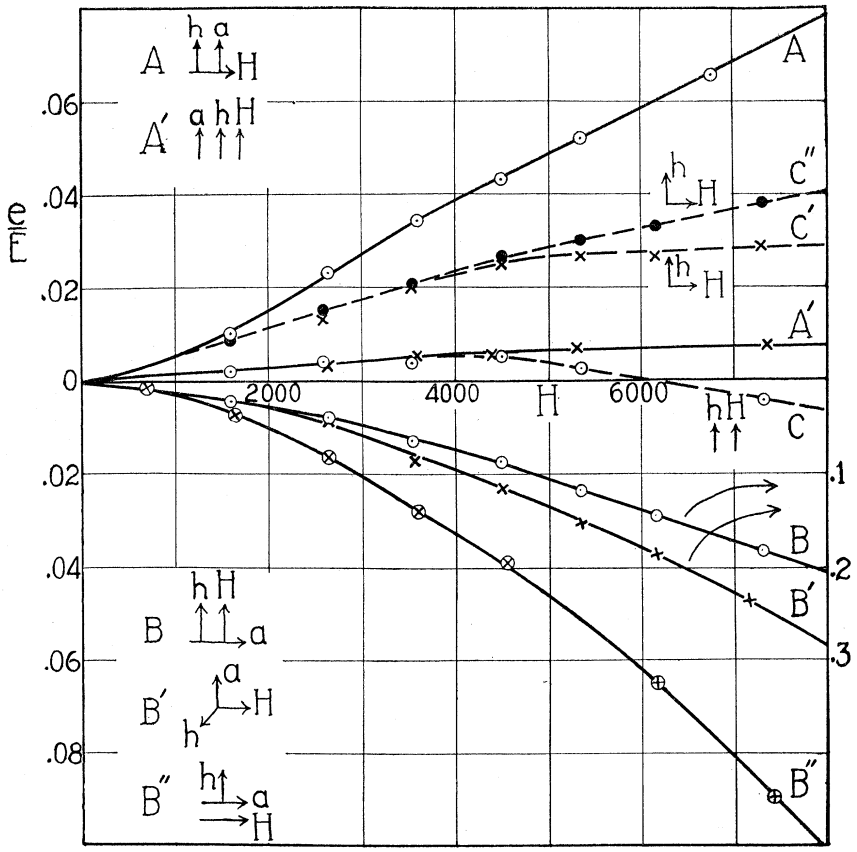

Fig. 1. Variation with magnetic field of the fractional change of thermoelectromotive force for different crystal orientations. The symbols for each curve give relative directions of heat current h, magnetic field H, and crystal axis a. The right hand scale of ordinates is used for curves B and B'.

the heat flow being in all cases along the long dimension which was cut from the large crystal so as to be parallel to the crystal axis.

The curves marked B were obtained with a plate of dimensions $1.3\times0.47\times0.115$ cm. This plate was the one designated as B in the writer's work[4] on the Hall effect, its dimensions being slightly altered by removal of side arms.

[4] Heaps, Phys. Rev. **30**, 61 (1927).

The dotted curves C are for a plate of compressed bismuth powder, (also one used in the experiments on the Hall effect) the powder having been made by grinding a piece of the crystal in a mortar. For C' the field H was perpendicular to h and to the plane of the plate; for C'' the field was perpendicular to h but parallel to the plane of the plate. For C both h and H were in the plane of the plate.

It appears from the curves that when the heat current is perpendicular to the crystal axis the magnetic field produces an apparent decrease of thermoelectromotive force for the different orientations of the field. When the heat current is parallel to the crystal axis the field produces an apparent increase of thermoelectromotive force.

At first sight it appears surprising that the crystal conglomerate should give a positive effect. Two of the B curves give a negative value of e/E several times larger than any positive effect observed. For a random distribution of the component crystals of a conglomerate there are as many crystals with their axes perpendicular to h as parallel; it might be supposed, therefore, that since the decrease of thermoelectric power for the first type of orientation is so large, the resultant would be a decrease. The fact that it is not may be due to a very rapid change in the magnitude of the effect as the crystal orientation passes through the perpendicular position. Such a change would have to be considerably more rapid than in the case whcre the orientation passes through the parallel position in order to account for the observed curves.

In the present experiments we find that the direction of the heat current is of considerable importance. If the magnetic field is kept perpendicular to the crystal axis and to the heat current we note that the value of e/E is changed from its maximum negative value, when h is perpendicular to a, to a maximum positive value when h is parallel with a. We may interpret this observation as follows. The magnetic field, maintaining a fixed direction with respect to the crystal axis, produces some sort of temporary atomic structural change such that thermoelectric power is increased along the axis but decreased at right angles to the axis. It is improbable that the magnetic field produces its effect by direct action on the electrons concerned in the thermoelectric process, since in each of the above cases the field was normal to the flow of these electrons and yet produced quite different effects.

For the plate of compressed powder the plane of the plate (which was perpendicular to the direction of compression) is a plane of symmetry as regards crystalline structure. For both C and C'' the magnetic field was in the plane of the plate, consequently the marked difference between these two curves must be attributed to the difference of orientation of H with respect to h in the two cases. It appears probable that the magnetic field affects atomic relationships in such fashion that the thermoelectric process parallel to H is essentially different from that parpendicular to H, no matter how the crystal axis may be orientated.

There is at present no theory of electrons in metals which adequately accounts for the observed facts of thermoelectricity in crystals. The results

reported above are of a type which it is especially difficult to fit into any simple theory.

For purposes of comparison with other experiments some of the data of this experiment are given in the following table. In calculating L electromagnetic units are used.

TABLE I

Values of e/E. Comparison with the results of others.

	T_1 °C	T_2 °C	E microv.	H gauss	L	e/E Lownds	e/E Defregger	e/E Heaps
A	23.0	40.5	1540	6100	−.086	+.085	+.069	+.060
A'	23.0	40.5	1540					
B	17.3	29.5	552					
B'	16.5	30.0	587	6100	+.132	−.035	−.0006 +.0069	−.185
B''	7.0	27.8	886	4400	+.037	+.0097	+.0085 +.0060	−.038
C	18.0	31.3	1120					
C'	18.2	32.0	1160					
C''	18.2	32.0	1160	7300	−.044			

For each of the cases B' and B'' the two results of Defregger (quoted by Lownds) are for different specimens. The values of e/E of Lownds and Defregger are for average temperatures of about 50°C, and while this is considerably higher than the mean temperatures of the present experiment the difference does not seem to be sufficiently great to account for the poor agreement of results.

For a cast bismuth plate A. W. Smith finds L to be -0.13 at 20° and with a field of 9600. This value is considerably larger than the result of the present experiment on a pressed plate at 25.1° in a field of 7300.

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