MAGNETIC PROPERTIES OF GOLD-IRON ALLOYS

By J. W. Shih
Physics Department, University of Illinois

(Received October 1, 1931)

Abstract

The alloys of gold and iron of different compositions ranging from 0.07 to 10 percent iron by weight have been studied. It was found that the alloys containing 0.1 to 5 percent iron are paramagnetic. Their susceptibilities decrease with rising temperature in a characteristic way, but do not follow either Curie's law or Weiss' law exactly. The square root of susceptibility increases linearly with the percentage of iron atoms added. Thus the gold-iron series does not show the same property as the nickel-copper alloys whose susceptibility increases with temperature in certain ranges. The behavior of the iron atoms in the alloy and some correlations between magnetic susceptibility, density and melting point are discussed.

Introduction

Dr. E. H. Williams[1] of this laboratory has found that alloys of nickel and copper in certain compositions yield paramagnetic substances, in which the paramagnetic susceptibility increases with increasing temperature. This phenomenon also appears in some pure elements such as titanium, chromium, rhodium, boron and one modification of solid oxygen ($13° - 33°K$) but is in conflict with all theories of magnetism. Kamerlingh Onnes[2] has suggested that if paramagnetic atoms unite into a crystal structure, they will only be able to show typical paramagnetic behavior if the carriers are free to change their orientation, but this will be impossible if the magnetic electrons form the binding links which build up the stable crystal structure. Increased temperature, resulting in increased freedom, allows the magnetic carriers to change their orientation under the influence of a field to a greater extent than at low temperature and there may actually be an increase in paramagnetic susceptibility. At the same time the temperature becomes more and more effective in disturbing the magnetic equilibrium. An increasing or decreasing susceptibility will therefore be observed according to the predominating effect. This explanation might be applicable to the nickel-copper alloys, but the question arises as to whether this anomalous paramagnetic phenomenon is a general property of alloys of ferro-magnetic and diamagnetic elements. It would therefore be very interesting to study other alloys of this type to determine whether this anomalous paramagnetic property appears in them likewise. Unfortunately there are only a few pairs of diamagnetic and ferromagnetic metals which lend themselves to such investigations. One of these consists of gold and iron.

[1] E. H. Williams, Phys. Rev. **38**, 828 (1931).

[2] E. C. Stoner, Magnetism and Atomic Structure, E. P. Dutton and Co., New York, 1926, p. 170.

Experimental Details

Pure gold was supplied by Baker and Company and pure iron was kindly furnished by Dr. T. D. Yensen of the Westinghouse Electric and Manufacturing Company. The purity of the former was not guaranteed but the latter was believed to be the purest obtainable in this country. Gold and iron form homogeneous solid solutions[3] in the range 0 to 15 percent iron by weight. The melting point of the alloy depends upon the amount of iron. It has a minimum of about 1040°C for an iron content of about 5 percent. Nine samples of different compositions from 0.07 to 10 percent iron were prepared in an atmosphere of hydrogen (which is insoluble in the alloy). In order to make the alloy very homogeneous the process of melting and cooling was repeated three times for each sample and the ingot was then annealed for two hours. Among all the alloys prepared only the 10 percent specimen changes its color from golden to gray.

The magnetic susceptibility was determined with a Curie balance having an electric control torsion head.[4] The apparatus was calibrated both with distilled water and with cobalt sulphate. The latter was used as practical standard because of its convenience in handling and since its paramagnetic susceptibility[5] is accurately known. The non-uniform field was produced by a large Dubois magnet with two pole pieces specially designed.[6] It was found that these pole pieces gave a region of about two cm in length in which the product $H(\delta H/\delta X)$ is practically constant, where H is the field strength and $\delta H/\delta X$ the field gradient. The value of H at the position of the specimen is about 4500 gausses. The sensitivity of the apparatus depends on the size of the suspension. Phosphor-bronze wire of diameter 0.0202 cm (32 B. & S.) gave about 20 cm deflection at a scale distance of one meter for one gram of water in a field of the above value.

The furnace was such that a temperature of about 1000°C could be obtained. A chromel-alumel thermocouple was used for the temperature measurement. In order to prevent the specimen from oxidizing at high temperatures, hydrogen was passed gently into the furnace during the time of the experiment. The alloy did not lose its lustre after heating, thus indicating that oxidation was completely eliminated.

