THE HALL EFFECT IN BISMUTH WITH SMALL MAGNETIC FIELDS

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Abstract

The Hall coefficient for a bismuth plate of dimensions $0.011 \times 0.9 \times 2.0$ cm has been measured for magnetic fields ranging from 0.07 to 2.40 gauss. The average value of the Hall coefficient, R, in this range was 11.5, and variations of R due to change of field strength in this range were less than experimental errors. For larger fields the Hall coefficient of this specimen decreased from 13.5 for a field of 650 gauss to 5.9 for a field of 8600. It is concluded that for similar ranges of field the data reported by Palmer H. Craig are erroneous, probably because of insulation leakage or uncompensated thermomagnetic effects. A simple method of making very thin bismuth plates is described.

Introduction

It is a well known fact that the coefficient of the Hall effect for ordinary cast bismuth increases as the magnetic field is diminished.[1] Recently Palmer H. Craig has reported[2] surprisingly large values of this Hall coefficient when magnetic fields smaller than about 0.3 gauss were used, and he suggests that modifications will have to be made in the theory of the Hall effect in order to account for his results. There are already several other phenomena connected with the Hall effect which theories have not explained; the genuineness of this new phenomenon should therefore be very thoroughly established.

The writer on several occasions has measured very small electromotive forces produced by the Hall method and has experienced some difficulties because of insulation leakage in various parts of the circuit. This leakage, if it exists, will usually result in a specious magnification of the Hall constant. Another difficulty sometimes arises if thermoelectric currents have to be balanced out of the Hall circuit. The Joule heat of the primary current must be dissipated in the specimen, and it is very difficult to secure uniform temperature under these conditions. Convection currents and irregularities of structure of the specimen are apt to produce slight temperature differences, and these result in thermal e.m.f.'s when associated with contacts used for detecting the Hall e.m.f. Such thermal e.m.f.'s may be balanced out by the potentiometer when no magnetic field acts. Putting on the field, however, will destroy this balance, since the thermoelectromotive force of bismuth with respect to copper is altered by the presence of a field.

[1] Campbell, "Galvanomagnetic and Thermomagnetic Effects," p. 42.

[2] Craig, Phys. Rev. **27**, 772 (1926).

The result might be an apparent exaggeration of the Hall e.m.f. To detect such an effect the primary current must be broken and the effect of a magnetic field on the potentiometer setting noted before there is time for equalization of temperature in the specimen.

To eliminate errors of this kind it is often sufficient to reverse the direction of the magnetic field and calculate the mean of the Hall e.m.f.'s for the two directions of field. The thermal effect is thus averaged out, since it does not reverse with the field while the Hall e.m.f. does.

Craig appears to have been very careful about mounting his specimen but does not mention any special precautions taken to keep his electrical circuits insulated from each other. Also, he states that "potentials due to Thomson and allied effects were accurately measured the instant the longitudinal current was broken,"—however, he apparently did not test for the effect of the field on these potentials. Furthermore, it does not appear in his paper that spurious temperature effects were averaged out by reversing the magnetic field.

Because of the possibility of these sources of error in Craig's work the writer has made some measurements of the Hall coefficient in weak magnetic fields and has not found the abnormal values reported by Craig.

Apparatus

A thin plate of bismuth (listed by Eimer and Amend as c.p.) was made by the following method. A glass tube with one end drawn down slightly was clamped vertically and a bismuth rod inserted. The rod was prevented from slipping out of the bottom by the slight constriction there. About 10 cm below the end of the tube was placed a clean, horizontal glass plate. The lower end of the glass tube was now heated with a small flame till the bismuth melted and a single large drop was allowed to fall on the glass plate below. By a little practice in adjusting temperatures and distance of fall very thin, uniform, circular films of metal can be produced on the glass plate in this way.

The film chosen for experimentation was 0.011 cm thick, and was cut into a rectangular shape of dimensions 0.9×2.0 cm. Small arms of bismuth were left projecting from the sides of the specimen and the terminals for the Hall e.m.f. were soldered to the ends of these arms with Wood's metal. The leads for the primary current were soldered to strips of sheet copper which in turn were fixed with Wood's metal to the bismuth specimen.

Manipulation of the plate was not difficult because it was rather tightly adherent to the glass upon which it was formed. Hence, it was possible by carefully scraping the edge of the plate to adjust the Hall electrodes so that they were quite accurately on an equipotential surface when the primary current flowed and there was no magnetic field.

For the sake of thermal insulation a thick coat of paraffin was put over the plate and over the junctions of all wires leading to it, and a layer of cotton was wrapped around the whole assembly. It was then mounted, with ebonite insulation, on a stand arranged with a graduated circle so that the specimen could be rotated about a horizontal axis in the plane of the plate and parallel to its length.

The Hall electrodes were connected through a potentiometer to a galvanometer of resistance 16.6 ohms and sensitivity 17.3 mm per microvolt. The primary current electrodes were connected through an ammeter and rheostat to a 6-volt storage cell. The galvanometer circuit and the primary current circuit were insulated from the earth and from each other by ebonite,—except, of course, where interconnection occurred in the bismuth plate.

When a primary current of 1.3 amperes was sent through the specimen it required about half an hour to secure constant temperature conditions. After that length of time the galvanometer reading remained quite constant, or drifted so slowly as not to interfere with observations.

