A Sensitive Magnetometer

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XXIX. *A Sensitive Magnetometer.* By P. E. SHAW, B.A.,
D.Sc., and C. HAYES, B.Sc.

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In a research recently published by one of us* there is a description of a torsion balance of special delicacy for gravitation research. A diagrammatic representation of this apparatus is

FIG. 1.—FRONT AND SIDE VIEWS OF THE MAGNETOMETER.

The axis of the solenoid is, as shown, in the first case perpendicular to the plane of the paper and in the second case in the plane of the paper.

shown in Fig. 1. A fibre, *FF*, 600 mm. long, 15μ diameter, carries a beam, *B*, 35 mm. long, from the ends of which are

* "The Newtonian Constant of Gravitation as Affected by Heat," Shaw, "Phil. Trans.," 1916, A. Vol. CCXVI., p. 349.

hung, by fine wires of length 150 mm. and 350 mm. respectively, two small spheres of silver, each weighing about 3 gm. This torsion system is hung in a low vacuum of about 15 mm. pressure. The movements of the torsion beam, carrying a mirror which reflects a distant scale, are observed through the window *W* by a powerful telescope distant about $4\frac{1}{2}$ metres. The vacuum tube *V* is wrapped by several layers of cotton-wool, and this latter is surrounded by a helix of lead "compo" tubing. The cylindrical envelope *C* encloses the cotton-wool and tubing, and all the vacuum tube except the extreme upper portion. The lead helix contains cold water. Further details of this apparatus are given in the Paper quoted.

In the course of the research mentioned it was necessary to heat the vacuum tube. This was attained by the passage of a current through a coil of wire wrapped on the outside of the vacuum tube. It was found later that on account of the field thus produced the silver spheres had become permanently but weakly magnetised with vertical axes. This permanent magnetisation was observed as follows: When the *N.* pole of a bar magnet, 20 cm. long, was brought to about 6 cm. from one sphere, the latter moved, and a scale deflection of several centimetres (right or left, according as the pole was above or below the sphere) was observed. The coercivity was considerable; the field required to remove the permanent magnetism from the spheres being of the same order as that used in its production. After much trial the required field was obtained, and the vertical permanent magnetism was so far removed that the scale deflection due to the presence of the *N.* pole, was reduced to less than 0.5 mm.

The spheres were of silver of the highest purity from Messrs. Johnson, Matthey & Co., who described it as "absolutely pure." Care was taken, during the mounting of the spheres on the torsion system, to avoid any contamination of their surfaces. Clean hands were used by the operator, and after mounting and before entering the vacuum tube, they were washed in nitric acid, followed by distilled water.

This behaviour of such pure silver came as a surprise. One did not expect either silver or the small amount of residual iron to display permanent magnetism and great retentivity. So an investigation was commenced to ascertain the nature of these effects.

Some scraps of the same silver as used for making the spheres were analysed. Specially pure nitric acid was tested, and

found by the ferrocyanide test to be free of iron. The silver scraps were then dissolved in this nitric acid. After boiling off any excess of acid, iron-free hydrochloric acid was added, and the silver chloride precipitated. The iron was left in the solution, which was now tested by the colorimetric ferrocyanide test. The result of the analysis was that the proportion of iron to silver was found to be 30/1,000,000. The silver spheres were probably much purer than the scraps used in the analysis, as the latter were the turnings from the spheres.

After searching for authorities on the subject of the susceptibility of the less magnetisable elements, the work of Honda* was taken to be the best on silver up to date. The method employed by Honda was to place a small quantity of the silver in a capsule carried by a torsion beam and to observe the couple produced on the beam when a very powerful field was applied by an electro-magnet near the capsule. He then deduced that the susceptibility of silver is $K = -2 \times 10^{-6}$ c.g.s.

In order to observe the effects of a field on our suspended silver spheres, we brought up a solenoid, **ZZ**, of length 38.5 cm., outside diameter 10.8 cm. and having 528 turns of about 16 S.W.G. copper wire, close to the vacuum tube, opposite to the upper sphere *S*, so that the axis of the solenoid was horizontal, and passed through the centre of the sphere. On passing currents through the solenoid and an ammeter, the field developed at the sphere was varied from 1.3 gauss to 12.0 gauss. The silver sphere being in a divergent field, was urged along the axis of the solenoid and a scale deflection was read by the telescope. As silver is diamagnetic we expected that the sphere would be repelled. But, on the contrary, there was an attraction to the solenoid. Thus, there must be, apparently, sufficient iron impurity present to give it a preponderating effect over the diamagnetic silver. For fields of about 5 gauss, iron has a susceptibility of about 170 c.g.s. Then, supposing silver and iron act independently in a magnetic field in the presence of one another, the proportion of iron to silver in our sphere must considerably exceed 1 to 80,000,000. But we have no authority for supposing that this principle of proportionality holds good. The experimental evidence is, in fact, that the iron loses some or all of its magnetic power when melted into other metals. To quote two examples of this principle :—

* "Ann. der Physik.," XXXII., pp. 1027-1063.