Results

Nine alloys ranging from 0.07 to 10 percent iron by weight have been measured in the temperature range from 20° to 800°C. Paramagnetism begins for the alloy containing about 0.1 percent iron and continues to a point between 5 and 10 percent iron where it is replaced, at room temperature, by ferromagnetism. The paramagnetic susceptibility decreases first very rapidly and then slowly with rising temperature. The diamagnetic susceptibility of the pure gold is practically constant over the same temperature range. Its

[3] G. Tammann, Zeits. f. anorg. Chem. **53**, 281 (1907).
[4] A. N. Guthrie and L. T. Bourland, Phys. Rev. **37**, 309 (1931).
[5] E. C. Stoner, reference 2, p. 134.
[6] G. Foëx and R. Forrer, Jour. de physique [6], **7**, 180 (1926).

value, as here measured, is -0.148×10^{-6} at room temperature and -0.150×10^{-6} at 800°C. This checks very well with Honda's[7] results. A test on the variation of susceptibility with field has been made on the 5 percent alloy which is important in regarding this effect. It shows that its susceptibility is fairly constant in a wide range of field strength (300-5700 gausses).

TABLE I. *Mass susceptibilities of gold-iron alloys at room temperature.*

Percent of Fe	Suscept., $\chi\times10^6$	Percent of Fe	Suscept., $\chi\times10^6$
0.07	−0.041	2.0	4.33
0.085	−0.023	3.5	12.72
0.1	+0.01	5.0	29.76
0.5	0.559	10.0	Ferromagnetic
1.0	1.52		

Table I gives the susceptibilities of the different alloys at room temperature and their variation with temperature is shown in Fig. 1. In order to show

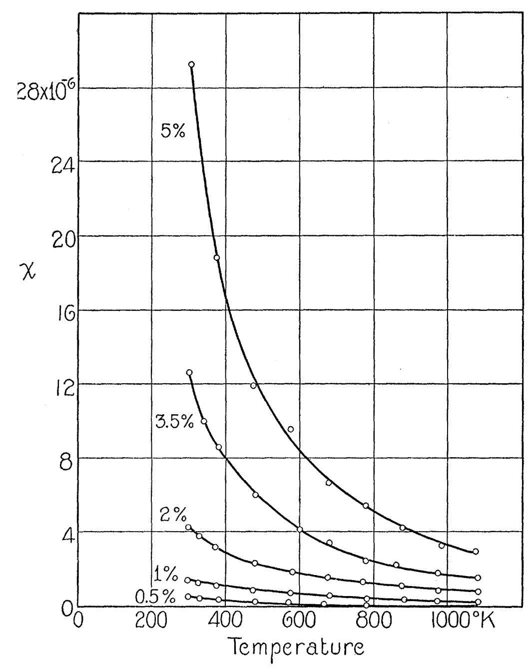

Fig. 1. $\chi-T$ curves for gold-iron alloys.

how the temperature-susceptibility relation deviates from Curie's or Weiss' law, a typical $\chi^{-1}-T$ curve is given in Fig. 2.

Since the volume susceptibility of hydrogen is only about one six-thousandth of that of the 0.5 percent alloy, its maximum possible effect upon the susceptibility is negligibly small. The total error introduced due to the un-

[7] K. Honda, Ann. d. Physik [4], **32**, 1027 (1910).

certainty of the position of the specimen in field, to the fluctuation of field strengths, to the inaccuracy of weighing, etc., is less than 1 percent.

