ON THE SUSCEPTIBILITY OF MIXTURES OF SALT SOLUTIONS.[1]

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IN the following paper an account is given of some measurements made on the magnetic susceptibility of solutions of manganese, aluminium and copper sulphates in water, and several mixtures of these with the object of obtaining information which might be of service in explaining the behavior of the magnetic alloys recently discovered by Heusler,[2] and more recently studied by Gumlich,[3] Austin,[4] Fleming and Hadfield,[5] Take,[6] Hill[7] and Guthe and Austin.[8]

The method followed in measuring the susceptibility of the solutions was that suggested by Lord Kelvin,[9] and afterward used by Wills[10] in his experiments on the susceptibility of weakly magnetic solids and liquids, and later by Burton and Phillips[11] in their investigation of the magnetic properties of iron in the colloidal state.

The arrangement of the apparatus is indicated in Figs. 1 and 2. A rectangular slab *S*, Fig. 1, of the substance whose susceptibility is to be studied was suspended from one arm of a balance *B* with its long axis vertical, and its lower face in the strongest part of the field midway between the poles of an electromagnet.

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[1] Read before the American Physical Society at the December meeting in New York, 1906.

[2] Fr. Heusler, W. Starck, and E. Haupt, Verh. der Phys. Ges., 5, p. 219, 1903. Heusler, Starck, and Haupt ueber der ferromagnetischen Augenschaften von Legierung unmagnetischer Metalle, Marburg, 1904.

[3] Gumlich, Annalen der Physik, 16, p. 535, 1905.

[4] Austin, Verh. der Deut. Phys. Gesell., 6, p 211, 1904.

[5] Fleming and Hadfield, Proc. Roy. Soc., 76, p. 271, 1905.

[6] R. Take, Verh. der Deut. Phys. Gesell., 7, p. 133, 1905. Take, Ann. der Physik, Vierte, Folge, Band 20, p. 849.

[7] Hill, Phys. Rev., 21, 335, 1905; 23, No. 6, p. 498, 1906.

[8] Guthe and Austin, Bulletin of the Bureau of Standards, Washington, Vol. II., No. 2, August, 1906, p. 297.

[9] Brit. Assoc. Rep., 1890, p. 745.

[10] Wills, Phys. Rev., April, 1898; ib., March, 1905.

[11] Burton and Phillips, Proc. Camb. Phil. Soc., Vol. XIII., Pt. V.

If k = the susceptibility of the material of the slab.
A = the area of the horizontal base of the slab.
H = the strength of the magnetic field at the point midway between the poles.
H_1 = the strength of the magnetic field at the upper surface of the slab.

Then the pull P in grams due to the magnetic field is given by

$$P = \frac{kA(H^2 - H_1^2)}{2g} \text{ grams.}$$

The electromagnet used in the investigation was provided with prismatic pole pieces with plane vertical faces 5 cm. wide, and about 1.5 cm. in height. These were adjusted to approximately 1.5 cm. apart, and kept in one fixed position throughout the different measurements. In determining k for a selected liquid the slab S was replaced by a deep rectangular glass vessel, Fig. 2, which measured internally 8 cm. in height, .78 cm. in width and 2.44 cm. in breadth. Preliminary measurements were first made on the pull exerted on the empty cell when currents of different intensities were passed through the electromagnet. The solution to be examined was then placed in a glass cell, and the pull on the filled cell again ascertained for different strengths of field. By combin-

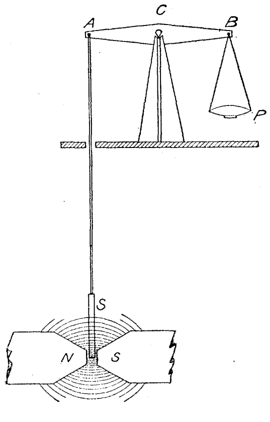

Fig. 1.

