XXXIV. The magnetic balance of MM. P. Curie and C. Cheneveau

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arenaceous group. The former may be taken as approximating to 1.3×10^{-5} , making allowance for some small amount in the alkaline solutions; the latter to 0.6×10^{-5} gram per gram.

Accepting the estimate cited by F. W. Clarke ("A Preliminary Study of Chemical Denudation," Smithsonian Miscellaneous Collections, vol. lvi. No. 5, June 1910) that the calcareous rocks compose 5 per cent., the arenaceous 15 per cent., and the argillaceous 80 per cent. of the sedimentaries, my results on thorium measurements (assuming 0.06×10^{-5} to represent the mean for the calcareous rocks) give for the sedimentary rocks generally a thorium content of 1.16×10^{-5} gram per gram.

July 11th, 1910.

XXXIV. *The Magnetic Balance of MM. P. Curie and C. Cheneveau.* By C. CHENEVEAU, with an Appendix by A. C. JOLLEY*.

THIS apparatus is intended for the measurement of the coefficient of specific magnetization, or the susceptibility or permeability of feebly paramagnetic or diamagnetic bodies †.

Principle and Theory of the Apparatus.

The body whose magnetic properties are to be determined is suspended from one end of the arm of a torsion balance. By means of this balance the force is measured, which is experienced by the body when placed in a non-uniform magnetic field, produced by a permanent magnet whose lines of force cross the space occupied by the body. The method of calculating this force will first be briefly indicated.

Suppose that the body is placed at a point O in a field of direction Oy and of intensity H_y . The force f which tends to move the body will be normal to the direction of the field,

* Communicated by the Physical Society: read April 22, 1910.

† The coefficient of specific magnetization K is the ratio of the intensity of magnetization $\mathcal{I} = \frac{M}{m}$ (where M is the magnetic moment and m the mass of the body) to the magnetizing field. The magnetic susceptibility $\kappa = K\Delta$, where Δ is the density of the body, and the permeability is obtained from the susceptibility by the relation $\mu = 1 + 4\pi\kappa$.

i. e. in the direction Ox (fig. 1). If $\mathcal{J}$ is the intensity of specific magnetization, the value of the force is *

$$f = m\mathcal{J} \frac{\partial H_y}{\partial x} \dots \dots \dots (1)$$

$\frac{\partial H_y}{\partial x}$ representing the space variation of the field.

As we are only concerned with feebly magnetic bodies, the demagnetizing force arising from the magnetization of the body is negligible, and we may assume that the intensity of magnetization is proportional to the field. If we denote the constant ratio between the intensity and field, or *coefficient of specific magnetization*, by K , we have

$$\mathcal{J} = KH_y, \dots \dots \dots (2)$$

consequently combining equations (1) and (2)

$$f = KmH_y \frac{\partial H_y}{\partial x} \dots \dots \dots (3)$$

Let us first suppose that the magnet producing the magnetic field is at a considerable distance from the body. Then $H_y = 0$, and by (3) the force is zero.

The body being always situated at O , let the magnet be brought up to the position I (fig. 2). If the force f is one of attraction the body is of course paramagnetic, if of repulsion, diamagnetic †.

* We have $f = \frac{\partial W}{\partial x}$, $W = MH_y$, and $M = \mathcal{J}m$.

Hence $f = m\mathcal{J} \frac{\partial H_y}{\partial x}$.

† If the sense Ox is taken as positive and we employ the true formula for the force, $f = -\frac{\partial W}{\partial x}$ the negative sign for the force indicates attraction and the positive sign repulsion.

Suppose first that the body is paramagnetic.

When the magnet is situated so that the body O coincides with the centre G, the force will again be zero, as $\frac{\partial H_y}{\partial x}$ is zero at the centre (position II, fig. 2).

Fig. 2.

Hence the force f is zero when $x=\infty$ and $x=0$ and it passes through a *maximum* in the interval, which occurs at a certain point O' where the product of the field H_y by its gradient $\frac{\partial H_y}{\partial x}$ is a maximum.

If the magnet is continually turned in the same sense of rotation, so that its centre G passes through the point O and arrives at G' (position III, fig. 2), we observe that the force, which was nil at O , reaches a *minimum* or negative maximum at a point O'' symmetrical with O' , relatively to O , and becomes zero again after the magnet is withdrawn far from the body.

Hence the curve in fig. 3 shows the variation of the force f with the displacement x . The body is first displaced in the direction of the arrow marked I from O to O' , where it stops and moves back with the magnet along the arrow

marked 2 to O'', where it again stops and afterwards returns to O, as shown by the arrow 3.

