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THE EMISSIVITY OF BISMUTH IN A MAGNETIC FIELD

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Abstract

Electromagnetic theory and the experiments of Hagen and Rubens lead to the formula $\delta E/E=\delta\sigma/(2\sigma)$, where δE is the change produced in the emissivity E of a metal for long heat waves by a change $\delta\sigma$ in the electrical conductivity σ. Using a thermopile to detect δE a magnetic field of 4900 gauss was used to produce the $\delta\sigma$ in bismuth plates kept at about 100°C. No effect of the field on E was observed for polished surfaces, surfaces etched with nitric acid, or surfaces of a plate cast in vacuum. A change of E ten times smaller than the expected result could have been detected. Possible causes of the negative result are (1) the presence of emitted energy of too short a wave-length, (2) the absence of magneto-resistance in bismuth for high frequency currents, and (3) the absence of magnetoresistance in surface layers of bismuth. Reasons are given for rejecting (1) and (2) and accepting (3) as an explanation of the experiment.

THE behavior of a metal towards radiation of sufficiently long wave-length can be predicted in many respects from a knowledge of the conductivity of the metal. Maxwell's theory gives for the reflecting power, $R=100-200/\sqrt{\sigma T}$, where σ is the conductivity of the metal and T the period of the incident radiation. For waves longer than 4μ Hagen and Rubens[1] have verified this relation experimentally. If A is the absorbing power we have $A=100-R=200/\sqrt{\ T}$. By Kirchhoff's law we may write $A=E/e$, where E is the amount of radiation emitted per second by the metal and e is the amount emitted by a black body of the same area and temperature. Thus $E/e=200/\sqrt{\sigma T}$.

Any factor, therefore, which changes the electrical conductivity of a metal should change its emissivity for radiation of a particular period. It follows from the above equation that a small change, $\delta\sigma$, in the conductivity will produce a change δE in E, given by the equation $\delta E/E=-\delta\sigma/(2\sigma)$. A similar relation gives the change of absorbing power of the metal when its conductivity changes.

In 1898 Buisson[2] attempted to detect the change of absorbing power of bismuth when its resistance was increased by a magnetic field, but he failed to obtain positive results. His bismuth, in the form of thin electrolytically deposited plates, was transparent enough to allow visual observation of an illuminated window through the metal. A magnetic field capable of increasing the resistance of the plate by 60 percent failed to change the brightness of the observed image by any appreciable

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[1] Hagen and Rubens, Ann. d. Physik **11**, 873 (1903).

[2] Buisson, Comptes Rendus **126**, 462 (1898).

amount. Buisson suggested as an explanation of his negative result that a magnetic field does not affect metallic resistance for the high frequencies of light waves. The more recent work of Hagen and Rubens has shown, however, that the equations given above, deduced by Maxwell's theory, do not apply for the high frequencies of visible light, but for waves in the infra-red, beyond 5μ, a very perfect agreement was obtained.[3] For these long waves the emissivity and reflecting powers of metals were found to vary in accordance with the theory when the conductivity was changed by altering the temperature of the metal. Constantan showed very little change of optical properties with temperature because its resistance changed very little.

It would appear probable, therefore, that Buisson's negative results were due to the employment of too short a wave-length. If the resistance change produced in bismuth by a magnetic field is similar in nature to the resistance change produced by a temperature elevation we should certainly expect an effect on the absorption and emission for radiation beyond 4μ.

The writer has performed experiments on bismuth using long waves and the expected effect has not been found.

EXPERIMENTS

For several reasons it is more convenient to measure the energy emission of bismuth than its absorbing or reflecting power. The first experiment was performed on a bismuth plate, cast and polished. This plate, of dimensions $3\times5\times0.2$ cm approximately, was soldered to one side of a copper box and placed between the poles of a Weiss electromagnet. The pole-pieces were 3.5 cm apart and 10 cm in diameter. Water in the copper box was kept boiling by means of an electric heater, and a thermopile connected to a high sensitivity galvanometer was used to receive the radiated heat. The thermopile was mounted in a case provided with the usual shielded aperture and care was taken to exclude all radiation except that from the bismuth plate.