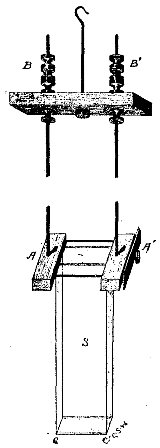

Fig. 2.

ing these two sets of measurements the pull in the selected solution itself was obtained and the susceptibility calculated for the different strengths of field from the formula

$$k = \frac{2pg}{A(H^2 - H_1^2)}.$$

In measuring the intensity of the magnetic fields used in the experiments, a slab of wood whose dimensions were approximately the same as the internal dimensions of the glass cell was inserted in the frame in place of the cell. To the narrow vertical and lower sides of this wooden slab a strip of tinfoil was pasted, and connection was made by contact pieces at A and A', Fig. 2, to the supporting rods. Wires were attached to these at B and B', and through them currents of different strengths sent to the tinfoil circuit.

If the current carried by the tinfoil circuit be i amperes, and the length of the horizontal portion of the foil be l cm., then the pull P in grams exerted by a field H on the lower strip of the foil can readily be shown to be given by the relation

$$P = \frac{Hli}{10g}$$

and consequently the strength of the field by the equation

$$H = \frac{10Pg}{li}.$$

The use of this method permitted the field strengths to be determined with accuracy and also with considerable ease. In all the experiments the current strengths were measured by Weston instruments which previously had been standardized.

I. DETERMINATION OF MAGNETIC FIELD.

As wood itself is slightly diamagnetic the different magnetic fields were found to exert a force on the slab even when no current was passing through the foil. It was therefore necessary to allow for this effect in calculating the field strengths. A set of measurements on the different fields used is given in Table I.

TABLE I.

Magnetic Field.

i in E.M.	i in Foil.	Pull on Slab no i in Foil.	Pull on Slab with i in Foil.	Pull on Foil.	$H = 10Pg/li$. $l = 3.025$ $g = 980.5$.
6.25	.13	−.0094	.1697	.1791	4465
6.4	—	−.0098	—	—	—
6.8	.13	−.0106	.1783	.1889	4710
7.15	.13	−.0113	.1837	.1950	4862
7.4	.13	−.0115	.1899	.2014	5022
7.95	.13	−.0132	.1959	.2091	5214
8.73	.13	−.0149	.2068	.2217	5528
9.05	—	−.0157	—	—	—
9.4	.13	−.0164	.2153	.2317	5777
10.0	.13	−.0177	.2235	.2412	6014
10.25	—	−.0185	—	—	—
10.6	.13	−.0190	.2297	.2487	6201
10.95	.13	−.0198	.2337	.2535	6321
11.41	.13	−.0204	.2363	.2567	6500
11.55	—	−.0209	—	—	—
12.15	.13	−.0224	.2466	.2690	6707
12.95	.13	−.0244	.2553	.2797	6974
14.05	—	−.0268	—	—	—
14.10	.13	−.0269	.2687	.2956	7367

In column I. are given the strengths of the current in amperes in the electromagnet, in column II. the strengths of the current in amperes in the foil circuit, in column III. the pulls on the wooden slab when there was no current in the foil circuit, and in column IV. the pulls on the slab, with the current passing through the foil circuit. Columns V. and VI. contain respectively the deduced values of the pulls on the foil circuit and the corresponding calculated values of the magnetic field strengths.

TABLE II.

Strength of Upper Part of Field.

i in E.M.	i in Foil.	Pull on Slab no i in Foil.	Pull on Slab with i in Foil.	Pull Due to i in Foil.	H (Calc.). $H = 10Pg/li$.
5.85	.1	−.0085	−.0008	.0077	248
9.0	.1	−.0155	−.0062	.0093	302
10.27	.1	−.0183	−.0088	.0095	308
12.6	.1	−.0235	−.0127	.0108	340
14.7	.1	−.0280	−.0164	.0116	376

A second set of measurements was made with the slab reversed, so that the current in the foil circuit passed over the upper surface of the slab instead of along the lower one, as in the previous measurements. A set of these weighings is given in Table II., and from them the value of H_1 deduced. These values, it will be seen, are small compared with the corresponding one for H, and are therefore negligible compared with the latter.

II. SUSCEPTIBILITY OF WATER.

As a control experiment a preliminary set of measurements was made upon the susceptibility of water, and the mean of a number of results found with fields ranging from 4,000 to 8,000 C.G.S. units, gave -7.33×10^{-7}, a value which is in good agreement with the results of other investigators.[1]

III. SUSCEPTIBILITIES OF SALT SOLUTIONS.

Manganese Sulphate, $MnSO_4$. — In experimenting with this salt a standard solution was prepared which was found by a gravimetric analysis to contain .0792 gram of manganese per c.c. The susceptibility was determined for fields ranging from 4,700 to 7,315 C.G.S. units, and the results of the different weighings are recorded in Table III.