Fig. 3.

It is easy to explain in a similar manner the motions of a diamagnetic body which will of course be the reverse of the above, as the force is opposite in sign. Fig. 4 shows the curve in this case.

Fig. 4.

At every instant the action of the force is balanced by the torsion of the balance wire. If c is the moment of torsion per unit angle, and α the maximum deviation of the arm at O or O' (fig. 2), the equilibrium condition is

$$fl = c\alpha, \quad \dots \dots \dots (4)$$

if l is the length of the balance arm.

If the deviation is measured by lamp and scale,

$$\alpha = \frac{D}{2L}, \quad \dots \dots \dots (5)$$

D being the deflexion of the spot upon the scale, and L the scale distance.

Hence from equations (3), (4), and (5)

$$KmH_y \frac{\partial H_y}{\partial x} l = c \frac{D}{2L}, \quad \dots \dots \dots (6)$$

from which

$$K = \frac{cD}{2mlLH_y} \frac{\partial H_y}{\partial x} \dots \dots \dots (7)$$

This formula (7) thus permits the *absolute value* of the coefficient K to be determined for a body if the other quantities are accurately determined. By an analogous method P. Curie * has determined the absolute value of the coefficient of specific magnetization of water.

But the apparatus is especially adapted for relative measurements, and in this case it becomes extremely simple and practical.

If we have a body of unknown coefficient K and of mass m, we have from equation (6)

$$KmH_y \frac{\partial H_y}{\partial x} l = c \frac{D}{2L} \dots \dots \dots (8)$$

For a body of known coefficient K' and mass m' occupying the same volume

$$K'm'H_y \frac{\partial H_y}{\partial x} l = c \frac{D'}{2L} \dots \dots \dots (9)$$

Hence by division

$$\frac{K}{K'} \cdot \frac{m}{m'} = \frac{D}{D'} \dots \dots \dots (10)$$

Equation (10) thus enables K to be determined.

It is evident that it is much more convenient to measure the displacements D and D' of the spot corresponding to the angular deviations 2α and $2\alpha'$ between the two positions O' and O'' of the body (fig. 2), for, without altering equation (10), the displacements of zero are eliminated and the accuracy of measurement doubled.

If the body is placed in a tube of glass or other substance, this tube being subjected like the body under test to the magnetic forces, an experiment must be made with the tube alone, and the effect due to the tube represented by a displacement of the spot D'' added or subtracted.

* P. Curie, *Annales de Chimie et de Physique*, 7^e Série, t. v. p. 341 (1895).

We thus have

$$\frac{K}{K'} \cdot \frac{m}{m'} = \frac{D \pm D''}{D' \pm D''} \dots \dots \dots (11)$$

Whence

$$\frac{K}{K'} = \frac{D \pm D''}{D' \pm D''} \cdot \frac{m'}{m} \dots \dots \dots (12)$$

This formula is not corrected for the effect due to the magnetization of the air ; the exact formula may be obtained as follows :

Let κ' and κ'' be the susceptibilities of the substance taken as standard, assumed to be paramagnetic, and of the air respectively. Let Δ' be the density of the comparison body, and A a constant of the apparatus. In reality the exact expression for the force when one deals with the standard body is

$$f' = (\kappa' - \kappa'') \frac{m'}{\Delta'} A = \left(K' - \frac{\kappa''}{\Delta'} \right) m' A, \dots \dots (13)$$

since

$$K' = \frac{\kappa'}{\Delta'}.$$

When a measurement is made with a paramagnetic body of susceptibility κ and density Δ the true value of the force in this case is

$$f = (\kappa - \kappa'') \frac{m}{\Delta} A = \left(K - \frac{\kappa''}{\Delta} \right) m A, \dots \dots (14)$$

Dividing (14) by (13) we have

$$\frac{f}{f'} = \frac{K - \frac{\kappa''}{\Delta}}{K' - \frac{\kappa''}{\Delta'}} \cdot \frac{m}{m'}$$

or

$$\frac{f}{f'} \cdot \frac{m'}{m} = \frac{K - \frac{\kappa''}{\Delta}}{K' - \frac{\kappa''}{\Delta'}} \dots \dots \dots (15)$$

If we put $r = \frac{f}{f'} \cdot \frac{m'}{m}$; this is the approximate ratio of the coefficients of specific magnetization K and K' previously determined by the aid of formula (12) *.