The galvanometer deflection was 27.0 cm and a magnetic field of 4900 gauss failed to produce any observable change in this deflection. The bismuth plate was then etched with nitric acid so that the crystal structure showed up very clearly, but the new surface gave no different result. There appeared, however, to be a thin film of impurity over the surface of the metal so a new plate was made as follows.

Bismuth was melted in a Pyrex bulb to which a second bulb with flat bottom had been sealed. The air was pumped out and the melted

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[3] Wood, Physical Optics, p. 475. Hagen and Rubens found, however, an anomalous behavior in the case of bismuth.

bismuth agitated and heated for some time while the pump was running. By tilting the evacuated container the molten bismuth was now allowed to run into the flat-bottomed bulb where it solidified in the form of a plate. This plate was removed by breaking the bulb.

Both surfaces of the plate were apparently very clear and highly reflecting. By viewing these surfaces when illuminated by a single distant lamp, crystal faces could be observed flashing into view as the plate was rotated.[4] The average area of these separate crystal faces was probably about one square millimeter. This plate was clamped to one side of the copper box and the effect of the magnetic field on its emissivity determined. Neither face of the plate showed any change of emissivity capable of being observed.

The galvanometer deflection was 30.0 cm and a change as large as 0.2 cm could not have escaped detection. The value of $\delta E/E$ was thus less than 0.007. The value of $\delta\sigma/\sigma$ for bismuth spirals in the field used is about 0.15, and is probably of about this magnitude for the bismuth plates used. Thus the effect of the magnetic field on the emissivity must be at least ten times smaller than the effect to be expected from the conductivity change.

Discussion

To explain the absence of any effect of a magnetic field on the emissivity we may consider the possible operation of the following three factors.

1. The radiation may contain enough short waves to mask the effect of the field on the long wave emission. From the work of Hagen and Rubens we may assume that the emission of waves shorter than 4μ will be unaffected by the resistance change of the bismuth, while the emission of waves longer than 4μ is represented by the equations given above.

To get an estimate of the relative amounts of energy above and below 4μ we must know the form of the energy distribution curve. Aschkinass[5] has developed a theory for metals radiating waves longer than 4μ and has shown that Wien's displacement law becomes $\lambda_m\theta = 2660$, if θ is absolute temperature and λ_m is wave-length in microns. His theory also gives $S/E = 0.0221\,(r_0\theta/\lambda)^{\frac{1}{2}}$, where E is the ordinate of the energy distribution curve for a black body according to Planck's formula and S is the ordinate at the same temperature and wave-length of the energy distribution curve for the metal. r_0 is the resistivity of the metal at 0°C in ohm cms. It appears, therefore, that the

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[4] This method of observing crystal structure is due to P. W. Bridgman, Proc. Amer. Acad. **60**, 305 (1925).

[5] Aschkinass, Ann. d. Physik **17**, 960 (1905).

energy distribution curve for the metal is of the same general shape as for a black body, but the maximum is displaced to shorter waves and the whole curve is relatively higher in the short wave region.

Wien's law, therefore, as modified by Aschkinass, gives $\lambda_m = 7.13\mu$ for the bismuth plate if its temperature is 100°C. Since the temperature must have been lower than this λ_m was somewhat greater than the above value. The theory of Aschkinass will not apply for radiation below 4μ. Rough graphical methods, however, may be applied to the curve for black body radiation, modified beyond 4μ in accordance with the theory of Aschkinass. Such methods make it appear very unlikely that more than one-twelfth of the energy radiated by the bismuth plate had a wave-length less than 4μ. This amount of energy, unaffected by the magnetic field, would not be sufficient to mask the effect of the field on the greater amount of energy in the long waves.