1. A certain alloy of iron and nickel can be made, which has practically no ferromagnetic qualities. Thus each of these strongly magnetic metals loses magnetism through the presence of the other.

2. Honda* found that for *very large fields* the magnetic influence of the iron impurity is never more than 50 per cent., and sometimes as little as 5 per cent. of that which it would be on the basis of proportionality.

After obtaining the above preliminary result, the current in the solenoid was varied from 2 to 9 amperes (Table I.) and the scale deflections noted. Next, the solenoid was moved along its axis nearer to the silver sphere, and the experiment repeated with the currents 1 to 9 amperes (Table II.). Details as to the form and use of the torsion balance will be found in the gravitation research, as quoted.

TABLE I.

Current. Amps.	Field H .	$\frac{\partial H}{\partial x}$	d_1 . mm.	d_2 . mm.	$K_a \times 10^6$.
2	1.81	0.40	2.24	0.49	0.176
3	2.72	0.46	4.83	2.45	0.272
4	3.63	0.60	8.43	4.53	0.277
5	4.53	0.80	12.33	8.20	0.264
6	5.44	0.98	17.37	12.00	0.258
7	6.35	1.14	23.35	17.17	0.262
8	7.25	1.30	28.50	21.45	0.248
9	8.16	1.42	35.23	28.78	0.258

TABLE II.

Current. Amps.	Field H .	$\frac{\partial H}{\partial x}$	d_1 . mm.	d_2 . mm.	$K_a \times 10^6$.
1	1.34	0.29	1.17	0.17	0.159
2	2.67	0.57	4.98	2.03	0.214
3	4.01	0.72	10.65	6.30	0.274
4	5.34	1.14	21.13	12.28	0.256
5	6.68	1.45	28.15	20.93	0.236
6	8.02	1.76	39.95	31.25	0.235
7	9.35	2.02	53.93	42.10	0.237
8	10.69	2.29	71.91	59.39	0.250
9	12.02	2.59	88.19	75.31	0.245

It should be observed that care was taken throughout to have the silver sphere in a cyclic state. Before commencing the readings in Table I. the largest field about to be used

* *Loc. cit.*

was developed in the solenoid, and this field was slowly reduced with alternations until it became zero. Again, before every reading, direct or reverse, the current in the solenoid was reversed, say, 10 times.

To Find a Value for the Susceptibility of the Silver Used,

Let

K = Susceptibility of absolutely pure silver.

K_a = Susceptibility of the (impure) silver used.

V = Volume of the sphere.

a = Arm of the torsion balance.

G = Couple required to produce a deflection of 1 mm. on the scale. (In this apparatus G has the small value 4.5×10^{-7} dyne cm.)

P = Permanent magnetism (this is a magnetic moment).

Then the sphere is in a divergent field whose gradient along the axis of the solenoid is $\partial H / \partial x$; and we have then—

For a Direct Current—

Couple acting on torsion balance

$$= (VK_a H + P) \partial H / \partial x \cdot a = G \cdot d_1, \quad \dots \quad (1)$$

where d_1 = scale deflection.

For a Reverse Current—

$$\text{Couple} = (VK_a H - P) \partial H / \partial x \cdot a = G \cdot d_2, \quad \dots \quad (2)$$

where d_2 = scale deflection.

Whence—

$$K_a = \frac{G(d_1 + d_2)}{2VH\partial H / \partial x \cdot a} \quad \dots \quad (3)$$

The value of H is calculated from the usual expression—

$$H = 2\pi ni(\cos \beta - \cos \alpha),$$

and $\partial H / \partial x$ is calculated from a graph for H/x , specially drawn for the purpose.

The last column in Tables I. and II. show the values of K_a , ascertained from equation (3). Notice that the values of d_1 and d_2 differ considerably, showing that the permanent magnetism is an important factor.