* We have in fact, from what has been proved above,

$$f l = K m A = B (D \pm D''),$$

$$f' l = K' m' A = B (D' \pm D'');$$

A and B as well as l being constants ; whence

$$\frac{f}{f'} = \frac{K m}{K' m'} = \frac{D \pm D''}{D' \pm D''}; \quad \frac{f m'}{f' m} = \frac{K}{K'} = \frac{D \pm D''}{D' \pm D''} \cdot \frac{m'}{m}.$$

From (15)

$$r = \frac{K - \frac{\kappa''}{\Delta}}{K' - \frac{\kappa'''}{\Delta'}};$$

$$K - \frac{\kappa''}{\Delta} = rK' - r\frac{\kappa'''}{\Delta'};$$

$$\frac{K}{K'} = \frac{\kappa''}{K'\Delta} + r - r\frac{\kappa'''}{K'\Delta'};$$

$$\frac{K}{K'} = r \left[1 + \frac{\kappa'''}{K'} \left(\frac{1}{\Delta'} - \frac{1}{\Delta} \right) \right], \quad . \quad . \quad . \quad (16)$$

in which

$$r = \frac{D \pm D''}{D' \pm D''} \cdot \frac{m'}{m}.$$

When the comparison body is water

$$K' \text{ exactly } = -0.79 \times 10^{-6} \text{ (P. Curie).}$$

As for air the susceptibility $\kappa'' = 0.0322 \times 10^{-6}$.

If r is *positive* we have for a paramagnetic body

$$\frac{K}{K'} = -r \left[1 + 0.041 \left(\frac{1}{r\Delta} + 1 \right) \right],$$

and for a diamagnetic body

$$\frac{K}{K'} = r \left[1 - 0.041 \left(\frac{1}{r\Delta} - 1 \right) \right].$$

Hence the apparatus lends itself very readily to relative determinations, and if we take water as the standard body ($K' = -0.79 \times 10^{-6}$) it enables us to obtain an absolute value of the coefficient of specific magnetization of a body.

But the comparison substance may be a liquid or solid other than water, and such that its coefficient of magnetization is of the same order of magnitude as that to be determined. A choice can be made from the tables of magnetic constants. It is convenient if the masses of the bodies compared correspond to the same volume; on this account the tube containing the substance is always filled to a given mark. When the substances tested are very strongly magnetic, a smaller length may be employed, but in that case it is absolutely necessary that the comparison substance should have the same length.

The apparatus could be made still more sensitive with the aid of an electromagnet. On the other hand, with a torsion wire of larger diameter, the magnetic properties of iron or

other ferro-magnetic metals and alloys could be determined. It would doubtless suffice to use an extremely fine wire of the metal, and to employ the method of experiment and the corrections already proposed by P. Curie in a work on the magnetic properties of bodies (*loc. cit.* p. 5, note 1).

Fig. 5.

Description of the Instrument, Magnetically Damped Form.

The arm of the torsion-balance is formed by a rod TT (fig. 5), which carries from one of its two extremities a hook *c*, from which the glass tube *t*, which contains the body,

can be suspended. To this end the glass tube is closed by a cork carrying a metallic ring which hangs on the hook *c*. The tube *t* is therefore in a vertical position. On the other end of the arm TT is fixed a copper sector, S', which moves between the poles of a fixed damping magnet A. To vary the sensitiveness the torsion-wire can be changed, and the damping varied by the position of the copper sector in the field.

On the horizontal arm TT is fixed a vertical copper strip which carries a hook to which the torsion-wire f ($\frac{1}{10}$ mm. platinum) is attached. Below, this strip is turned at right angles as shown by the portion DE parallel to TT. Balance is obtained partly by the aid of a small copper cylinder B, sliding on the rod TT, when the tube is empty, and partly by copper or aluminium riders, *pp*, to compensate for the weight of the solid or liquid material which fills the tube to the level marked.

The displacement of the magnet N.S. is obtained by a movement of rotation around an axis O; this movement is smoother than the sliding motion of our earlier model. The movements of the torsion-balance are followed by the observer upon a divided scale C. (fig. 6). For this purpose a 2-metre

Fig. 6.

radius concave mirror *m* is attached to the balance-arm, and the image of a straight filament is employed. The displacement of the magnet is effected by a controller M (fig. 6), fixed in

front of the scale, which consists of a horizontal rod PQ turning about a vertical axis in a heavy base, and furnished with a large milled head G, which can be turned by the observer. This rod is provided with two clamps P and Q, which are attached by two cords to two rings R and V on a similar rod attached to the axis of the magnet NS. If the cords are initially arranged so that the rods PQ and RV are parallel, the position of the magnet is at once determined by the direction of the rod PQ, and it can be turned either by the milled head G, or preferably by holding the two cords as like reins.