For producing the magnetic field a pair of Helmholtz coils was used. Each coil had a radius of 10.2 cm and consisted of 5 turns of No. 24 enamelled wire on a carefully turned micarta form. The field for a given current was calculated from the dimensions of the coils. The effect of the earth's field was eliminated as in Craig's work, by setting the plane of the bismuth plate parallel to the earth's field.

Measurements were made as follows. The galvanometer readings were noted in quick succession for the field in one direction, for the field reversed, and for the field in the original direction. The reading for the reversed field was subtracted from the average of the first and third readings and the difference divided by two. The result gave the deflection due to the Hall effect for the field used, and errors due to slow drift of the galvanometer were eliminated. The corresponding e.m.f. was calculated from the known sensitivity of the instrument. This method is quick and accurate, and it gives the same result as the potentiometer method provided the potential drop in the specimen due to the galvanometer current is negligible compared with the Hall e.m.f. [3]

[3] Heaps, Phys. Rev. **12**, 346 (1918).

The potentiometer in the galvanometer circuit was used for balancing small thermal e.m.f.'s and for obtaining the sensitivity of the galvanometer.

The sensitiveness of the apparatus was such that turning the plate over so as to reverse the earth's field gave a deflection of 24 mm.

Results

The table gives a set of results obtained for small magnetic fields.

TABLE I

The Hall coefficient for bismuth for small fields, with a primary current of 1.3 amps.

H (gauss) :	0.07	0.09	0.13	0.23	0.29	0.35	0.40	0.51	0.77	1.06	1.54	2.40
R :	11.4	11.3	11.0	11.3	11.3	11.8	11.5	11.7	11.9	11.6	11.6	11.7

Here H is the magnetic field strength and R is the Hall coefficient calculated in the usual way. Each value of R recorded above is the average of at least five values. These five values for any one field differed among themselves by about as much as the different values of R in the table. Apparently the change of R for a range of magnetic field from 2.4 to 0.07 gauss is no greater than the errors of the experiment. Craig found R increasing by a factor of more than 10 in this same range.

To test the effect of electric leaks one side of the potentiometer was connected by a wire to the slate bench on which the apparatus was disposed. Craig states that such a connection in his apparatus was found to increase stability, so presumably he used it in his work. It introduces a leak to ground in the galvanometer circuit. Another wire was next used to connect the enamelled iron tube of the rheostat in the primary current circuit to the floating side of the reversing switch in the circuit of the Helmholtz coils. No particular care had been taken to insulate these coils from the slate table top, and the 6-volt storage battery used for exciting the coils was standing directly on the tile floor supporting the table. This second wire thus served as a leak from the primary current circuit to ground, and the effectiveness of the leak was altered by closing the reversing switch.

With these leaks in operation and a current in the coils to give a field of 0.06 gauss, the galvanometer deflections were 4.1 and 2.0 cm, respectively, for the two settings of the reversing switch. The smaller of these deflections gives an apparent Hall coefficient about 17 times too large for this field. When larger magnetic fields were used the effect of these leaks was not so apparent because the deflections which they produced were in this case smaller than the deflections due to the Hall e.m.f.

The curve of Fig. 1 shows how the Hall coefficient of this particular specimen varies for strong magnetic fields. These fields were produced by a Weiss electromagnet with pole pieces 10 cm in diameter and 2.3 cm apart. The fields were measured with a bismuth spiral. There is no evidence of a rise in the curve as the field increases, though Craig found R increasing from 15 to 29 as the field increased from 1000 to 4220.

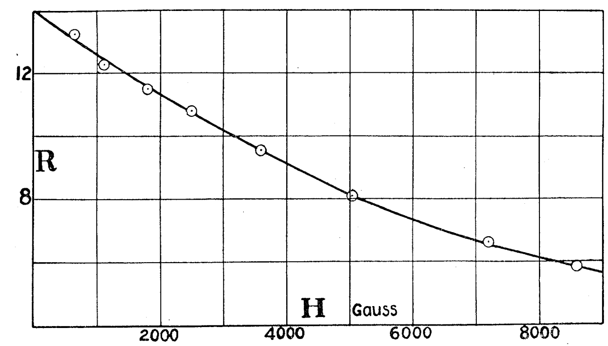

Fig. 1. Variation of the Hall coefficient, R, with the field strength, H.

The curve of Fig. 1 indicates a larger value of R for small fields than the data of Table I show. This apparent discrepancy is due to the fact that a primary current of only 0.2 amperes was used in getting the curve, while 1.3 amperes were used for the data of the table. The larger current heated the thin bismuth plate very perceptibly and the resulting rise of temperature diminished the Hall coefficient.[4]

Conclusions

For bismuth in the form of a crystal conglomerate the Hall coefficient diminishes in regular fashion as the magnetic field increases. There is no abnormal increase of the coefficient as the field becomes very small.

It appears probable that Craig's results are incorrect because of imperfect insulation of his apparatus. He states that the stability of his system was increased by grounding his potentiometer. There should, however, be no instability which could be corrected in this fashion unless leaks of variable resistance are present.

It is also possible that the lack of agreement of Craig's results with those reported in the present paper is due to his not having eliminated thermomagnetic effects.

The Rice Institute,
Houston, Texas,
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[4] Campbell, "Galvanomagnetic and Thermomagnetic Effects," p. 49.