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[1] Susceptibility of water from a Table given by H. D. Stearns, PHYS. REV., Vol. 16, pp. 1–10, January, 1903.

	T	$k \times 10^7$	Reference.
1885 Quincke.	20°C.	−8.4	Wied. Ann., Vol. 35, p. 137, 1888.
1888 DuBois.	15 C.	−8.6	Wied. Ann., Vol. 35, p. 137, 1888.
1892 Henrichsen.		−7.5	Wied. Ann., Vol. 45, p. 38, 1892.
1895 Curie.	18 C.	−7.9	Jour. de Phys., p. 106, 1895.
1896 Townsend.	10 C.	−7.7	Proc. Roy. Soc., London, 60, p. 186, 1898.
1898-1901 Koenigsberger.	20 C.	−8	Wied. Ann., Vol. 66, p. 698, 1898, and Drude's Ann., Vol. 6, p. 506, 1901.
1898 Fleming & Dewar.		−7.4	Proc. Roy. Soc., 63, p. 328, 1898.
1899 Jaeger & H. Meyer.	18 C.	−6.6	Wied. Ann., Vol. 67, p. 712, 1899. Drude's Ann., Vol. 6, p. 870, 1901.
1903 H. D. Stearns.	22 C.	−7.33	Phys. Rev., Vol. 16, pp. 1–10, 1903.
1904 A. P. Wills.		−7.22	Phys. Rev., Vol. 22, p. 188, 1905.

Table III.

Solution $MNSO_4$. .0792 *gm. per c.c.*

H	Field Pull on Cell Water.	Pull on Cell Solution.	Pull on Salt in Solution.	$10^7 \times K$. $K = \frac{2Pg}{AH^2}$ $A = 1.9$ sq. cm. $g = 980.5$ dynes.
4,700	−.0267	.4448	.4715	213.38
4,955	−.0296	.4953	.5249	213.82
5,250	−.0334	.5545	.5877	213.26
5,500	−.0370	.6173	.6543	216.32
5,550	−.0375	.6245	.6618	214.87
6,000	−.0445	.7383	.7828	217.47
7,315	−.0638	1.0833	1.1471	214.40
				Mean 214.79

If we define molecular susceptibitity, M_s, by the equation

$$M_s = \frac{MK}{d}$$

where M is the molecular weight of the salt, K the susceptibility of the solution, and d the number of grams of the salt per c.c. in solution, we obtain from the above table the value .014915 as the molecular susceptibility of the salt.

In order to test whether the molecular susceptibility depended on the concentration, the standard solution was diluted and the susceptibility found for different concentrations. The results which are given in Table IV., show that the molecular susceptibility did not vary appreciably with the concentration.

Copper Sulphate. — Similar measurements made on a solution of

Table IV.

$MnSO_4$. *Relation of Concentration to Susceptibility.*

Concentration Grams of Mn per c.c.	Susceptibility of Solution 10^7K.	Molecular Susceptibility M_s.
.0792	214.7	.014925
.0264	74.51	.01552
.01582	41.28	.01433
.0088	23.78	.01486
		Mean M_s = .01491

copper sulphate containing .0191 gram of copper per c.c., gave a molecular susceptibility of + .00153.

Aluminium Salts. — When the susceptibility of a solution of aluminium sulphate containing .018 gram of metal per c.c. was measured, it was found to give a small negative value showing that this salt in solution is slightly diamagnetic. On account of the fact that aluminium is generally given as being weakly paramagnetic, and that no results seem to have been recorded for the salts of this metal, the susceptibilities of aluminium nitrate and of aluminium chloride were also determined and the results obtained are given in Table V.

TABLE V.

Salt.	Concentration gms. of Metal per c.c.	Susceptibility of Solution $10^7 K$.	Molecular Susceptibility M_s.
Aluminium Sulphate $Al_2(SO_4)_3$	.018	− .64	−.00018
Aluminium Nitrate $Al_2(NO_3)_6$	.097	+ .33	+.00002
Aluminium Chloride Al_2Cl_6	.094	−1.04	−.00005

From this table it will be seen that while the sulphate and the chloride are diamagnetic, the nitrate is paramagnetic. This difference between the susceptibilities of the metal and some of its compounds forms a parallel to the case of copper, where the pure metal is diamagnetic at ordinary temperatures while the salts are largely paramagnetic.