Discussion

The results show that the paramagnetic susceptibility of gold-iron alloys decreases with increasing temperature. It changes in a characteristic way but it follows neither Curie's law nor the Weiss law, exactly. Thus, the gold-iron alloy does not behave in the same way as the nickel-copper alloy. There is no sudden change of susceptibility in the neighborhood of 790° which is the Curie point of pure iron. It seems that the iron atoms lose their ferromagnetic pro-

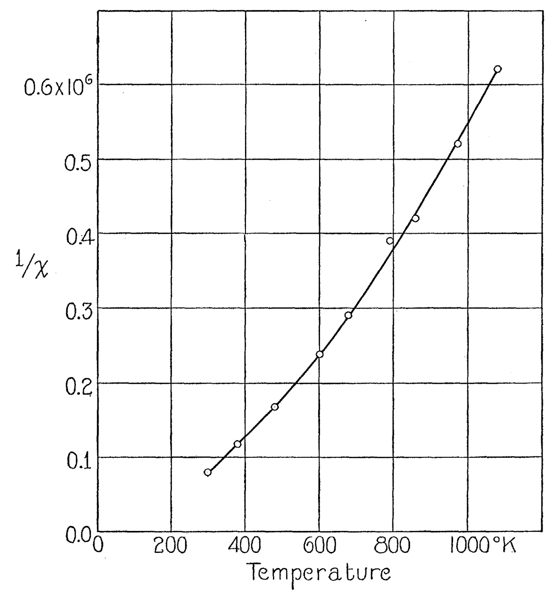

Fig. 2. $\chi^{-1}-T$ curve for the 3.5 percent Fe alloy.

perties in the alloy. Moreover, if the iron atoms remain in their ferromagnetic state only about three ten-thousandths of 1 percent of iron would be necessary to compensate completely all the diamagnetic effect of the gold. But the alloy remains diamagnetic until the iron content amounts to 0.1 percent. This fact is completely in accord with the recent quantum interaction theory[8] of ferromagnetism which deduces the fundamental mechanism of the Weiss molecular field from the resonance between the spinning electrons of neighboring atoms, i.e., if the iron atoms are sufficiently separated they will become nonferromagnetic.

Another interesting result is observed if we plot (Fig. 3) the square root of susceptibility at different temperatures as ordinates and the percentage of iron atoms as abscissas. Except for the point at the lowest iron content the variation of $\chi^{1/2}$ is linear. There is another point [(a), as indicated in Fig. 3]

[8] W. Heisenberg, Zeits. f. Physik **49**, 619 (1928).

corresponding to the 5 percent alloy at room temperature, far from the straight line. This, perhaps, is due to the possibility that this alloy begins to become ferromagnetic or it may not be so homogeneous magnetically as the others at the low temperature. Davies and Keeping[9] found in both copper-magnesium and copper-antimony alloys the maximum susceptibilities which correspond to the eutectics. The 5 percent alloy has the lowest melting point and also its density suffers a greater decrease than would be expected from

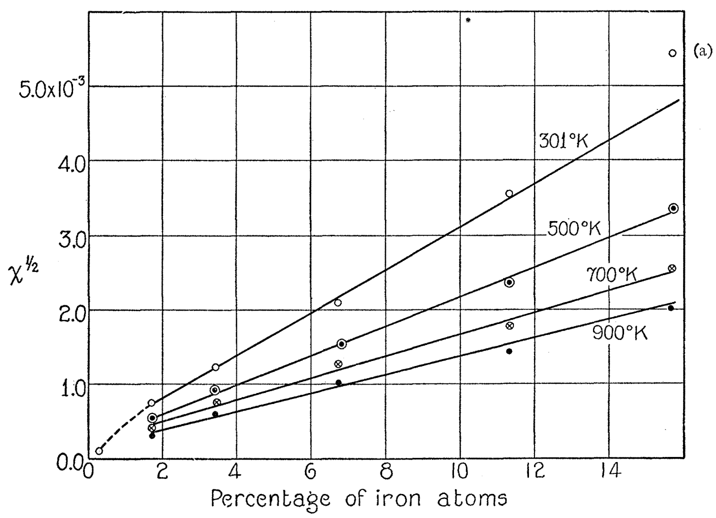

Fig. 3. The square root of susceptibility at different temperatures plotted against the percentage of iron atoms.

the density-percentage curve (not shown). Thus, it may have a peculiarly high susceptibility due to its structure at room temperature, masked by the effect of thermal agitation at high temperature.

In conclusion the writer wishes to express his thanks to Professor J. Kunz for the suggestion of the problem and discussion of the results, and also to Professor E. H. Williams for his valuable help in conducting this investigation.

[9] W. G. Davies and E. S. Keeping, Phil. Mag. [7], 7, 145 (1929).