The advantage of employing a rectilinear filament lamp (such as is made by the Pintsch Glühlampenfabrik in Berlin) is considerable in practice, as the spot is always visible on the scale even if the torsion-arm is not perfectly balanced horizontally.

Appendix.

By the courtesy of M. Cheneveau and the Cambridge Scientific Instrument Co., we have been able to set up and test the performance of one of these balances in the laboratories of the Northampton Institute.

The instrument was of the magnetically damped type described above, and was used with a lamp and scale at some two metres distant from the mirror.

No attempt was made to obtain absolute values of the coefficients of specific magnetization; but relative determinations only were made, using as a standard substance distilled water, and assuming for it the value

$$K' = -0.79 \times 10^{-6},$$

as found by M. Curie and given above.

The results obtained are set out in the accompanying table, and show some interesting figures.

The first portion of the table contains figures for a few materials selected quite at random in order to test the behaviour of the balance. Of these the first five are chemically pure liquids, and all exhibit diamagnetic qualities.

The four samples of aluminium are all magnetic, and we have not been able to get a sample which is less magnetic than the first of these. The eleven samples of brass indicate the range over which the magnetic qualities vary, while some of the samples examined, but not here tabulated, have been too magnetic to be used in the apparatus without changing the suspension.

It is interesting to note that during some inductance tests

SUBSTANCE.	Density, Δ.	Coefficient of Specific Magnetization, K.	SUBSTANCE.	Density, Δ.	K.	Specific Resistance, Microhms per cm. cube at 0° C. ρ.	Temperature Coefficient % at 17° C.	Thermo E.M.F. to Cu Microvolts per ° C.	Effect of Volume on Value of K.	Effect of Length on Value of K.
Water	1.0	-0.79×10^{-6}	Nickelin, I	9.09	4.88×10^{-6}	43.13	0.00245	37.5	NICKELIN, I.	COPPER.
Alcohol	0.79	-0.78	Nickelin, 1	8.77	3.75	40.62	0.021	20.0		
Amyl Alcohol ..	0.815	-0.929	Nickelin, 5	8.79	2.11	39.29	0.0187	19.06	Mass, m.	Length.
Benzene	0.85	-0.962	Nickelin, 13	8.82	5.76	39.73	0.021	20.75		
Luxor Oil	0.8	-0.594	Extra Prima	8.8	2.1	29.35	0.028	16.55	K.	K.
Methyl Ether ..	0.725	-0.785	Platinoid	8.83	1.75	33.62	0.0224	23.52		
Aluminium	2.67	1.19×10^{-6}	"	..	1.61				0.198	5 cm.
"	..	1.79	"	..	1.63				1.985	4.5
"	..	2.03	Constantan Vogel	8.99	9.67	47.06	-0.00122	37.5	1.784	4.0
"	..	2.99	"	..	10.25				1.583	3.5
Brass	8.1	-0.026×10^{-6}	"	..	9.72				1.385	3.0
"	..	3.95	Constantan, 12	8.97	12.37	48.3	0.001437	35.75	1.187	2.5
"	..	0.3	1A 1A	8.97	9.23	50.7	-0.0029	39.12	0.989	2.0
"	..	0.09	German Silver, 2 A	9.06	6.77	42.89	0.00385	35.75	0.789	1.5
"	..	0.083	New Metal	8.97	6.87	51.10	-0.0038	35.8	0.592	1.0
"	..	2.02	"	..	6.77				0.393	0.5
"	..	1.94	Eureka	8.96	..	47.4	0.0048	40.6	0.192	
"	..	0.232	Manganin, 14	8.61	28.05	36.62	0.00175	1.4	EXTRA PRIMA.	EFFECT OF ACID TREATMENT. COPPER.
"	..	3.09	Manganin Isabelenhutte ..	8.6	28.7	39.14	0.00176	1.44		
"	..	4.05	Rheotan	8.61	..	47.55	0.024	13.8	0.21	Mass, m.
"	..	2.45	Superior	8.24	..	81.024	0.1148	7.44		
Copper	8.9	0.707×10^{-6}							2.1 $\times 10^{-6}$	K.
"	..	0.455							0.434	
"	..	1.06							0.635	2.545 gr.
"	..	0.68							0.836	
"	..	0.54							1.033	After Treatment with Hot Conc. HCl:—
"	..	0.36							1.233	
"	..	0.83							1.435	2.542
"	..	0.537							1.637	
"	..	-0.097							1.835	Further Treatment with HCl:—
Tin	7.3	0.151×10^{-6}							2.033	
Zinc	6.9	0.043×10^{-6}							2.237	2.540
"	..	0.212							2.437	
" (Pure)	..	0.224							2.634	0.774
									2.834	