The results for $H-K_a$ are shown in Fig. 2. It will be seen that the value of K_a rises with an increasing field, and attains a maximum for a field $H=3.0$ gauss. This is the field which gives the maximum susceptibility for pure soft iron, and we might expect that, since the value of K for iron drops rapidly as the field increases thereafter, the curves in Fig. 2 would also drop rapidly. But, in fact, the value of K_a is practically constant with increasing field. This means that, at least for fields of 3.0 to 9.0 gauss, either the values of K for iron and for silver vary together, or neither of them changes. Supposing (as is generally done) that the susceptibility of *pure* silver is constant, then that for the iron impurity is also constant over this range.

Honda worked with the range of field 5 to 23 kilo-gauss, and in the case of the slightly impure silver used, he found only a

FIG. 2.—CURVE SHOWING THE RELATION OF FIELD IN GAUSSSES TO APPARENT SUSCEPTIBILITY $\times 10^6$.

small change in the susceptibility (at most about 30 per cent. of the whole) for this range. The proportion of iron to silver in his specimens was about 6/1,000,000 (as shown by chemical analysis). For these fields the effect was diamagnetic—*i.e.*, the silver effect preponderates over that of the iron. This again is another disproof of any simple superposition theory, as the figures for purity and susceptibility show.

For the very large fields used, Honda found a hyperbolic relation—

$$\chi = \chi_{\infty} + \sigma/H,$$

where

χ = Specific susceptibility for the silver specimen in a field H .

χ_{∞} = Specific susceptibility for an infinite field.

σ = A constant, the specific intensity of magnetisation for the iron impurity.

In our experiments there is no trace of a hyperbolic relation; in which case σ , in the above expression, is not constant, but variable..

Two researches other than that of Honda should be noticed:—

(1) A. P. Wills* worked on weakly magnetic bodies with fields of 1 kilo-gauss and upwards. He failed to establish any permanent magnetic state in the substances used. For these high fields the permanent magnetism would have been very small in proportion to the temporary magnetism, and in any case would be imperceptible, except with such a delicate instrument as was used by us.

(2) Fleming and Dewar† worked on silver at low temperatures for high fields only (2 to 3 kilo-gauss).

The above are the only recent researches at all kindred to ours which we have discovered.

It would have been interesting to extend the investigation by increasing the field and by varying the purity of the silver sphere, but as the torsion system was required for further research on gravitation (*see* introductory remarks), the vacuum could not be opened, and the investigation extended. We are thus forced to leave the problem at this stage, having satisfactorily tested the magnetic qualities of the spheres for low fields, which alone are important as regards the gravitation research.

We suggest that on a torsion balance of extreme delicacy such as that used by us (which is about 10^6 times as sensitive as that used by Honda), it would be possible to carry out a systematic investigation of the magnetism of feebly magnetic materials even for weak fields. This would be untrodden ground.

ABSTRACT.

A torsion balance of extreme delicacy carries a pair of purest silver balls, each 3 gm. weight. A solenoid with horizontal axis passing through one of the silver balls, is brought close to the balance. On exciting the solenoid, divergent fields of known strength are obtained in the region of the ball. The resulting attraction of the ball to the solenoid is shown by a mirror reflecting a distant scale to a telescope. The couple on the torsion beam required to produce 1 mm. scale deflection is 4.5×10^{-7} dyne cm., and this torsion balance is 10^6 times as sensitive as any known to have been used previously in this kind of work.

* "Phil. Mag.," May, 1898.

† "Proc." Roy. Soc., p. 311, 1898.

The results of these experiments are :—

1. The magnetic properties of the silver are ascertained even for weak fields of 1–10 gauss.
2. The silver has a pronounced retentivity ; this effect being presumably due to the small trace of iron impurity.
3. The relation of susceptibility of the silver to the field used is found. The susceptibility of each of the constituent materials (a) pure silver, (b) residual pure iron, appears to be greatly modified by the presence of the other material.

DISCUSSION.