IV. MIXTURES OF SALT SOLUTIONS.

In view of the behavior of Heusler's alloys which exhibit a maximum permeability when the manganese and aluminium are present in the alloy in the ratio of their atomic weights, it seemed of interest to ascertain whether or not the susceptibility of a solution of manganese sulphate was affected by the addition of varying quantities of aluminium sulphate.

With this object in view a solution of manganese sulphate containing .0182 gram of manganese per c.c. was prepared, also one of aluminium sulphate containing .018 gram of aluminium per c.c., and one of copper sulphate containing .019 gram of copper per c.c., and the following mixtures of these solutions were examined.

(1) 8 c.c. $MnSO_4$ sol. + 8 c.c. H_2O.
(2) 8 c.c. $MnSO_4$ sol. + 2 c.c. $Al_2(SO_4)_3$ sol. + 6 c.c. H_2O.
(3) 8 c.c. $MnSO_4$ sol. + 4 c.c. $Al_2(SO_4)_3$ sol. + 4 c.c. H_2O.
(4) 8 c.c. $MnSO_4$ sol. + 8 c.c. $Al_2(SO_4)_3$ sol.

The susceptibilities of all the above solutions were found to be practically the same, showing that the aluminium present in the mixtures produced no modification in the susceptibility of the manganese such as it does in Heusler's alloys.

A second series was prepared in which the water added to make up the mixtures to 16 c.c. in the first series was replaced by the copper sulphate solution, and measurements made with these mixtures are given in Table VI.

Table VI.

Mixtures.	Susceptibilities $10^7 K$.	Atomic Ratio of Aluminium to Manganese.
I. $MnSO_4$ sol. 8 c.c. $Al_2(SO_4)_3$ sol. 8 c.c.	24.37	2.02
II. $MnSO_4$ sol. 8 c.c. Al_2SO_4 sol. 4 c.c. $CuSO_4$ sol. 4 c.c.	26.04	1.00
III. $MnSO_4$ sol. 8 c.c. Al_2SO_4 sol. 2 c.c. $CuSO_4$ sol. 6 c.c.	26.65	.50
IV. $MnSO_4$ sol. 8 c.c. $CuSO_4$ sol. 8 c.c.	27.49	——

A curve representing them is shown in Fig. 3, where the abscissæ represent the susceptibilities × 10^7 and the ordinates the volumes of copper sulphate in the mixture.

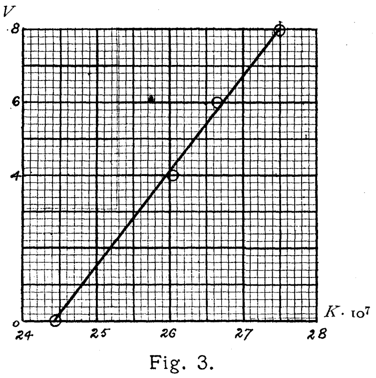

Fig. 3.

These results show a regular increase in susceptibility proportional to the amount of copper added, which indicates that the susceptibilities of the mixtures followed a simple additive law, such as was found by Wiedemann[1] to hold for other salts. The susceptibility of aluminium sulphate has been shown to be extremely small, and on the basis of an additive law, its effect in the two sets of mixtures tested should be inappreciable. The susceptibility of any mixture should

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[1] Wied. Elect., III., pp. 955–972.

therefore be determined by the respective susceptibilities of the manganese and copper sulphates, and from the measurements given above it will be seen that this was the result obtained.

With the mixtures tested the atomic ratios of the aluminium to the manganese present in the solutions varied from 2.02 to zero. It is evident, therefore, from the above experiments that the relations the two metals bear to each other under the conditions of the present investigation are quite different from those which exist between them in the alloys. In the latter the aluminium by its presence produces a very pronounced increase in the permeability of the manganese but the measurements made in the experiments described above go to show that no such action takes place between the metals when solutions of their salts are mixed.

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