in progress in the laboratory, circumstances compelled us to use brass conductors, and the results obtained were higher than those given by calculations based on theory. This could only be accounted for by assuming a permeability for the brass greater than unity, and although the magnetism in the metal was not detectable by a fairly sensitive magnetometer, it was readily shown when samples of the conductors were tested in the balance.

Nine samples of copper are tabulated, and one only is diamagnetic, again emphasizing the difficulty of obtaining really non-magnetic conductors.

The tin sample was chemically pure and is also magnetic. Of the three samples of zinc the first two are ordinary commercial sheet metal, and the third one is a rod of chemically pure metal for use in standard cells.

The next portion of the table is devoted to an examination of the series of resistance alloys, whose electrical properties were investigated by the writer some time ago and published by Dr. Drysdale in connexion with his paper upon the Comparison of Standard Resistances, before the British Association at Leicester, 1907.

The first point which strikes one in connexion with these is the fact that every alloy is magnetic, but that those alloys containing relatively a large proportion of the magnetic metal nickel, *i. e.* Nickelines, are among the least so. The first sample is very different from the other three, and we have reason to believe that the second and fourth samples are of the same manufacture although obtained from different firms.

The samples of Platnoid fall into this group with properties very comparable with the Nickelines, and the material sold under the trade name of Extra Prima probably also belongs to this group.

The Constantans come next in order, being more magnetic than the Nickelines, and it is not difficult to see that the material catalogued as 1A1A belongs to this group of alloys, together with the alloy supplied to us under the title of New Metal, while the sample German Silver 2A, but for its high density and positive temperature coefficient, would also be classed among the Constantans.

Eureka is a resistance material which is often classed as a Constantan, but the balance easily disproves this, as it shows it to be so magnetic that observations would have had to be made with a stiffer suspension than we were using, ~~and this~~, coupled with its positive temperature-coefficient, rule it out of the group.

Superior and Rheotan behave like steels in the apparatus and probably contain considerable quantities of iron in their composition.

The magnetic behaviour of Manganin is remarkable, it being, with the exception of the last two alloys and Eureka, the most magnetic of all the materials examined. This is of particular interest in view of its almost universal adoption for the construction of accurate resistances, but it is not altogether unexpected when we remember that the remarkable Heusler alloys have a Copper-Aluminium Manganese composition.

The figures in the rest of the table indicate the variation in the value of K , with increase in mass of the specimen and increase in length. In the first case the sample, in the form of a bare wire 1 mm. in diameter, was cut up into standard length (approx. 2.8 cms.), and successive lengths of measured mass were introduced into the tube until it would hold no more; it will be observed that the value of K tends to diminish as the mass increases. (Curve A, Extra Prima, fig. 7.)

The apparatus is, of course, very sensitive to the length of specimen, and an extreme range of length was taken in a wire of 1 mm. diameter, and the results are shown in the curve B (copper).

The difficulty of obtaining non-magnetic copper has already been referred to, and every instrument-maker knows how difficult it is to wind a really non-magnetic D'Arsonval coil. In order to see how far this is dependent upon surface conditions a sample of copper was taken and treated with concentrated hydrochloric acid and re-tested, and it was found that the value of K was reduced to nearly one-half, and that further treatment had but little effect.

From these results it will be seen that there is a considerable field of usefulness for the balance. Firstly, for examining the materials to be used in the construction of standard apparatus where the permeability becomes of first importance. Secondly, in grading and examining alloys whose properties are materially dependent upon minute traces of alloying constituents which are so difficult to estimate by chemical means, and which play such an important part in their electrical behaviour. Thirdly, it could well be used to maintain the standard of purity in the commercial production of such a metal as Aluminium, whose chief impurity is iron, the last traces of which are so difficult to remove.

Fig. 7.

In conclusion the writers' thanks are due to Mr. A. F. Burgess, B.Sc., for his help in the experiments and calculations.