The Magnetic Susceptibilities of Lead, Silver and Their Alloys

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The magnetic susceptibilities of lead, silver and their alloys have been determined by a modified Curie balance. They may be expressed by $10^9\chi=(116.44\pm0.68)+(0.764\pm0.012)P$, P being the weight percent of silver. The anomalous results reported previously by Spencer and John in regard to the magnetic behavior of these alloys are not confirmed.

THE general behavior of the magnetic susceptibilities of alloys of nonferromagnetic metals has been established by numerous investigators,[1] and certain rules may be laid down regarding it. In particular, if the alloy series consists of a heterogeneous mixture of two phases, then the magnetic susceptibility should vary linearly with the composition by weight from the value of one phase to the value of the other. The validity of this rule seems obvious, and in addition it has been well checked by careful observers. Therefore, it is quite surprising to find in the literature, several alloy series which appear flagrantly to disobey it. Spencer and John[2] in 1927 investigated a number of alloys of the noble metals, silver and gold, with a base metal, lead, tin or cadmium. None of these alloys behaved as would be expected. In particular, lead and silver are practically insoluble in each other, and their alloys of all compositions consist of merely mechanical mixtures of lead and silver. The magnetic susceptibility of these alloys should then vary linearly from the value of lead to that of silver. This was not found to be true, and, in fact, alloys containing from 3.6 percent to 47.6 percent by weight of lead were found to be strongly paramagnetic, notwithstanding the fact that both pure lead and silver are diamagnetic. The present work was undertaken to reinvestigate this phenomenon.

The apparatus used for the measurement of the magnetic susceptibilities was a modified Curie balance which has been previously described.[3] For this work an electrodynamometer was added so that the force on the beam in the magnetic field could be balanced out by the force between two current-carrying coils. A device for additional damping was also used which consisted of a small sheet of aluminum attached to the beam. This aluminum was in a magnetic field produced by a small electromagnet. The electromagnetic damping could be easily controlled by changing this field and was adjusted until the motion of the beam was critically damped. Care was taken to avoid the production of convection currents in the room. It was found that these improvements contributed materially to the convenience for use and to the accuracy of the apparatus.

The magnetic susceptibilities were determined by comparison with a standard of gold of purity 99.99 percent or better obtained from Baker and Company. It was cut in the form of a small cylinder of about the same size as the alloy samples. Its susceptibility per gram was taken[4] as -141.0×10^{-9}. The susceptibility per unit volume of air was taken as 29×10^{-9}, and hence the susceptibility of the standard relative to air as -142.5×10^{-9} per gram. The current necessary to balance out the deflection of the sample was determined for several values of the field strength. At each field strength four readings of the current were taken, reversing either the direction of the field or the compensating current

[1] K. Honda and T. Soné, Sci. Rep. Tohoku Univ. [1] **2**, 1–14 (1913); H. Endo, ibid. **14**, 479–512 (1925); recently F. L. Meara, Physics **2**, 33–41 (1932).

[2] J. F. Spencer and M. E. John, Proc. Roy. Soc. **A116**, 61–72 (1927).

[3] Carol G. Montgomery, Phys. Rev. **36**, 498–505 (1930).

[4] H. J. Seeman and E. Vogt, Ann. d. Physik [5] **2**, 976–990 (1929).

each time in order to eliminate any effect of stray fields upon the electrodynamometer. Similar determinations were made for the effect of the holder and the standard at each run of the apparatus. All the measurements were made within a few degrees of 20°C. The masses of the alloys were determined on an analytical balance with calibrated weights. The densities were computed from the relation[5] $v=0.09551-0.0000760p$, where v is the specific volume in cubic centimeters and p the weight percent of lead. The susceptibilities were then computed from the expression: $\chi_a=\chi'(m'/m)[(i_a-i_h)/(i'-i_h)]+\kappa/\rho$, where χ_a is the susceptibility of the alloy per gram relative to vacuum, χ' the susceptibility of the standard relative to air; m and m' the masses of the alloy and the standard respectively; i_a, i_h, i' the currents necessary to compensate for the alloy plus holder, the holder, and the standard plus holder respectively; κ the volume susceptibility of air; and ρ the density of the alloy.

The alloys of high silver content were made from the pure materials by fusing in quartz in an oil-pump vacuum. The rest were fused in a graphite crucible in air, by using a cover of molten borax to prevent oxidation. The melts were allowed to cool quickly to prevent any tendency for segregation. The crucibles were broken away and the alloys cut to a convenient size either on a lathe or with a clean file. Care was taken to prevent contamination before melting. After the sample was prepared, it was necessary to clean the surface carefully to get rid of ferromagnetic impurities. This was accomplished by a prolonged etching in a 5 percent solution of nitric acid in alcohol. The etching process was continued until a constant value of the susceptibility was obtained. The samples were small cylinders about one centimeter long and weighed between two and five grams.