Dr. S. W. J. SMITH thought that the results obtained by the authors, showing the susceptibility of nearly pure silver in weak fields, were both interesting and instructive. He thought the authors, in discussing their significance, had overlooked the fact that the minute amount of iron (not exceeding 30 parts per million) shown to be present by chemical analysis, would not have the same effective susceptibility as iron in the form, for example, of long rods magnetised in the direction of their length. It was true that iron, when alloyed with other substances, could lose its characteristic ferromagnetic properties ; but there was no reason to suppose that it would do so when present in silver, except in so far as the properties of a very minutely divided substance might differ from those of the same substance in bulk. So far as he knew, iron and silver were mutually insoluble. In that event the impurity found to be present should be regarded as minute particles of iron scattered about in a matrix of silver. To obtain an approximate idea of the effect of these particles upon the susceptibility of the material as a whole, it would be sufficient to regard them as spheres. Since the apparent susceptibility of a sphere is equal to $K/(1 + \frac{4}{3}\pi K)$, where K is the true susceptibility, and since the true susceptibility of iron in weak fields is considerable, the apparent susceptibility of such spheres would be practically constant in weak fields and equal to $3/4\pi \doteq 0.24$. Hence, if the fraction of the total volume occupied by the iron were $n \times 10^{-6}$, the observed susceptibility of the material would be of the order $K_a = (0.24n - 2)10^{-6}$, where -2×10^{-6} represents the susceptibility of the silver. It was found by the authors that the susceptibility was practically constant over the range $H = 4$ to $H = 12$ c.g.s., and approximately equal to 0.25×10^{-6} . This would agree with $n \doteq 9.4$. In other words, the results would indicate that the amount of iron present as impurity was of the order 10 parts per million (by volume). The curves given by the authors seemed to show that the apparent susceptibility varied considerably in fields lower than $H = 4$; but part of the appearance of variability was due to the fact that, by inadvertence, the curves had been made to pass through $K_a = 0$ at $H = 0$. A possible source of uncertainty in the measurements in the weaker fields was the relatively great importance, under these circumstances, of P , the (assumed) permanent magnetism of the sphere. It seemed unlikely that the value of K for the iron in the weaker fields would be such as to make the effective susceptibility much less than $3/4\pi$, although there would be some tendency in this direction. The conclusion which he would draw from the data would be that the magnetic analysis of the material agreed with the chemical analysis and supported the inference, from other experiments, that iron and silver are mutually insoluble. The results obtained in strong fields (by Honda and others) did not, as the authors suggested, conflict with this conclusion, but confirmed it. The diamagnetic susceptibility of silver probably remains constant as the field strength is increased (within experimental limits) ; but, in intense fields, the susceptibility of iron is small compared with $3/4\pi$. For

instance, in fields of the order 25,000 c.g.s., the value of K may be of the order 0.1 to 0.05. Taking the latter figure, the effective susceptibility of the iron spheres would be approximately 0.04. The observed susceptibility of the material as a whole would be of the order $K_n = (0.04n - 2)10^{-6}$. Hence, assuming the value of n already deduced, we should expect K_n to be of the order -1.6×10^{-6} . Therefore, we should expect that the material used by the authors would become diamagnetic in strong fields. That it would, in fact, behave in such fields like the silver, of similar purity, examined by Honda.

Dr. CHREE said it was of the utmost importance in working with weak fields to get rid of effects due to electric tram and railway systems. This was not an easy matter nowadays. He had expected to hear some reference to the bearing of these results on Dr. Shaw's gravitational experiments, and would like to know if the magnetic experiments had caused any modification in Dr. Shaw's conclusions on the effect of temperature on gravity.

Prof. BOYS said that in his own experiments on gravitation, and also in the design of the radio-micrometer, the magnetism of impurities had always to be considered. The magnetic forces involved are so minute, that in most instruments—galvanometers, for example—they are ignored. In the radio-micrometer the field that could be employed was limited by the magnetism of the purest copper that could be obtained. He had drawn some copper himself which, after being cleaned with acid and gilt to protect it from air, had worked very satisfactorily. In the case of his gravitation experiments, he had used gold balls, of the greatest purity the Mint could supply, cleaned with nitric acid. No consistent magnetic disturbances were detected on moving a permanent magnet about in their neighbourhood.

Dr. SHAW, replying for the authors, was gratified that Dr. Smith's calculations had confirmed their numerical results. His theoretical treatment had been very instructive, and had enlightened them on several important points. He would like to ask Dr. Smith if superposition of magnetic properties would still occur in the case of two mutually soluble metals?

Dr. SMITH: In general, no.

Dr. SHAW, continuing, said, in reply to Dr. Chree, that in order to test whether the magnetic force between the large lead spheres and the silver spheres would vary appreciably with temperature in the gravitational experiments, he had inserted an iron bar in one of the lead spheres, but even then he had been unable to detect any variation in the force exerted on the silver when the lead and its contained rod were heated to 200°C. Since the magnetic material in the lead was very much less than this in the actual gravitation experiments, it was certain that the results were not affected by thermo-magnetic phenomena.