2. The resistance of bismuth for high frequency currents may not be changed by a magnetic field. It is known that the magnetoresistance of bismuth for alternating currents differs from that for direct currents. Heurlinger's theory,[6] however, which ascribes this difference to the interaction of galvano- and thermo-magnetic effects, appears to give a satisfactory explanation of the observed phenomena (which have been confined to lower frequencies than those of light). Heurlinger gives the equation $\rho' - \rho = -PQH^2$, where ρ' is the resistivity of the metal in the field H as the frequency of the current approaches infinity,[7] and ρ is the resistivity in the field for direct currents. P is the coefficient of the Ettingshausen effect and Q the coefficient of the Nernst effect. For bismuth in a field of 6000 gauss Heurlinger finds $-PQH^2/\rho_0 = 0.003$, where ρ_0 is the resistivity when $H = 0$. There is thus a difference of 0.3 percent between the a.c. and d.c. resistance of bismuth in a field of 6000 gauss when very high frequencies are used. The d.c. resistance change produced by this field is about 20 percent, so it appears that if Heurlinger's theory is complete, the high frequency magnetoresistance of bismuth differs very little from the d.c. magnetoresistance.

3. The surface layers of bismuth may be unaffected by the magnetic field while the body of the metal has its resistance changed. For several reasons[8] it appears probable that a magnetic field changes the resistance of bismuth by altering the number of electrons effective at any instant in carrying the current. If equilibrium exists between a group of conducting electrons and a group of bound electrons it is entirely conceivable that a magnetic field may alter the equilibrium

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[6] Heurlinger, Phys. Zeits. **17**, 221 (1916).

[7] Resistance change due to skin effect is not considered in the theory.

conditions so as to change the number of electrons in the respective groups. The molecules on the surface of the metal will be subjected, because of surface tension effects, to conditions different from those in the body of the metal. These molecules may react differently, therefore, towards a magnetic field.

There is considerable evidence in favor of this view. Magnetoresistance for thin bismuth films is smaller than for bismuth in bulk; and the thinner the film the less appears to be the magnetoresistance. Films which have been examined in this respect by Curtiss[9] consisted of small crystals of random orientation. If the crystal composition of the films of different thicknesses (as determined by resistance measurements) was the same the magnetoresistance differences must have been due to the increased relative importance of surface layers for the thinner films. There is some doubt, however, of the identity of crystal structure of the different films.

It seems to be certain that the position relationship of molecules of a metal to each other is of profound influence on the magnetic quality of the metal. Thin amorphous films of nickel are non-magnetic.[10] Liquid metals do not show a true magnetoresistance. Surface layers of iron appear to have a smaller induction than deeper layers, while the converse is true for nickel.[11]

CONCLUSION

While the experimental evidence is not conclusive it nevertheless seems probable that the failure of a magnetic field to affect the emissivity of bismuth is due to the absence of magnetoresistance in the surface layers of the metal. Hagen and Rubens found bismuth occupying an anomalous position as regards reflection and emission coefficients in the list of metals which they investigated. They suggested as reasons for this peculiarity the difficulty of securing good reflecting surfaces of bismuth and the known anomalous behavior of bismuth in other respects. It is possible that the electrical resistance of surface layers of bismuth is different from the body resistance even when no magnetic field acts.

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[8] Heaps, Phys. Rev. **19,** 7 (1922); **12,** 340 (1918); Phil. Mag. **50,** 1001 (1925).

[9] Curtiss, Phys. Rev. **18,** 255 (1921).

[10] Ingersoll and DeVinney, Phys. Rev. **26,** 86 (1925).

[11] McKeehan, J.O.S.A. and R.S.I. **11,** 169 (1925), has attributed this effect to strains in the surface layers produced by previous treatment, but on this view it is difficult to explain some of the results of E. H. Williams, Phys. Rev. **33,** 60 (1911).