After the magnetic measurements were complete, the samples were rolled out and sampled for analysis by clipping. The analysis was effected by making a corrected fire assay for the silver, the lead being determined by difference. The fire loss amounted to between 2 and 3 milligrams of silver for a 100-milligram button and was determined from two blanks. The percentage of silver present was determined to within an estimated error of one-third of one percent. Although tests were made, both by microscopic examination and by means of analysis, no evidence for segregation was obtained. The authors wish to express their sincere thanks to Mr. W. E. Milligan of the Hammond Metallurgical Laboratory of Yale University for carrying out these cupellations.

TABLE I. *Measurement of diamagnetic susceptibilities.*

Alloy	% Ag by weight	Mass (g)	Diamagnetic susceptibility per g$\times 10^9$
Lead *a*	0	4.851	116.0
" *b*	0	5.466	119.5
" *c*	0	5.770	115.1
" *d*	0	5.767	116.1
1	10.6	4.845	122.9
2	10.9	4.558	125.0
3	21.6	4.807	133.1
4	26.4	4.055	135.8
5	27.3	4.152	136.5
6	38.4	3.340	144.1
7	39.6	4.284	146.4
8	47.4	4.663	158.3
9	68.4	2.695	170.2
10	80.8	4.046	178.6
11	85.5	2.220	182.6
Silver *a*	100.0	2.514	190.2
" *b*	100.0	2.141	191.4
" *c*	100.0	3.715	194.4

Table I contains the results of these measurements. Each value of the susceptibility given in the table is derived from the mean of twenty or more readings of the electrodynamometer current, taken at several values of the field strength and in several cases at quite different times. There was never observed any variation of susceptibility with the strength of the field, and hence the samples may be regarded as free from ferromagnetic impurities. The separate values listed for pure lead and silver were obtained from as many different melts. These values are represented graphically in Fig. 1. It is impossible to represent Spencer's and John's reported values on this figure as they extend to a paramagnetic susceptibility of 2000×10^{-9}.

The mean deviation of the susceptibilities from the mean susceptibility for each sample amounts to 2.23×10^{-9} per gram or from 1 to 2 percent. As the analyses of the alloys are more accurate than this, we may find by least-squares methods the best straight line to fit the points, regarding the percentages of silver as accurate.

[5] E. Maey, Zeits. f. physik. Chemie **38**, 295 (1901).

The result of such a computation is $10^9\chi = (116.44 \pm 0.68) + (0.764 \pm 0.012)P$, where P is the weight percent of silver. The points fit the line closer than is to be expected. The value of 0.6745 $[\Sigma v^2/(n-2)]^{\frac{1}{2}}$, where v is the residual, is 1.15×10^{-9}, while computing the probable error of a single observation by $0.8453 \times 2.23 \times 10^{-9}$ (Peter's method), we get 1.88×10^{-9}. As this value is larger than the other, it was adopted and the probable errors in the expression for the susceptibility computed from it. By this means it is possible to get more accurate values of the susceptibilities of pure lead and silver than by direct observations. The values so determined are, per gram,

$$\text{for lead} \quad \chi = (116.4 \pm 0.7) \times 10^{-9},$$

$$\text{for silver} \quad \chi = (192.8 \pm 0.8) \times 10^{-9}.$$ [6]

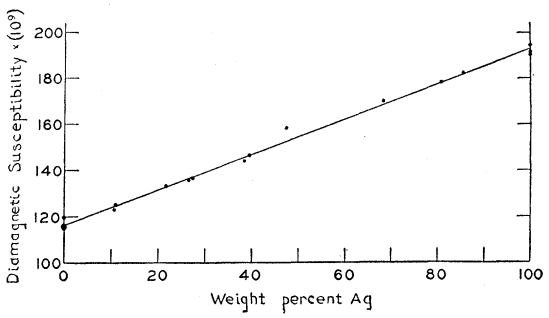

FIG. 1. Diamagnetic susceptibility of lead-silver alloys as a function of silver content.

Thus, it is shown that lead-silver alloys do behave as expected within the observation errors of these experiments.

It remains to suggest that the results of Spencer's and John's work are incorrect because of iron contamination. The values determined above are all more diamagnetic than theirs. Their magnetic field was comparatively weak, of the order of one thousand gauss, and iron contamination has a larger effect at low field strength. Hence it appears probable that this is the reason for the anomalous behavior of the alloys that Spencer and John measured.

In conclusion, the authors wish to express their thanks to Professor L. W. McKeehan for his helpful guidance, and the senior author to the Sterling Fellowship Fund for financial assistance.

[6] These experiments offer no support to so low a value as $\chi_{Ag} = 179.4 \times 10^{-9}$ found by E. Vogt, Ann. d. Physik [5] **14**, 1–39 (1932).